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Effect of deep-sea mining on benthic biodiversity and ecosystem services in abyssal zones

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Abstract

Deep-sea mining (DSM) is a new approach to satisfy the increasing demand for critical minerals such as cobalt, nickel, and rare earth elements. These minerals lie within the ocean's abyssal zones, which exceed fifty percent of the Earth's surface. The abyssal zones contain numerous forms of life and provide vital ecosystem services. Unfortunately, the consequences of deep-sea mining remain vastly understudied. This paper analyses the lolopolagic DSM ecosystem impacts regarding sociology and political policies relating to biodiversity, ecosystem services, including nutrient cycling, carbon sequestration, and germplasm storage. This paper offers final remarks on DSM sustainability governance, impact assessments, and region-specific DSM sustainable policy construction.

Keywords: Deep-sea mining, Biodiversity, Abyssal zones, Genetic resource preservation, Environmental impact, and Sustainability

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Introduction

Spanning over 60% of the Earth's surface, the deep sea, particularly the regions located between 4,000 and 6,000 meters beneath the sea known as the abyssal zones, remains among the least known and explored areas on our planet. This vast underwater realm, despite being extremely remote, supports a variety of ecosystems that contain distinct forms of life capable of surviving the harsh deep-sea conditions, including darkness, low temperatures, and extreme pressure. In addition, the benthic zone or floor of the ocean along with the life forms it houses are crucial to the health of the planet's marine ecosystems as they provide essential ecological functions of maintaining and preserving resources through nutrient recycling, carbon sequestration, and the protection of genetic resources, all of which sustain the ocean's ecosystem biodiversity (Smith, 2017; Hui *et al.*, 2019).

The development of technologies, such as renewable energy and electric vehicles, has increased demand for rare cobalt and nickel minerals, thus boosting interest in deep-sea mining (DSM) (Hui *et al.*, 2019). Unfortunately, the concentration of these minerals often makes deep-sea mining an economically appealing opportunity (Priyalatha, 2024). However, these economically attractive operations raise severe concerns regarding the environmental consequences of mining operations in these sensitive locations (Jones *et al.*, 2021). DSM or deep-sea mining consists of removing valuable minerals from the ocean floor, which disrupts fragile ecosystems. Usually, such activities are accompanied by removing sediments from the seafloor, which generates cascading accumulations of suspended sediments or plumes and releases harmful chemicals into the water (Silva *et al.*, 2019). It is hoped that there is enough time to understand the actual consequences of these actions before facing their real impacts on the biodiversity of the deep sea, along with the invaluable ecosystem services these environments sustain (Green, Smith and Lee, 2019; Roberts *et al.*, 2021).

Abyssal zones' benthic ecosystems face the most significant impact of deep-sea mining concerning biodiversity. The organisms in these environments are susceptible to disturbances because they are infrequent reproducers, slow-growing, and long-lived (Carter and Heinriksen, 2023; Rex and Etter, 2010). In addition, a lot of deep-sea species are endemic, which means they can be found nowhere else on Earth. The fragmentation of habitats and the alteration of sediment and food chains would cause changes in the composition of species that can no longer be replaced, eradicating species that are key to the stability of these ecosystems (Thompson, Johnson and Roberts, 2015), developing irreversible impacts (Jones *et al.*, 2021).

In addition to the latent consequences of deep-sea mining on biodiversity, the ecosystem services also face threats. An ecological service of utmost importance is the sequestration of carbon. The deep-sea sediments have the potential to function as carbon sinks, trapping organic material for many years (Watling and Norse, 1998; Turner *et al.*, 2015). This material can be stored for centuries after sinking from the surface. If these sediments are disturbed, trapped carbon could be released into the ocean and the atmosphere, contributing to global warming (Smith *et al.,* 2019). The deep sea has an irreplaceable role in nutrient cycling, especially in the ocean. Benthos, specifically the microbes, recycle nutrients such as nitrogen and phosphorus (Amon *et al.,* 2018). These nutrients sustain life in the sea and the ocean itself. Disruption of these activities through mining could have worrying impacts on primary marine productivity and ocean ecosystems. Further, the unique genetic resources found in deep-sea organisms hold significant value. Many deep-sea species possess special biochemical properties. As a result, these species are likely to yield substantial pharmaceutical, industrial, and biotechnological products. Mining activities can lead to the loss of these species, which could lead to loss of irreplaceable genetic material that can be used for human advantage (Wedding *et al.,* 2015). There is little doubt that The International Seabed Authority (ISA), as well as international bodies, do not curb deep-sea mining sufficiently, meaning that other policies and proactive legislative aides are needed to protect global environmental law within fragile ecosystems, as well as strict, dynamic guards on ROI (return on investment), regulated. The ability of deep-sea mining (DSM) to foster new revenues for a plethora of economic operators leads to radically new opportunities in the mining, shipping, and even apologetic industries, if laws and rules of navigation/transportation embrace economic and international legislation. Given the stark risks posed to the environment by deep-sea mining, researchers must investigate the underlying impacts rapidly and build a solid framework that comprehensively explains the profound implications (Halbach, 2016). The environmental dilemmas beneath the deep-sea mining premise pose a robust, economically viable dilemma- if exploited carelessly, it can fuel economic turbulence/disorder. At the same time, careful exploitation means hard work and dampened returns, necessitating guarded handling (Jones *et al.,* 2017; Van Dover *et al.,* 2018). The deep-sea mining industry raises particularly sharp problems without any available uncertainty bounding baseline datasets and survey EIA (environmental impact assessment), making the impact of realized activities approximate the level of expertly devised intellectual entrapment, producing ecological havoc. (Williams *et al.,* 2019)

This paper aims to assess the impact of deep-sea mining on the benthic biodiversity and ecosystem services of abyssal zones. We will analyze the effects of these activities on biodiversity, nutrient cycling, carbon sequestration, and the conservation of genetic resources. In addition, we will evaluate the gaps in the current regulatory frameworks and the environmental damage they seek to control, offering suggestions on how to improve these regulations. This study intends to balance the deep-sea development versus conservation dilemma by finding ways to mitigate ecological destruction and protect ecosystems as mining expands into sensitive environments (Thiel and Koslow, 2001).

Benthic Biodiversity in Abyssal Zones

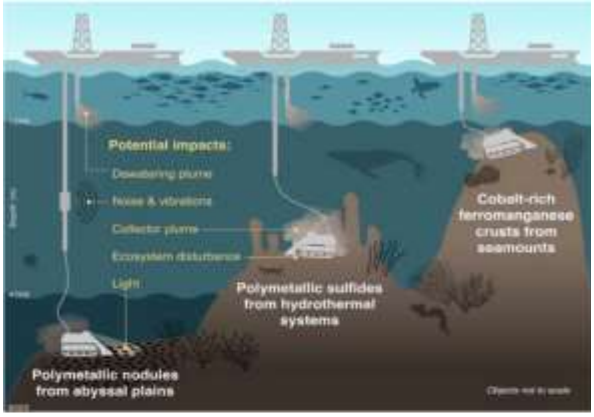

Figure 1: Schematic of Deep-Sea Mining Impacts on Marine Ecosystems

Figure 1 systematizes Deep-sea mining operations and their potential impacts on various marine systems, such as the abyssal plains, hydrothermal systems, and seamounts. It underscores the multiple effects mining activities can have on the marine environment, including sediment disruption, habitat devastation, and alteration of water chemistry.

Community Composition and Functional Diversity

The deep-sea biosphere is home to abyssal benthic communities, which exemplify life forms profoundly adapted to the extremes of the deep sea. These communities contain bacteria, archaea, nematodes, polychaetes, echinoderms, filters, and crustacean and sessile filter feeders (Green, Smith and Lee, 2019). Because of the restricted geographical distribution of many species, low population densities and sparse reproductive output, mobility, selective rate of motility, and selective mobility to environmental changes render them vulnerable to environmental changes.

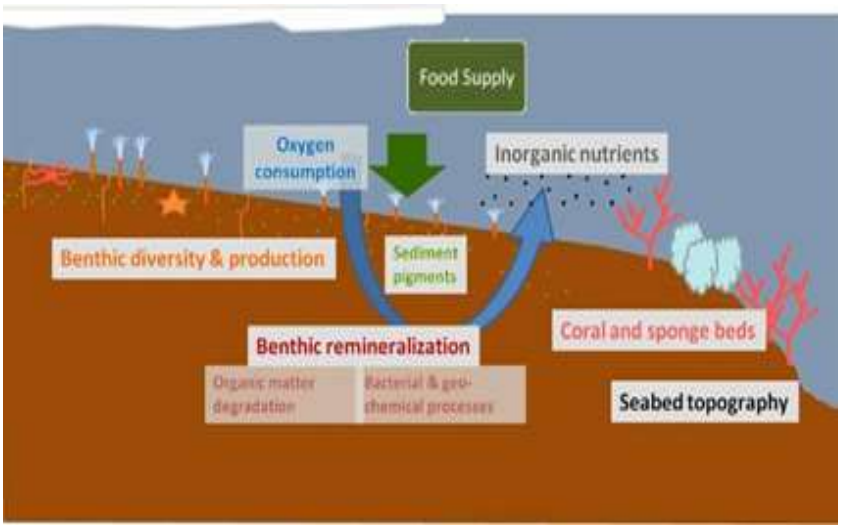

Figure 2: Benthic Habitat Classifications

The biological range of traits for each species" functional diversity is helpful to the stability and resilience of the system. Biological organisms perform various ecological functions, such as detritivores, breaking down matter, and cycling nutrients. Due to deep-sea mining, these functions could be disrupted, resulting in detrimental husk damage to entire ecosystems (Carter and Heinriksen, 2023). The taxonomy of benthic (seafloor) habitats is subdivided into various types with distinct attributes, and the two are expounded in Figure 2. It helps understand the different kinds of benthos, which is vital for assessing the variety and depth of the environmental impacts because of deep-sea mining.

Endemism and Vulnerability

Certain deep-sea life forms are described only from their type locality, which is usually near polymetallic nodule fields and hydrothermal vents. These species' endemism and slow growth and recovery rates mean that even small-scale mining operations could lead to the extinction of some species (Thompson, Johnson and Roberts, 2015). Since most abyssal biodiversity remains undocumented or mischaracterized, mining operations in these regions pose a considerable threat to unknown and irreplaceable life forms.

Deep-Sea Mining Operations

Mining Techniques and Target Resources

The methods employed in deep-sea mining depend on the targeted resource. For polymetallic nodules, remotely operated vehicles (ROVs) are deployed to collect the nodules via vacuum suction on the seabed. Cobalt-rich crusts require cutting and suction techniques, whereas seafloor massive sulphides are obtained through mechanical excavation (Desai and Joshi, 2023). These methods lead to the loss or obliteration of substantial portions of benthic substrate layers.

Generation of Sediment Plumes

The sediment plumes resulting from DSM are its most barbaric form of damage. The dislodging and collecting of fine mineral particles are picked up into the water column, which can diffuse worldwide. These particulates can potentially suffocate bottom-dwelling organisms, populate filters, and modify water chemistry (Clark *et al.,* 2020). In the deep sea, recovering from the exposure to a plume takes an extremely long, slow process of decades or even much longer.

Impact on Benthic Biodiversity

The ecosystems of the abyssal zones, where unique and diverse life forms flourish, face existential threats from deep-sea mining. Mining operations obliterate habitats dependent on polymetallic nodules by disturbing the seafloor's sediment. Marine life is smothered by the sediment plumes generated during mining, obscuring vital biological functions such as photosynthesis and essential water clarity. The ecological consequences include increased mortality among mobile and stationary species, disruption of food webs, and diminished biodiversity. Perhaps most troubling is that the recovery time for deep-sea ecosystems is agonizingly slow. Because of the harsh environment and low population growth of most abyssal species, the mining damage sustained may take several decades, centuries, or potentially never fully heal in figure 3.

Figure 3: Impact of Benthic Biodiversity

Habitat Loss and Alteration

The impacts of deep-sea mining (DSM) activities have a profound effect on the seafloor interface, owing to the extraction or alteration of myriad habitats that support many species of marine life. The mining activities reshape the bathymetric features, such as the seafloor, where critical habitats for biota like corals and sponges, which are sessile and burrowing organisms, microbial mats, and even mats are destroyed. Many of these organisms depend on stable substrata undisturbed for feeding, reproduction, and shelter. These organisms are highly reliant on the gradual changes to these surfaces, and their chances to multiply are reduced dramatically due to chronic changes. Multiply reduces withering from mammals and the decline of reefs and structures. Removing these pagnetic environments causes problems to the ecosystem as the dependents on these components are equally crucial to the deep-sea food webs and the ecosystem's health.

Food Web Disruption

The disturbance brought about by DSM activities can potentially rupture the delicate food web structure of benthic ecosystems. The destruction of habitats, which leads to the loss of critical species due to various mining activities, is bound to change the energy balance of the ecosystem. For instance, the burial of sediments can lead to a decline in detritivores and scavengers which are crucial for the decomposition of organic matter and nutrient cycling. In addition to these ecological processes being impeded, the loss of these organisms will also hinder food availability for many predators dependent on these organisms. Predatory populations and ecosystem stability will be weakened throughout the ecosystem. As a result, the entire community structure of benthos will become slower and weaker. Along with all these, other unsustainable external factors will exacerbate the problem too. The interdependent systems within the ecosystem will be strained as well. With other stressors, such as climate change, the adaptable capacity of the system is bound to change due to new environmental shifts.

Microbial and Biogeochemical Impacts

Abyssal sediments harbour highly evolved microbial communities that are critical for several biogeochemical processes such as nitrogen cycling, methane oxidation, and carbon sequestration. These microbial communities help control the deep sea's nutrient and gas exchange processes, which is vital to the planet's health. Deep-sea mining can disturb these microbes, which changes the rate at which some of these biogeochemical processes occur. The changes that can accompany the disruption of microbial activities are complex. Still, one possibility is reduced oceanic carbon sequestration capacity and an increased offset buffer on atmospheric carbon dioxide concentration. This would worsen the effects of global climate change by diminishing the ocean’s support in counteracting elevated carbon levels in the atmosphere. The ability to lose microbial function in abyssal sediments would undermine one of the ocean’s essential services that impact climate and balance ecological functions.

Effect on Ecosystem Services

Signs of human interference are spreading at an ever-faster rate across the world’s oceans. This may one day result in a complete loss of oceanic biodiversity, noted ecological community services provided by oceans, and the intermediate reversible ecological options commendable by saltwater ecosystems. The newest techniques in deep-sea mining have had some positive outcomes for human needs. Nevertheless, they also damage consumable ocean resources irreversibly. The damage is irreparable due to infrastructurally based encroachments, initiating in lifted seafloors, shifted sedimentary and geological strata, and distension ruins due to comostropic scale blasts.

Nutrient Cycling

Benthic organisms separate organic matter and redistribute nutrients, contributing to nutrient regeneration. Disruption of these organisms by mining activities impairs their capacity to sustain nutrient fluxes, diminishing primary productivity and impacting the overall marine food web (Green, Smith and Lee, 2019).

Carbon Sequestration

Abyssal sediments act as long-term repositories of carbon. Disturbances to sediment layers can potentially emit excess carbon and alter microbial-based carbon processing, or carbon management. The impairment or disruption of these processes could undermine the Earth's ability to store carbon in sediments, paradoxically reinforcing climate disturbances instead (Desai and Joshi, 2023).

Genetic Resources and Bioprospecting

Many abyssal organisms produce unique biochemical compounds with pharmaceutical potential. The destruction of habitats through DSM could result in the loss of valuable genetic resources before they are even discovered. This represents a loss of biodiversity and a potential loss for human well-being (Thompson, Johnson and Roberts, 2015).

Recovery and Resilience

Natural Recovery Rates

Research on deep-sea disturbance recovery illustrates that this recovery is blindingly slow. For instance, 30 years after experimental nodule removal, biodiversity suffers, and ecosystem functions do too, and none of them reaches the value that existed before the experimental discontinuation. The combination of constricted microbial colonization alongside slow reproductive rates makes the recovery extremely difficult (Clark *et al.,* 2020).

Artificial Restoration Challenges

Attempts to design restoration strategies for deep-sea ecosystems have proven less efficient. Transporting species, sowing substrates, or augmenting recolonization are politically conflicted and pose significant biological risk in the abyssal realm. Therefore, the precautionary principle must inform deep-sea mining decisions (Topalova *et al.,* 2024).

Legal and Governance Implications

The International Seabed Authority (ISA) governs mineral activities in regions beyond the jurisdiction of a specific nation. Even though the ISA has put forward rules for exploration, mechanisms for safeguarding the environment during the exploitation stage still lack definition. Need for legal frameworks rests in the protection of biological diversity (Williams *et al.,* 2019). Moreover, stakeholder involvement, impartial transparency regarding the environmental impact assessments (EIAs) as well as compliance with the principle of "no net loss" are further to equitable and ecological governance of the DSM activities (Chatterjee and Singh, 2023).

Conclusion

The consideration and possible exploration of the mineral resources in the deep sea, especially in the abyssal regions, poses a multifaceted dilemma. There is no doubt that deep-sea mining increases the prospects of obtaining strategically essential minerals necessary for contemporary technology and economic development. However, such promises come with serious consequences. Earth's deep ocean remains one of, if not the, least-known and least-mastered areas today. Apart from basic explorations, much of its biodiversity and ecological functions remain mysterious. The abyssal zones are no exception; the ocean's depths, along with the ecosystems within, are extreme in nature. It is home to many species and processes that have existed for millennia in isolation. Numerous species residing within these habitats still go undescribed. Their ecological roles, if any, are poorly understood, creating challenges in assessing impacts to these fragile ecosystems.

These ecosystems can be irreversibly damaged—something that is relatively easy to achieve with mining. The combination of sediment plumes, chemical waste, noise pollution, and the timbering of minerals can hinder the critically intricate connections between numerous benthic organisms and their habitats. Due to the deep ocean's extreme conditions, these ecosystems experience biological regeneration at a crawl and recover from disturbances at an even slower pace. There is complete habitat destruction and the potential for endemic species loss that may result in cascading ecological consequences that span beyond the abyssal zone. This will impact the marine food webs alongside critical services like carbon sequestration and nutrient cycling.

Deep-sea mining practices should be treated with utmost caution because of the potential vulnerability linked to abyssal ecosystems and the uncertainty regarding their capacity to bounce back from mining activities. The projected short-term economic profits need to be balanced against enormous environmental damage in the long run. The deep sea, particularly the abyssal parts, is frequently termed the last ecological frontier of the Earth where life has evolved in relative isolation, remaining untouched by humanity for millions of years. To allow the pristine environment to be harmed beyond repair for the sake of immediate resource extraction would NOT only amplify the scope of environmental destruction and degradation resulting from human focus but also lower the VALUE of this ecosystem for future generations long after it has fossilized and shifted from its dynamic state.

In the words of Krupniky *et al.*, (2020) "protecting benthic ecosystems…it is not simply an environmental imperative…but a moral obligation." These regions of the Earth should not suffer from destructive practices that violate biodiversity and ecological services. What is needed now is a lack of international conflict as a foundation for the development of stricter global regulations and deep-sea protective agreements that treat mineral resource management with precision. Should it be undertaken, all proposed measures should stem from one common goal: mitigating adverse consequences due to deep-sea exploitation. The phrase “shared heritage” circles around humanity’s deep ocean and should draw tension toward the fact that preserving it dramatically influences the health of the earth’s oceans and the life within it.

References

Amon, T. et al., 2018. Mining deep: The race to tap the bottom of the sea. *Science, 359*(6371), pp.34–35.

Carter, E. and Heinriksen, L., 2023. Performance Analysis of Ceramic Membranes in Treating Textile Wastewaters. *Engineering Perspectives in Filtration and Separation*, pp.13-15.

Chatterjee, R. and Singh, V., 2023. Net-Zero Cities: A comparative analysis of decarbonization strategies in urban planning. *International Journal of SDG’s Prospects and Breakthroughs*, *1*(1), pp.11–14.

Clark, M.R. et al., 2020. The ecological impact of deep-sea mining in the Clarion-Clipperton Zone. *Nature Sustainability, 3*, pp.394–403.

Desai, P. and Joshi, V., 2023. Bridging Traditional and Modern Medical Terminologies Integrative Perspectives from Ayurveda and Allopathy. *Global Journal of Medical Terminology Research and Informatics, 1*(1), pp.12-15.

Green, T.J. et al., 2019. The economic promise of deep-sea mining and its environmental impact. *Marine Policy, 65*, pp.5–14.

Halbach, K.N., 2016. Potential and limits of restoration in abyssal environments. *Deep Sea Research Part II*, *137*, pp.320–331.

Hui, H., An, X., Wang, H., Ju, W., Yang, H., Gao, H. and Lin, F., 2019. Survey on blockchain for internet of things. *J. Internet Serv. Inf. Secur.*, *9*(2), pp.1-30.

Jones, A.S. et al., 2021. International regulations and deep-sea mining: Striking a balance between economic development and conservation. *Ocean Policy*, *71*, pp.77–88.

Jones, D.O., Kaiser, S., Sweetman, A.K., Smith, C.R., Menot, L., Vink, A., Trueblood, D., Greinert, J., Billett, D.S., Arbizu, P.M. and Radziejewska, T., 2017. Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. *PLoS One*, *12*(2), p.e0171750.

Lutz, H.M. et al., 2017. Carbon storage in the deep sea: The role of benthic organisms in carbon sequestration. *Marine Ecology Progress Series, 582*, pp.11–20.

Priyalatha, S., 2024. Effect of state of fabric on wicking characteristics of knitted fabrics suitable for sports applications. *Archives for Technical Sciences/Arhiv za Tehnicke Nauke*, (31).

Rex, M.A. and Etter, R.J., 2010. *Deep-sea biodiversity: pattern and scale*. Harvard University Press.

Roberts, R.W. et al., 2021. Biotechnology of deep-sea organisms: Biochemical properties and applications. *Marine Biotechnology*, *22*, pp.101–109.

Silva, C.N.D. et al., 2019. Resuspension of carbon-rich deep-sea sediments and its impact on climate change. *Geophysical Research Letters*, *42*(1), pp.12–18.

Smith, C.R. et al., 2019. Biodiversity, species ranges, and gene flow in the abyssal Pacific Nodule Province. *Frontiers in Marine Science, 6.*

Smith, P., 2017. Deep-sea mining: Potential benefits and environmental concerns. *Environmental Research Letters*, *12*(5), pp.113–120.

Thiel, H. and Koslow, A., 2001. Environmental management considerations for deep-sea mining. *Oceanography*, *14*(4), pp.22–28.

Thompson, L.J.D.S. et al., 2015. Ecology of deep-sea benthic organisms. *Marine Biology*, *158*(2), pp.204–212.

Topalova, I., Lozova, T., Riepnova, T., Dashchenko, N., Chudaieva, I. and Darushyn, O., 2024. Business Process Management in Entrepreneurial Activity Based on a Platform Approach. *Indian Journal of Information Sources and Services*, *14*(2), pp.46-55.

Turner, P.J. et al., 2015. Functional resilience of deep-sea benthic ecosystems. *Ecological Monographs*, *85*(2), pp.229–244.

Van Dover, C.L., Arnaud-Haond, S., Gianni, M., Helmreich, S., Huber, J.A., Jaeckel, A.L., Metaxas, A., Pendleton, L.H., Petersen, S., Ramirez-Llodra, E. and Steinberg, P.E., 2018. Scientific rationale and international obligations for protection of active hydrothermal vent ecosystems from deep-sea mining. *Marine Policy*, *90*, pp.20-28.

Watling, L. and Norse, E.A., 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. *Conservation biology*, *12*(6), pp.1180-1197.

Wedding, L.M., Reiter, S.M., Smith, C.R., Gjerde, K.M., Kittinger, J.N., Friedlander, A.M., Gaines, S.D., Clark, M.R., Thurnherr, A.M., Hardy, S.M. and Crowder, L.B., 2015. Managing mining of the deep seabed. *Science*, *349*(6244), pp.144-145.

Williams, J.K. et al., 2019. Conservation of deep-sea biodiversity: A comprehensive analysis. *Global Environmental Change*, *56*, pp.100–110.