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Can the well-studied environmental impacts of bathyal bottom trawling be used in assessing the unknown environmental effects of deep-sea mining on the abyssobenthic environment?

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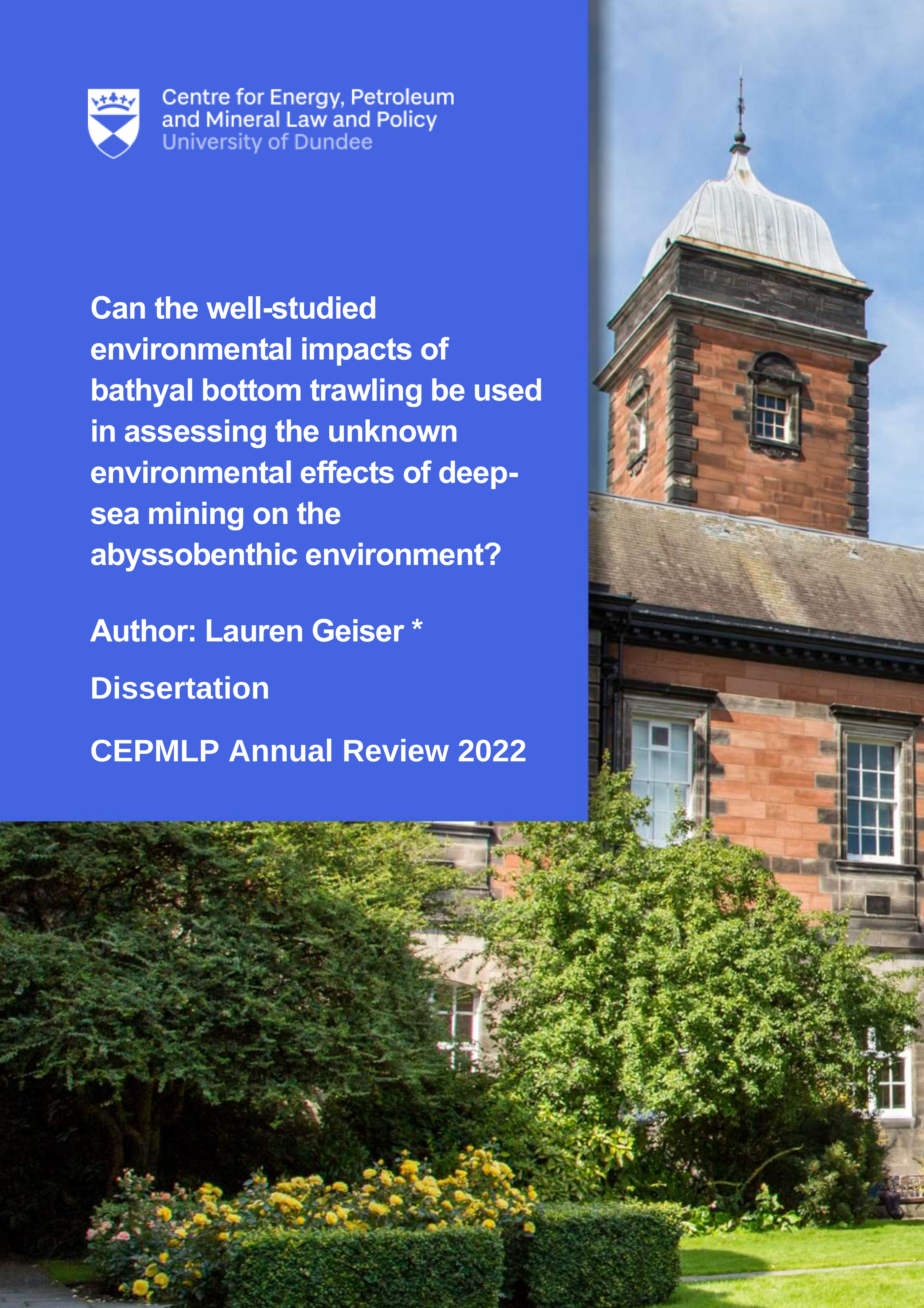
Dissertation

CEPMLP Annual Review 2022



Abstract

The deep-sea is the largest continuous ecosystem on Earth, yet it remains one of the least understood by scientists. Exploitation of the deep-sea takes several forms including commercial fishing and, in the near future, mining. Bottom trawling is a destructive, nonselective fishing method that is well established globally. Consequently, its environmental impacts have been well studied. Deep-sea mining (DSM), on the other hand, has not yet begun commercially, but is expected to commence in both national and international waters within the next few decades. Since no large-scale seabed mining has yet taken place, its environmental impacts remain uncertain. This thesis explores the similarities of deep-sea bottom trawling (DSBT) and DSM to determine if the well-known environmental impacts of DSBT can be used to predict those of DSM. Methodologies are compared, as well as the biotic and faunal aspects of their respective ecosystems. It is likely that the environmental effects of DSBT can and should be used in assessing the impacts of DSM. Because full-scale in situ testing remains challenging and expensive for submarine mining, this insight may prove helpful in establishing preliminary regulations and environmental protections for DSM.

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Acronyms, Tables, and Figures

Acronyms

CCZ	Clarion-Clipperton Fracture Zone
Co-FeMn	cobalt-rich ferromanganese
DSBT	deep-sea bottom trawling
DSM	deep-sea mining
DSMF	Deep Sea Mining Finance Ltd
EEZ	Exclusive Economic Zone
EIA	environmental impact assessment
FAO	Food and Agriculture Organization
FeMn	ferromanganese
GSR	Global Sea Mineral Resources
ISA	International Seabed Authority
JOGMEC	Japan Oil, Gas and Metals National Corp
LCE	low-carbon economy
PCZ	Prime Crust Zone
REE	rare earth element
SMS	seafloor massive sulfide
UNCLOS	United Nations Convention on the Law of the Sea

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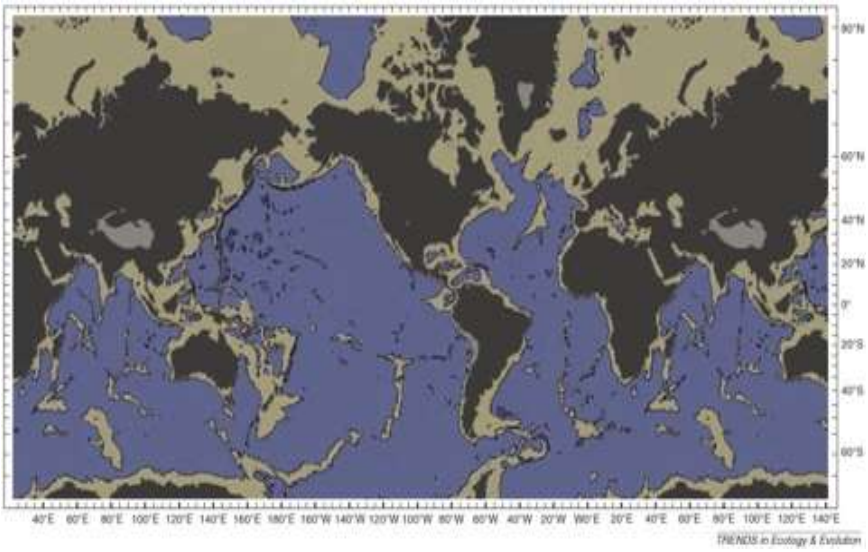
1. Introduction

The world's oceans cover approximately 75% of the Earth's surface and contain almost 98% of the planet's water (1). Consequently, the oceans provide crucial ecosystem services that benefit the entire world. For example, up to 80% of the oxygen we breathe is produced in the ocean — even more than what is produced from the Amazon rainforest and all other forests combined (2). Similarly, the oceans regulate the global climate and contribute to climate change resilience by acting as a carbon sink, absorbing carbon dioxide that would otherwise contribute to additional atmospheric warming; indeed, the oceans have absorbed over 93% of anthropogenic global warming-related heat trapped in Earth's atmosphere since 1971, significantly reducing the 'perceived' warming effect on land (3, 4). Other marine ecosystem services include the oxygenation of waters, remineralization of organic matter, and dissolution of calcium carbonate (5-8). Perhaps most prominent is the biodiversity and countless resources it provides to humans, including food, fuel, genetic resources and medicine, economic opportunities, and minerals. Because of these resources, marine ecosystems — which include everything from coastal zones and coral reefs to open ocean and the deep-sea — are some of the most heavily exploited ecosystems on Earth (9).

The deep-sea — or ocean beyond the continental shelf break — is the largest continuous ecosystem on Earth, covering over 65% of the planet's surface (Fig. 1) (10). The three deepest layers of the ocean--the bathyal, abyssal, and hadal zones--make up the deep-sea (Fig. 2).



TRENDS in Ecology & Evolution

Figure 1: Map of the global abyssal seafloor (depths >3000m in blue). Depths 0-3000m are tan and landmasses are black or gray (5).

However, extreme conditions make the deep-sea the most remote ecosystem Earth, and to this day it remains the least understood to scientists (11).

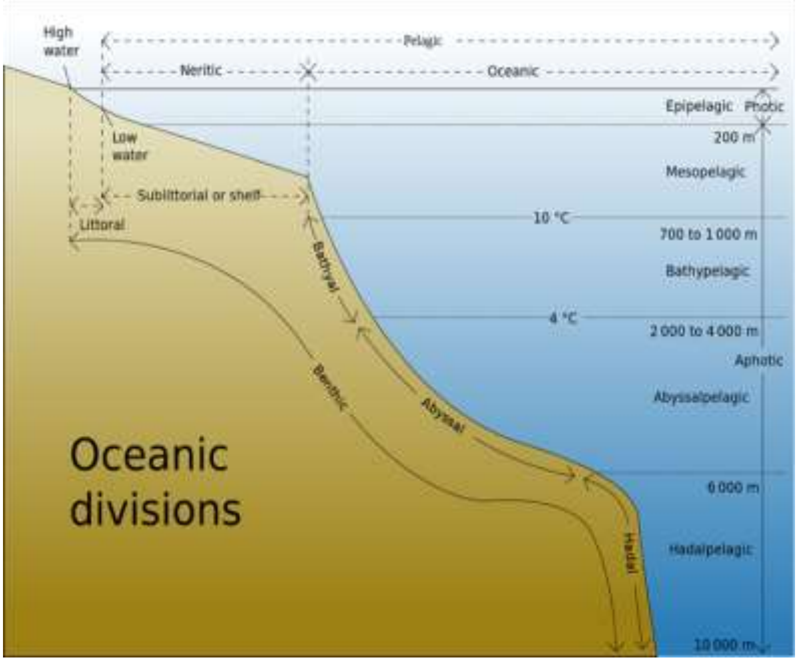


Figure 2: Key oceanic zones. The deep-sea includes the bathyal, abyssal, and hadal zones (12).

Even so, seafloor (or benthic) resources have drawn human attention for nutritional, economic, biological, and other interests. Most notably, the deep-sea has been tapped as a mega seafood reservoir for several decades. Further, deep-sea mining (DSM) is being considered as a viable alternative to terrestrial mining. The decreasing quantities and grades of terrestrial minerals has spurred DSM research and development. Many of these metals will continue to experience demand for higher grades in greater amounts if we transition to a low-carbon economy (LCE) since they are required for green technology (e.g., renewable energy) production (13, 14).

Despite potential economic benefits and scientific advancements that it may bring, DSM is highly controversial due to the presumably widespread adverse environmental impacts that it will inflict on the marine environment. Because DSM has not yet begun on the largescale, these environmental effects are largely unstudied and unknown. The scientific community is positioned at a unique place regarding environmental research and regulation for future a DSM industry. Historically, most industrial projects (e.g., construction, terrestrial mining) have seen development first and the studying of environmental impacts second (i.e., subsequent research). This behavior can by seen throughout the Industrial Revolution but continues still today despite postliminary efforts to regulate environmental impact such as environmental impact assessments (EIAs). However, because DSM is not yet fully established, the scientific community has the opportunity to study its environmental impacts before any largescale development begins (i.e., precautionary research). This approach stems from the precautionary principle, stating that if an action could potentially cause environmental harm, protective measures should be put in place until there is scientific evidence that it does not cause harm (15). Consequently, future policymakers will theoretically be able to use this research to regulate DSM efficiently and effectively, preventing environmental damage before it happens rather than mitigating it after the fact. However, because commercial DSM efforts are likely to commence within the decade, this window of opportunity to proactively study the environmental impacts is rapidly closing. Extensive research and the resulting environmental protective actions are imperative.

To date, the majority of environmental research regarding DSM has been theoretical; for example, research studying the impacts of natural stressors on deep-sea communities can be used to hypothesize the effects of various anthropogenic stressors on these same communities (16). However, the extent to which these comparisons can be made is often limited. For example, communities regularly exposed to natural stressors have demonstrated the ability to adapt to them. This is not necessarily the case for unfamiliar, human-induced stressors. Small-scale *in situ* experiments can also be used to study impacts of DSM, amplifying the experiments with evolving knowledge until they reach the size of full-scale operation (16, 17). However, research of this kind has not yet been conducted for DSM due to the technological and financial challenges presented by the deep-sea.

1.1 Aim and Research Questions

In this thesis, the environmental effects of DSM will be studied by analyzing a similar anthropogenic activity in the ocean—the commercial fishing practice of deep-sea bottom trawling (DSBT). To date, no research of this manner currently exists to the author's knowledge. However, the potential of the comparison arises from the similarities in stressors, receptors, and ecosystems impacted. The remainder of this paper will discuss the similarities and differences between DSM and DSBT with the aim to determine if inferences regarding the unknown environmental effects of DSM can be made by analyzing the well-researched impacts of DSBT.

Within this aim, six major research questions are considered in this dissertation. First, what are the significant characterizing features of DSBT? Within this, methodology, geography, relevant marine ecosystems, and environmental impacts are discussed. The same is asked for DSM, looking at proposed methodology and the areas and marine ecosystems that may experience mining. Once this baseline data is established, DSBT and DSM are compared. What are similarities and differences between the methods (or proposed methods) of DSBT and DSM? This includes type of impact imposed on the seafloor; the extent of impact regarding seafloor area and intensity; the equipment used, including size, weight, capacity, and operation speed and duration; and the relationship between these methodological stressors and environmental receptors. Next, the similarities and differences between the abiotic ecosystem components of DSBT and DSM are considered. This includes the general characteristics of the bathyal and abyssal seafloors (e.g., depths, current velocity, water temperature, salinity, and pressure) as well as the composition of the seabed (e.g., bathymetry, substrate, sedimentation, and deposition). The similarities and differences between the relevant affected fauna are also considered. For example, what are species compositions and biodiversity trends, as well as common growth rates and feeding mechanisms of bathyal and abyssal seafloor fauna? This also includes examining the general characteristics of bathyal and abyssal seafloor faunal groups including epifauna, infauna, megafauna, macrofauna, meiofauna, and microfauna. Lastly, can the environmental impacts of DSBT be used to predict the effects of DSM based on previously identified similarities in methodology, abiotic ecosystem components, and faunal trends? Furthermore, how can this knowledge influence future research into DSM?

1.2 Methodology and Hypothesis

To answer these questions, research consisted entirely of secondary research. An extensive literature review of both DSBT and DSM regarding their methods, marine ecosystems, and benthic fauna affected was conducted. An important source of this information was peer-reviewed academic journals along with official governmental and institutional reports, books, and conference papers. This information was compiled in a meaningful and useful way via descriptive analysis.

Once sufficient data was collected, a thorough cross-examination was conducted to reveal if there are sufficient similarities between DSBT and DSM to use the environmental impacts of one to predict those of the other. Detailed comparison of the methods, disturbances, ecosystems, and fauna affected provided insight into what aspects of trawling and mining can be used to evaluate the other. Predictive analysis was used to determine how insight from DSBT can apply to DSM. The relationships between stressors and receptors of DSBT environmental impacts was used to draw inferences between the expected stressors and receptors of DSM. Lastly, prescriptive analysis was used to develop this insight into what future steps should be taken regarding DSM research.

2. Deep-Sea Bottom Trawling

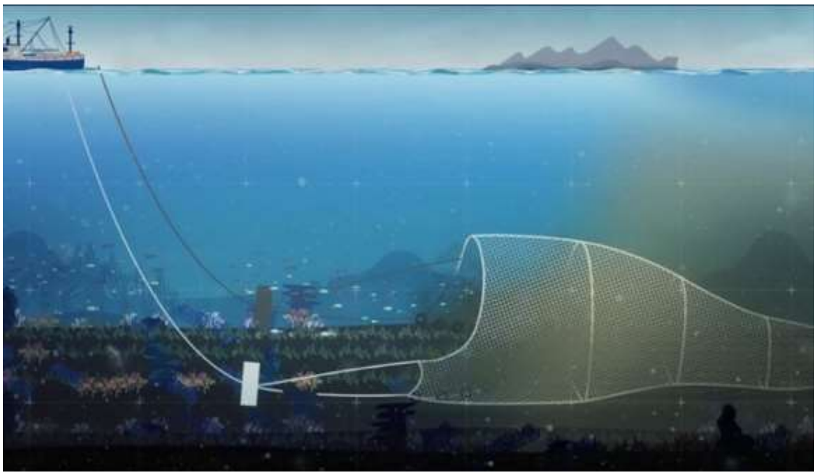


Figure 3: Conceptual image of commercial fishing via bottom trawling, which is characterized by the dragging of weighted nets along the seafloor (18).

Deep-sea species are targeted by the commercial fishing industry around the globe. Mechanized fishing first began in the late 1800s, and thus its environmental effects are relatively well-studied and widely known (19). One of the most destructive fishing methods is bottom trawling (Fig. 3). Most notably, the massive size of nets and turbulent scraping of the seafloor causes extensive bycatch, increased sedimentation, ruination of seabed integrity, and destruction of benthic ecosystems in their entirety (1, 20-22). Even so, bottom trawlers account for almost a quarter of all wild marine catches, landing 19 million tons of fish and marine invertebrates annually (23).

2.1 Background

2.1.1 Methods and Characteristics

Trawling is characterized by the pulling of heavy, weighted nets behind ships to catch marine organisms for seafood consumption (1). It is a non-selective fishing method, meaning that no specific species can logistically be targeted, and large amounts of bycatch (i.e., marine species caught unintentionally) are often caught (24). Sometimes bycatch can be kept and sold; however, it is predominantly unusable or otherwise unwanted, and thrown back overboard already dead or dying (25). Bycatch of pelagic trawling and bottom trawling can include sea turtles, crabs, juvenile fish, sharks, corals, and sea birds.

Industrial trawling nets can be massive, extending longer than 2km with enough volume to contain multiple jetliner airplanes (1, 26). Although trawling sometimes occurs in midwater column or the pelagic zone, most trawling occurs along the seafloor. This “bottom trawling” (or “dragging”) targets demersal or benthic organisms such as groundfish (e.g., cod, plaice, orange roughy), scallops, clams, shrimp, and sea urchins (27).

The most widely used bottom trawling method is the otter trawl, characterized by a pair of heavy ‘otter boards’ on either side of a large, cone-shaped net, through which the forward motion of the boat keeps the net open horizontally (Fig. 4) (27). To keep it open vertically, the trawl mouth is framed by floats on the top headrope and weights on the bottom. When organisms enter the net, they are funneled to the back in a narrow collection area called the cod-end (26). These nets can be over 12m in height and over 60m wide between otter doors; nets this large can weigh well over a ton when fully-rigged (28). Sometimes the groundrope (or footrope) is equipped with rollers or wheels to help the net ride over rough terrain such as boulders and coral while still maintaining ground contact (26). Otter trawls can be operated in a wide range of depths, from shallow environments of only a few meters to around 2,000m (29).

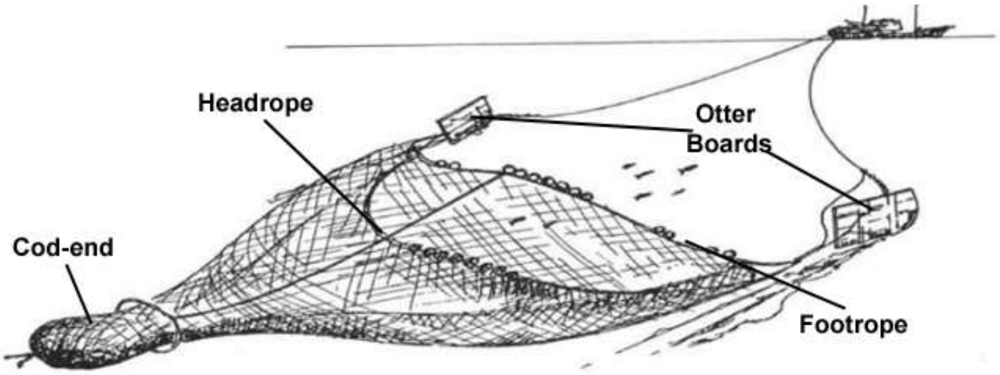


Figure 4: Illustration of bottom trawl fishing gear (26). Image originally from the National Oceanic and Atmospheric Administration (NOAA) Northeast Fisheries.

Another method is the beam trawl, in which a large, cone-shaped net is held open by a horizontal beam rather than otter boards (27). These nets are often equipped with ‘tickler chains’ meant to disturb fish and other organisms from the seabed (26). Typically, beam trawls are utilized in waters shallower than otter trawls, at depths of only a couple hundred meters (30). Consequently, these nets are typically smaller than those of otter trawls with widths reaching up to 12m (27).

The incorporation of synthetic fibers into the production of fishing nets in the 1950’s ultimately allowed trawling nets to be built larger and stronger without adding additional weight (31). This has allowed fishing vessels to catch increasing amounts of marine organisms; however, it simultaneously increased trawling's impact on the benthic environment. Another significant development was the evolution of 'twin' (or 'double') and 'multiple' parallel trawls rigged to a single fishing vessel. This technique enabled trawlers to increase horizontal fishing area, thereby catching fish and other organisms more efficiently and effectively (31).

DSBT is defined as any bottom trawling that occurs 200m (i.e., the typical shelf break) and deeper (generally up to 2,000m). Technological advances and pressures from the decline of shallow water fisheries prompted this expansion to deeper waters (32). DSBT first occurred in southern Pacific Ocean waters around New Zealand in the 1980s, and other maritime regions soon followed suit (31). Trawling at these depths requires further advanced technology, including strong vessel deck machinery and complex instrumentation to locate fish aggregations, provide navigation, and monitor gear performance during fishing (31, 33).

2.1.2 Geography of Bottom Trawling

The footprint of bottom trawling (i.e., area of seabed that is trawled at least once in any given region and time) has been widely debated and poorly detailed ever since its conception (23). Historically, trawling activity has been monitored on a relatively large spatial scale—with units of several km^2 and larger; the coarseness of this scale has provided inexact data of trawling distributions which can often be insufficient and misleading (34, 35). The advent of vessel monitoring systems with high-resolution position data has allowed more precise surveillance of fishing vessels (36). Additionally, local and regional studies provide improved data via vessel logbooks, overflight data, and direct tracking among other methods (23).

The United Nations Convention on the Law of the Sea (UNCLOS) of 1982 constitutes a complex set of rules that govern the oceans and the deep seabed (37). UNCLOS states that each coastal nation is permitted an Exclusive Economic Zone (EEZ) of 200 nautical miles adjacent to its territorial sea in which they have a wide range of rights including exploration and exploitation of the various marine resources (38). The combined EEZs of all nations cover only 35% of the oceans; however, the majority (99% in 1984) of all living resources harvested from the oceans are sourced from EEZs due to practicality (39).

This includes bottom trawling activity. In general, trawling footprint varies between regions with some areas of seabed seeing little to no trawling, and other areas being intensely trawled (i.e., aggregated distribution) (23, 35). Some of the most heavily trawled areas include the North Sea (British, Norwegian, Danish, German, Belgian, and French EEZs), the Yellow Sea/East China Sea (Chinese, Democratic People's Republic of Korea, and Republic of Korea EEZs), and the Sunda Shelf/Java Sea (Malaysian and Indonesian EEZs) (Fig. 5) (40).

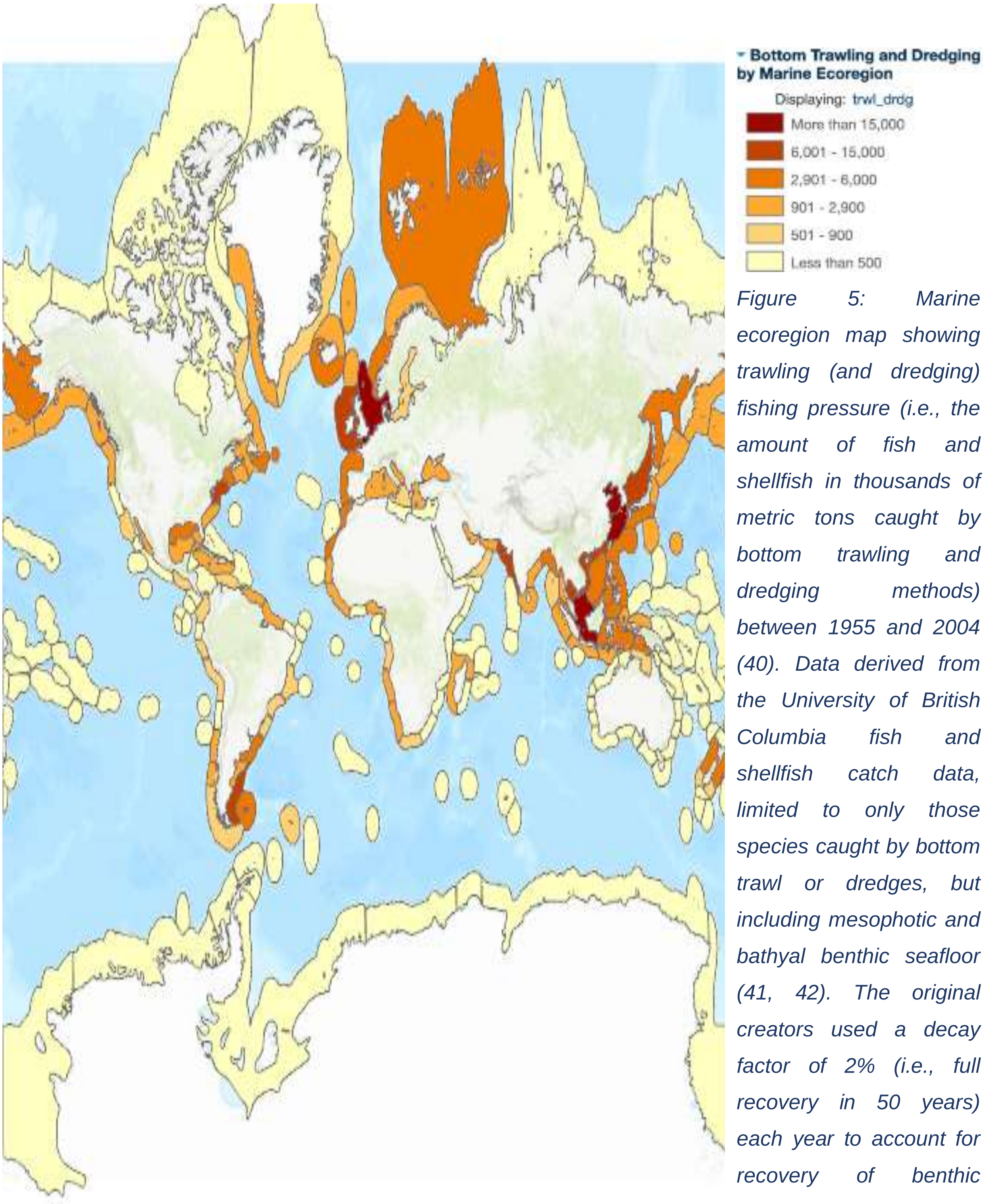


Figure 5: Marine ecoregion map showing trawling (and dredging) fishing pressure (i.e., the amount of fish and shellfish in thousands of metric tons caught by bottom trawling and dredging methods) between 1955 and 2004 (40). Data derived from the University of British Columbia fish and shellfish catch data, limited to only those species caught by bottom trawl or dredges, but including mesophotic and bathyal benthic seafloor (41, 42). The original creators used a decay factor of 2% (i.e., full recovery in 50 years) each year to account for recovery of benthic ecosystems.

More than 63% of mesophotic seafloor and more than 30% of bathyal benthic seafloor in the North Sea is trawled at least once yearly (21). Moreover, productive areas are often trawled over 30 times during peak season (36).

The area of continental shelf bottom trawled per year is significantly higher than the area of seabed affected by other seabed disturbances (e.g., offshore oil, marine renewable energy). Annually, trawling footprint amounts to half of all continental shelf area, equaling around 150 times the total forest land area annually clear-cut (27). However, representatives of the fishing industry tend to downplay these impacts, claiming that they are much more limited, boasting precise fishing grounds, and denying widespread seabed destruction (43).

2.1.3 Relevant Marine Ecosystems

DSBT most commonly affects the bathyal (Fig. 2) seafloor, at depths 200-2,000m (see Table 3) (44). Bathymetry of the bathyal zone is predominantly sedimentary plains obscured with interspersed topographic features including canyons, ridges, and trenches (45). Sunlight does not penetrate significantly beyond 200m and thus most of the bathyal zone is characterized by darkness (46). The bathyal seafloor experiences cool water temperatures of around 4.0°C and water pressure up to 200atm (10, 47).

2.2 Environmental Impacts

Due to the indiscriminate nature of its methods, bottom trawling directly affects the seabed by removing and harming organisms, reducing habitat complexity, stirring up sediments, enabling bycatch of non-target species, and causing pollution from various sources (48). To study the physical, biological, and geochemical effects of dragging fishing gear on benthic ecosystems, two main methodologies are typically employed: (a) comparing ecosystem parameters on a specific site before and after experimental trawling disturbances, or comparing an experimentally trawled site with a nearby undisturbed site, and (b) comparing heavily commercially trawled sites with sites that have only been lightly trawled or not fished at all (49). There have been numerous studies researching the environmental effects of DSBT; however, these studies remain scarce relative to the proportion of impacts that commercial trawling has on the seafloor (50, 51).

2.2.1 Habitat Destruction and Removal

First and foremost, the dragging of trawling gear along the seabed directly alters benthic habitats and topography. Rolling gear such as wheels causes depressions in sand and other soft substrate environments. A 2003 study found the mean penetration into soft sediments ranged from 7-10cm (51). Similarly, the pulling of groundrope and the rapid movements of tickler chain gear damage epifaunal coverage and structures (52). The weight of gear compresses sediments, making the top layers denser and causing bed armoring effects (53, 54). Soft sediments are more likely than coarse sediments and hard substrates to be affected by these types of changes (55).

Moreover, DSBT tends to smooth the ridges of continental slope canyons, making them more uniform (56). This can reduce structural complexity by smoothing bedforms, reducing bottom roughness and heterogeneity that provide microhabitats, and damaging or removing sessile fauna that provides structural diversity (57). For example, a 2009 study (Fig. 6) on deep-coral ecosystems showed that when bottom cover of stony coral was reduced by two orders of magnitude after bottom trawling, the richness, diversity, and density of other benthic megafauna also decreased by three-fold (58). Similarly, these types of impacts take many years to recover from, showing no clear sign of megabenthos recovery after 5 years in this case. These types of alterations can influence long-term seabed evolution.

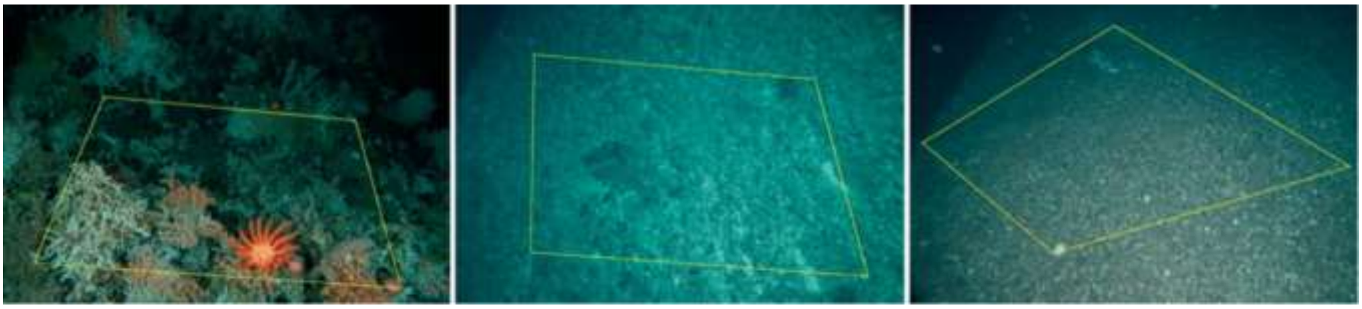


Figure 6: Images of Solenosmilia variabilis *coral thicket on seamounts (a) with no trawling history, (b) where trawling ended 5-10yrs before the image, and (c) with active trawling. The yellow outlines indicated virtual quadrats (58).*

2.2.2 Bycatch

Due to the non-selectivity of DSBT, many types of marine species are often caught unintentionally (24). This bycatch is perhaps one of the most significant environmental issues facing modern commercial fishing. Sometimes bycatch includes desirable species that are targeted by other fisheries, but most times it includes undersized or juvenile fish and crustaceans, and endangered or protected species including turtles, seabirds, and sea mammals (59). Depending on the fisheries and the species caught, bycatch can be either retained and sold (whether legally or illegally) or discarded back into the ocean. Bycatch can also include species such as corals (Fig. 7) that double as structural components of the seafloor. In this case, bycatch not only removes the coral organism, but also removes key habitat for many other species.

Figure 7: Bycatch of a branch of a red coral tree (possibly hundreds of years old) from a New Zealand bottom trawling fishing vessel (61).

A large proportion of bycatch—close to 100% in some cases—is discarded already dead due to extensive external and internal damage wrought from fishing apparatuses, turbulence, and rapid environmental change (60). This is especially true for bycatch brought to the surface from great depths. Rapid changes in pressure and temperature from among other variables from the deep-sea amplifies this damage.

Capture data from the Food and Agriculture Organization (FAO) combined with reconstructed catch data from the Seas Around Us project have suggested that the highest bycatches in all the world's oceans are Northeast Atlantic Greenland halibut, Northwest Pacific Longfin codling, and Southwest Pacific Grenadiers and Orange roughy (32). Beyond the mortality caused by bycatch, the discarding of bycatch back overboard can inject high levels of nutrients into ecosystems along the water column. This provides additional food for predatory species and birds; however, much of this detritus sinks to the seabed, potentially causing oxygen depletion in benthic ecosystems (62). This raises the oxygen demand from organisms as well as produces greenhouse gas hydrates in the deep ocean that may eventually rise to the surface and be released into the atmosphere (63, 64).

With the onset of fisheries conservation, technological developments have been made to reduce bycatch during fishing (31). For example, the Turtle Excluder Device--a large grate-like diverting addition to fishing nets--was developed in the 1980s and has been able to reduce total discards up to 60% even though total commercial catches were not significantly reduced (59). Design and technical changes to trawl doors, weights, bridles, and other ground gear have been explored (49). However, many technical innovations created to reduce bycatch tend to increase overall catch as well, which in turn creates more secondary damage (65).

Other measures to reduce bycatch have been employed around the world as well, such as policies and economic incentives. For example, discard bans have been enforced in Norway, Iceland, the Faroe Islands, Alaska, British Columbia, and New Zealand, though these have not been proven effective in the long-term without extensive surveillance, monetary incentives, and the reduction of total removals (66). Area closures, bycatch limits, and selective gear requirements have also been used with varying—but generally limited—success (67, 68).

2.2.3 Sedimentation

One of the most pervasive effects that DSBT has on the seafloor is its influence on sedimentation. The physical presence and movement of trawling gear causes the resuspension and transport of sediments along benthic ecosystems (69). Scraping actions of nets, weights, and otter boards can create highly dynamic turbid plumes that stay confined near the seafloor, smothering benthic fauna (48). This can be especially harmful to filter and suspension feeders (70). Trawling can multiply sediment concentrations several times over during peak fishing seasons, reaching up to 200mg/l in some cases (71).

A study researching DSBT in a Mediterranean submarine canyon (1750m deep) found a doubling in sediment deposition between the 1970s and 2008 (56, 57). Accumulation rates in this same canyon have increased from 0.25cm/yr in the 1970's to over 2.4cm/yr as of 2015 (69).

Besides resuspension and sediment transport, trawling alters the chemical and physical makeup of seabed sediments. Repeated trawling alters the quality of organic matter that accumulates in the upper layer of the seafloor. Sediment at chronically trawled grounds have been found with decreased organic matter of up to 52% and with organic carbon turnover 37% slower (72). As an example, sediments in a submarine canyon (350-800m) were characterized by labile amino acids, chlorophyll indicators, and monounsaturated fatty acids after trawling, all of which are important biochemical factors in organic matter (50). Therefore, trawled sediment sees a significant decrease in organic matter, and the remaining organic matter also sees a decrease in nutritional quality (52-70%) (73). This makes it harder for suspension- and deposit-feeding fauna to derive nutrition from sediments and it may also hamper the carbon burial capacity of ocean margins on a global scale. Trawled sites are also typically characterized by a significant decrease (approximately 30%) in mud content due to finer fractions winnowed by resuspension (71). Trawled sites typically have denser sediments with lower natural radionuclide surface concentrations, indicating erosion and organic carbon impoverishment (54). As a result of the substantial effects that bottom trawling has on sediment dynamics, anthropogenic depocenters have formed in submarine canyon environments, causing an increase in seafloor turbidity (20, 69). Anthropogenically remobilized sediments can accumulate in these depocenters, causing increased bioturbation. Additionally, the effects of trawling-induced resuspension and sedimentation alteration increases with water depth due to the decay of wave effects deeper in the ocean (71).

With the increase of sedimentation, certain contaminants and pollutants may be mobilized in the benthic marine environment. For example, studies have found increases in the concentrations of polycyclic aromatic hydrocarbons (naturally occurring compounds found in crude oil and coal), of which many are classified as “priority pollutants” due to their proven chronic toxicity and carcinogenicity (74, 75).

2.2.4 Indirect Effects

Trawling also causes indirect effects on the seabed which can include mortality and physiological changes to organisms post-fishing, as well as long-term changes to benthic ecosystems (62). For example, most research studying commercial fishing bycatch focuses on the sheer quantity of mortalities. Fewer studies have focused on organism-level sublethal effects, such as potential behavioral changes, physiological and energetic costs, and reductions in various quantifiers of fitness that may occur post-release from fishing gear. Impacts like these may persist, affecting marine populations long after trawling activity has ceased (76). Conservation and management efforts could benefit from further studies on sublethal fitness effects suffered by discarded organisms.

Persistent fisheries pollution also leads to significant amounts of marine organism injury and death. Derelict fishing debris (e.g., nets, rope, gear) is a major source of marine pollution, and trawling nets constitute a large proportion of this (77). Due to the near indestructible nature of this equipment in ocean conditions, this type of pollution can persist long after trawling has ceased.

Trawl ‘scars’—ripple marks and other lingering evidence of trawling operations—can also be found on the seafloor, even in areas that no longer experience trawling (Fig. 8). Scars modify seafloor bathymetry and habitat structure indefinitely. Areas that have experienced any levels of trawling—whether high or only one time—are both observed as having trawling scars; however, highly trawled areas can see up to 19 times more scars than areas with lower trawling pressure (55).

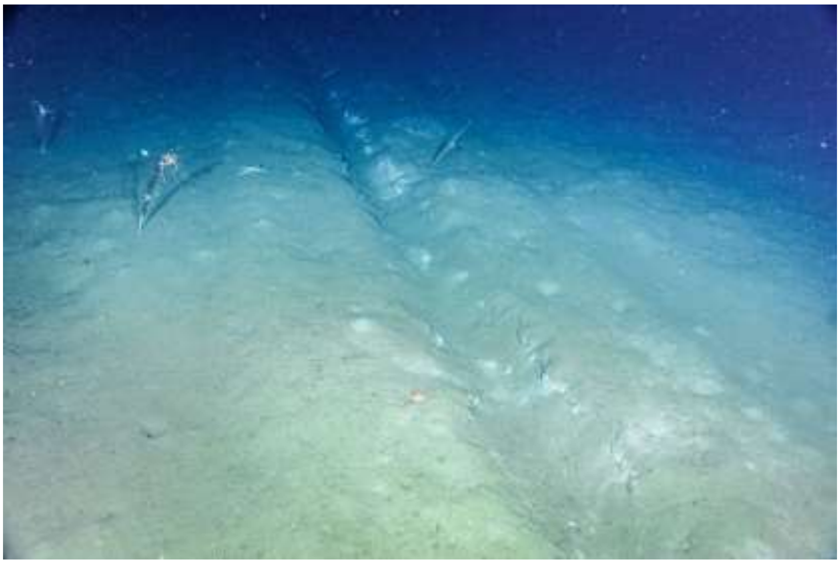


Figure 8: A trawling scar on the Clayoquot Slope at roughly 1,250m of depth (78).

Additionally, the pervasiveness of trawl marks is related to bottom type, and specifically the longevity of scars increases with sediment softness (79). For example, a greater number of trawl scars is typically found on muddy sediments followed by sandy seabed and lastly hard substrate (55).

Scars can be a range of sizes depending on the equipment and substrate, but geometric analysis has shown tracks up to 35cm deep with similar widths (71, 80). This type of lingering effect can influence benthic ecosystems indefinitely, long after trawling activity has ceased.

3. Deep-Sea Mining

Deep-Sea Minnig (DSM) refers to the retrieval of minerals from the deep seafloor. There are three main mineral deposits on the seabed that are currently of economic interest: polymetallic ferromanganese (FeMn) nodules, cobalt-rich ferromanganese (Co-FeMn) crusts, and seafloor massive sulfides (SMS) (81). FeMn nodules and Co-FeMn crusts are the primary foci in this study because the benthic environments in which they are found most closely resemble that of the environments where trawling predominantly occurs.

3.1. Background

DSM first became an intriguing concept in the 1870s after the *HMS Challenger* expedition (1872-1876) reported metal-rich nodules on the deep seafloor (82). However, the idea of mining in the abyss has remained only a concept for several decades due to the extreme conditions (e.g., depth, pressure, temperature) that must be overcome to mine the minerals.

3.1.1. Methods

Prospecting and exploration are the first steps in any mining development, which can take many years and require much financial input. A variety of field techniques must be employed so that mining efforts are optimized in areas with high-grade and high-tonnage deposits. Approaches include bottom acoustic profiling and imaging; mineral sampling using cores, grabs, or basket samplers; bottom video and photography; and multibeam bathymetric mapping using side-scan sonar (83, 84).

Each type of submarine deposit has its own criteria for potential sites used in exploration. For example, an ideal site for nodules is abyssal plains with low topographic relief characterized by slow rates of sediment accumulation, moderate primary productivity in surface waters, and >5kg/m^2 nodules density (83). Criteria is relatively similar for crusts including stable slopes, low relief topography, no local volcanic or hydrothermal activity, and a crust thickness of >4cm (83). Before any activity begins, it is important to note that mining companies will be required to undergo EIA to analyze significant environmental consequences of development in the Area (86, 87).

Once exploration is completed, deposit types and sites must be considered to determine the machinery and technology required for exploitation. All DSM operation concepts follow a general system (Fig. 9) regardless of deposit type. Key components include a surface support vessel, a remote-operated seabed resource collector, and a lifting system connecting the two (88). From here, additional specially designed machinery will be needed depending on the type of deposits due to their unique characteristics. Arguably the easiest type of deposit to extract is FeMn nodules (Fig. 10a), as they are loosely distributed on the seafloor. Mining will likely involve a form of hydraulic steerable dredge able to retrieve nodules off the seafloor and transport to the surface via the lift system while simultaneously discharging excess water back into the water column (83, 89). First generation technologies for nodule mining are currently being developed but have not yet been deployed. The financial constraints and the challenges of implementation mean these systems remain conceptual (90, 91).

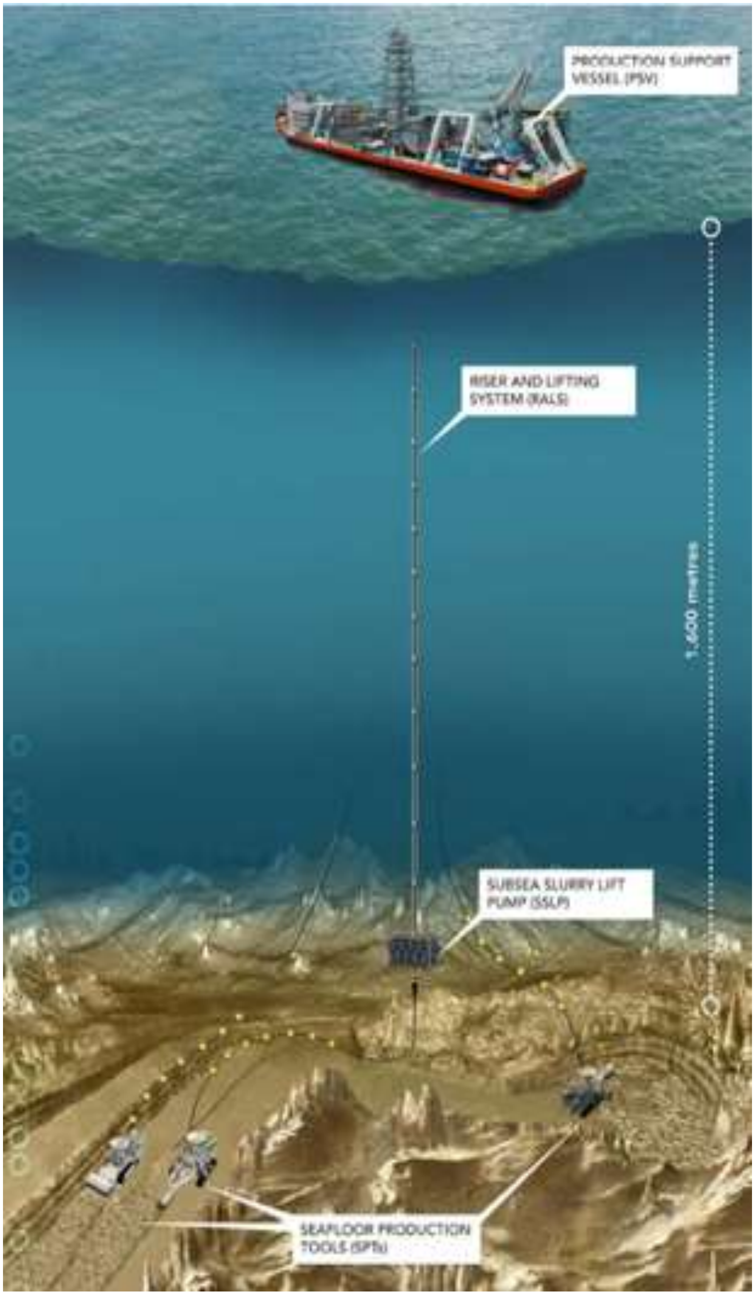


Figure 9: Conceptual image of a DSM system, including a production support vessel, riser and lifting system, subsea slurry lift pump, and seafloor production tools (85).

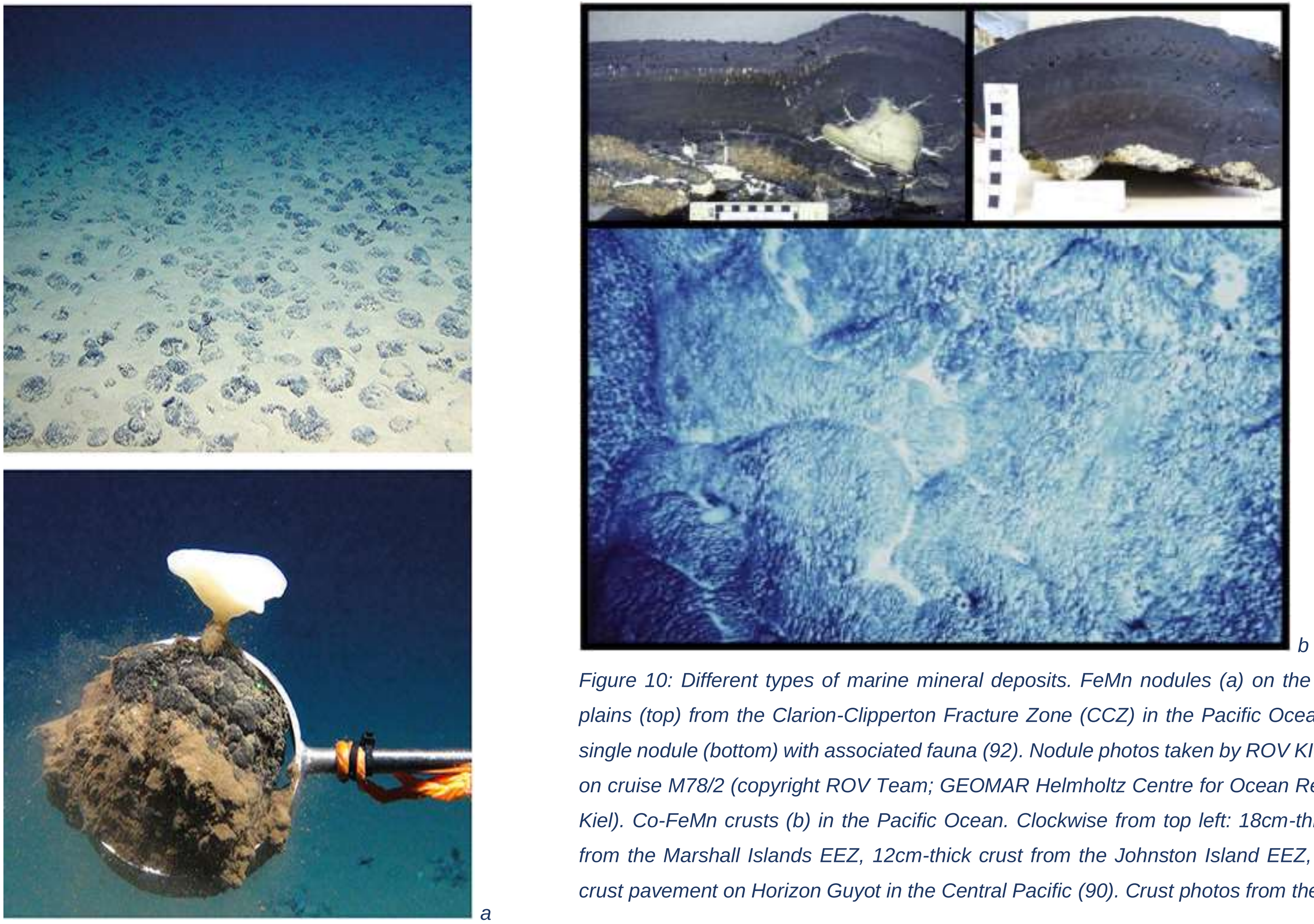


Figure 10: Different types of marine mineral deposits. FeMn nodules (a) on the abyssal plains (top) from the Clarion-Clipperton Fracture Zone (CCZ) in the Pacific Ocean and a single nodule (bottom) with associated fauna (92). Nodule photos taken by ROV KIEL 6000 on cruise M78/2 (copyright ROV Team; GEOMAR Helmholtz Centre for Ocean Research, Kiel). Co-FeMn crusts (b) in the Pacific Ocean. Clockwise from top left: 18cm-thick crust from the Marshall Islands EEZ, 12cm-thick crust from the Johnston Island EEZ, a 4x3m crust pavement on Horizon Guyot in the Central Pacific (90). Crust photos from the USGS.

Figure 11: Machinery owned by Deep Sea Mining Finance Ltd ("DSMF"; previously Nautilus Minerals Company) for exploitation of seabed minerals. From left to right: 'Collection Machine', 'Bulk Cutter', and 'Auxiliary Cutter' (94). For size, note the workers for reference in front of the Collection Machine on the left.

On the other hand, Co-FeMn crusts (Fig. 10b) are firmly attached to the substrate of the seafloor, and thus require additional remote vehicles to separate them. Methods such as fragmentation, vibration, suction, and water-jet stripping are potential techniques (83, 92). This separation requirement is an important barrier to overcome and will require highly specialized vehicles or machinery (Fig. 11); it will be important to not collect underlying rock along with the mineral deposits as this will dilute the grade of the ore and require additional processing (83, 90). To date, no conceptual plan for the mining of crusts has been made public due to the potential difficulties (37, 93). Most DSM concepts assume that once ore is recovered from the seafloor, it will be transported via ship back to land-based processing plants. Mineral processing either onboard the support vessel or within the underwater machinery is expected to be limited as the dewatering of the ore (and the return of this water back into the water column) will take priority (83). Including a sea-based mineral processing aspect would increase the size and cost of production vehicles, machinery, and tools. Nonetheless, some studies have considered some extent of seafloor mineral processing (95).

3.1.2 Potential Mining Locations and Status of Reserves

Nodules and crusts can both be found within "the Area," a maritime zone defined under UNCLOS as the "seabed and ocean floor and the subsoil thereof, beyond the limits of national jurisdiction, as well as its resources" (38). Whereas a country's EEZ (reaching 200 nautical miles from the State's baseline) are exclusive to the appropriate coastal State, the Area and its resources are directly stated to be the 'common heritage of all mankind' (38).

The economic viability of DSM varies according to type of mineral and deposit location. FeMn nodules can be found in all oceans, but are highly concentrated in the Pacific (Fig. 12) between 3,000 and 6,000m, making them difficult to reach with current technology (37). The Clarion-Clipperton Fracture Zone (CCZ, refer to Fig. 12) is particularly abundant with an average nodule density of 15kg/m^2, followed by the Peru Basin (10kg/m^2), the Penrhyn-Samoa Basin (located in the nearshore waters of the Cook Islands) (5kg/m^2), and the Central Indian Ocean Basin (5kg/m^2) (37, 90, 91). Within these areas, there are sometimes confined regions with extreme abundances—for example, there are small, isolated areas within the Cook Island's EEZ that contain nodules in abundances up to 58kg/m^2 (96). Of these locations, nodules in the CCZ tend to have high levels of manganese (Mn) and nickel (Ni), nodules in the Indian Ocean are high in Mn, Ni, and copper (Cu), and nodules near the Cook Islands are concentrated in iron (Fe), cobalt (Co), and REEs (91).

FeMn crusts have been found in deep abyssal waters up to 7,000m; however, those with sufficient mineral content to be economically valuable tend to be found in waters 800-2,500m deep—often within national jurisdictions (37, 83, 93).

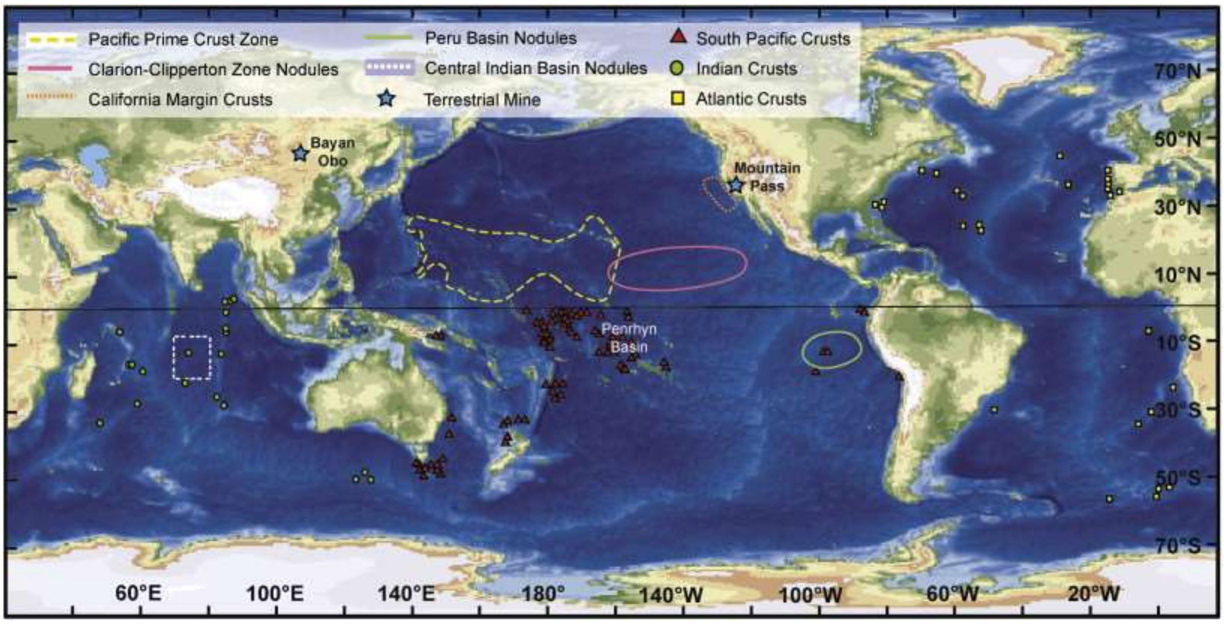


Figure 12: Locations of abundant marine mineral deposits including the CCZ, Peru Basin, and PCZ. The Bayan Obo and Mountain Pass terrestrial mines are denoted as they are the largest terrestrial REE mines (90).

The EEZs of Johnston Atoll (an unincorporated territory of the USA) and the USA state of Hawaii, the Marshall Islands, and the Federated States of Micronesia, as well as international waters such as the mid-Pacific's Prime Crust Zone (PCZ) are considered the most economically promising crust mining areas (37, 93).

There are an estimated 33,000 seamounts and 138,000 ocean knolls but it is likely that many more exist in uncharted waters—as of 2011, only 6.5% of the seafloor has been surveyed in any detail (97). Certain topological features tend to feature Co-FeMn crusts, including seamounts and knolls, as well as ridges, vents, and other rocky substrates. There are an estimated 8.304 million (dry) tons of crusts in the central Pacific Ocean alone (83). Furthermore, these Pacific crusts are estimated to contain approximately one-third the amount of Mn, half as much Bi, four times as much Co and yttrium (Y), and nine times as much tellurium (Te) as the entire known land-based mineral reserves (90, 91). Indeed, the largest mineral reserves of nickel, cobalt, manganese, and various rare earth elements (REEs) are estimated to be found in submarine deposits (98).

Aside from establishing EEZs and the Area, UNCLOS provides for marine environment protection and the conservation of living resources. It also establishes drilling, fishing, shipping, mining, and other development regulations (38). UNCLOS created the International Seabed Authority (ISA) to control and regulate all development and activity in the Area, especially in regard to its mineral resources (38, 99). However, the ISA may not be sufficiently effective, as some studies imply that it does not properly consider deep-sea environments and is unable to properly protect ecosystems and marine life from cumulative and far-field impacts (100). As of 2021 there has been no commercial DSM; however, the first license was issued in 2011 (for the Bismarck Sea located offshore Papua New Guinea and within its EEZ) and mining is expected to commence in international waters in the next couple decades (81, 101, 102). To date (2021), the ISA has yet to turndown an exploration license, despite some applications requesting to explore areas of confirmed ecological significance (100, 103).

Because no commercial DSM projects have reached deployment phases, UNCLOS remains largely untested for marine protection and conservation related to mining. Thus, it has not had the opportunity to be proven effective (or otherwise). Even though UNCLOS sets mandatory standards for marine environmental protection, very few environmental regulations exist for marine mining, especially beyond territorial waters (104).

3.1.3 Relevant Marine Ecosystems

Most deep-sea terrain is ‘abyssal plain’—expansive and flat seabed mostly covered by smooth sediment (46). FeMn nodules are predominantly deposited on the abyssal plains (Table 1) (105). However, bare rock in the form of seamounts, ridges, knolls, volcanoes, and plateaus is sometimes exposed, and Co-FeMn crusts can be found here (93, 106).

Table 1: Characteristics of the deep-sea ecosystems in which FeMn nodules, Co-FeMn crusts, and SMS are found.

	FeMn nodules	**Co-FeMn crusts**
Sites	Abyssal plains (105)	Seamounts, ridges, knolls, volcanoes, plateaus (93)
Depths	>3,000m (37, 105)	600-7,000m (93)
Minerals	Al, Co, Cu, Fe, Li, Mg, Mn, Mo, Ni, REEs*, Si, Y (83)	Bi, Co, Fe, Mn, Mo, Nb, Ni, Pt, REEs*, Te, Th, Ti, W, Y, Zr (83)
Growth rates	<250mm/My† (105)	1-5mm/My† (83, 107)
Abundance	21 billion tonnes‡ (37, 90, 108)	7,533 million tonnes§ (83, 90)
Size	4-25cm (diameter) (105)	<1-26cm (thickness) (90, 109)

**rare earth elements*

†millimeters per million years

‡refers to a modest (dry tonnage) estimate of nodules from the Clarion-Clipperton Fracture Zone (CCZ) in the NE Pacific, the best-studied area in the ocean for nodules (90)

§refers to a modest (dry tonnage) estimate of crusts from the Prime Crust Zone (PCZ) in the central Pacific, the best-studied area in the ocean for crusts (90)

Mining on the deep seabed presents unique, complex challenges based on the environments in which these deposits are located. The deep-sea is characterized by extreme temperatures, high pressures, complete darkness, slow currents, and minimal food availability (46, 110). Most of the abyssal seafloor has water temperatures of near freezing (46, 111). Additionally, sunlight does not penetrate causing total darkness, and pressure can reach up to 700atm (10, 46).

Due to these extreme conditions, deep-sea ecosystems typically experience low productivity and therefore low biological density and species richness (112, 113). Despite this, abyssal environments often host substantial biodiversity due to the consistency of abiotic environmental variables which leads to physically stable environments (106, 114).

3.2 Potential Environmental Impacts

While DSM provides an enticing opportunity for mineral extraction and production, it remains controversial due to environmental concerns. Since the very first concepts of DSM in the 20th century, detrimental environmental impacts have been expected but remain substantially unknown due the difficulties of research and development on the seafloor (115). However, because commercial DSM may commence in the near future, the environmental consequences must be well understood.

The following section analyzes abiotic and biotic features of the bathyal (related to DSBT) and abyssal (related to DSM) seafloors. Abiotic features include bathymetry, substrate, and deposition, and biotic features include biodiversity, community assemblages, and different types of fauna. Comparing these parameters between ecosystems will aid in determining whether the environmental impacts of DSBT may be extended to DSM in some level.

4. Cross-Examination

The authenticity of this comparison depends on the similarities of the relevant environments. Both DSBT and DSM exert (or will exert) significant pressures on their respective benthic environments, impacting abiotic and biotic features. For the sake of comparison, DSBT is hereafter considered only in bathyal environments and DSM only in abyssal environments. First, the methodology of DSBT and DSM are compared, looking at the type and extent of pressures as well as details of the equipment used. Then, abiotic parameters are examined, including depth and bathymetry, seafloor composition and deposition, currents, water temperatures, salinity, and pressure. Lastly, faunal aspects are compared, looking at biodiversity, abundance levels, and different categories of fauna (e.g., infauna, megafauna).

4.1 Methods

The validity of the comparison depends heavily on methodologies (or proposed methods). Both DSBT and DSM inherently influence benthic environments, but the type and extent of pressures differ to some degree. Characteristics of the equipment and their operation are important to consider. Lastly, analyzing how DSBT methodology affects the benthic ecosystems (i.e., how the stressors impact the receptors) will help to determine if similar comparisons can be made for DSM. These results are detailed in Table 2.

Table 2: Details of DSBT and DSM methodologies, including, type, duration, and extent of disturbances, as well as equipment size and operation details.

	DSBT	**DSM**
Type	Nets are pulled along the seafloor by fishing vessels to collect marine organisms from benthic and benthopelagic ecosystems (1).	Remote-operated seafloor vehicles are driven along the seafloor to remove mineral deposits, either by simply picking up nodules off sandy seafloor or by forcefully removing crusts from rocky substrates (83).
Extent	Annual bottom trawling footprint constitutes half of all continental shelves (27). The global footprint of bottom trawling is estimated	Six ‘pioneer claims’ of 75,000km^2 each were issued to different governments in 1984 for mineral exploration; these were made into official leases when the ISA was created in 1994 (100). To date, the ISA has issued 31

	to be over 1 million km^2 (116). Productive areas are often trawled multiple times per year—in some cases up to 30 times during peak season (36). Similarly, hundreds to thousands of individual trawling tows may be concentrated in any particular area (117, 118). A study found that 51,000km^2 of the European continental shelf was bottom trawled between 2010 and 2012, with trawling footprint of managed areas up to 94% in deep zones (201-1000m) (21).	contracts for exploration of different submarine minerals, covering over 1.4 million km^2 of international seabed (92, 119). Similarly, many governments are looking to begin deep-sea mining within territorial waters. For example, China has granted 263 licenses totaling over 161,000km^2, the UK has granted 2 licenses totaling over 133,000km^2, and the Republic of Korea has granted 257 licenses totaling over 87,500km^2 (100). Japan Oil, Gas and Metals National Corp (JOGMEC) successfully deployed ship-based excavation technology to extract zinc, gold, copper, and lead ore within the Japanese EEZ at depths around 1,600m (120). DSM has not yet commenced on international seabed; however, it is expected to commence in international waters by 2025 (101).
Equipment	Heavy, weighted nets pulled by fishing vessels (1). Large, cone-shaped nets composed of synthetic fibers funneling to a cod-end to collect organisms (31). Sometimes double or multiple parallel trawls are rigged to a single fishing vessel, thereby increasing horizontal fishing area (31).	Production support vessel on the ocean surface, remote-operated seabed production tools and resource collectors, and a riser/lifting system connecting the two (88). e.g., seafloor production tools developed by Deep Sea Mining Finance Ltd ("DSMF"; previously Nautilus Minerals Company) include a 'collection machine', 'bulk cutter', and 'auxiliary cutter' (Fig. 6) (94). FeMn nodules: Equipment must be able to retrieve nodules off the seafloor. Hydraulic steerable dredges have been proposed (83, 89).

	Otter trawls: ‘Otter boards’ keep the net open horizontally, a headrope with floats keeps the net open from above, and a groundrope (or footrope) with rollers helps the bottom of the net ride over submarine terrain (26). Beam trawls: Horizontal beams keeping the net open horizontally. ‘Tickler chains’ attached along the groundrope are equipped to disturb fish and other organisms from the seabed (30).	Co-FeMn crusts: Equipment must be able to remove crusts firmly attached to the rocky substrate. Techniques such as fragmentation, vibration, suction, and water-jet stripping have been proposed (83, 92).
Size	Otter trawl nets can be over 12m in height, 60m in width, and 2km in length (1, 28). Beam trawl nets tend to be smaller than those in otter trawls, reaching only 12m wide (27). Nets can weigh up to 10t when fully rigged (62). Nets can be massive enough to contain multiple jet airliners (1).	Exploration technology developed by DSMF ranges from 33.5kg to 5,100kg via public information sheets (121, 122). This technology is likely to be significantly lighter than collector components as they are just meant to recover samples and not harvest deposits on a commercial scale. Nodule collector components developed by Global Sea Mineral Resources (GSR) for small-scale testing was sized at 12x4.7x4.5m and weighed 35mT (123). However, machinery developed by DSMF (Fig. 6) shows vehicles much larger than this

		small-scale equipment, though dimensions and weight are not available. More size data will become available upon exploration and small-scale excavation tests.
Operation	Bottom trawlers are typically towed at speeds ranging from 1 to 7 knots, typically between 3 to 5 knots (124, 125). Tow duration can last anywhere from 10 minutes to 12 hours depending on fish density and seafloor bathymetry and slope, typically lasting between 3 and 5 hours (124).	The maximum speed of the nodule collector component developed for small-scale testing by GSR was 1m/s, corresponding to just under 2 knots (123). Duration data is scant as but for the small-scale GSR nodule collector component, up to 150m could be driven before the $3m^3$ container had to be emptied, requiring about 10 minutes in total for the driving and dumping of one 'lane' (123). Additional time was required for start-up, lane turning, container flushing, and downtime, but the vehicle could operate (assuming no technical downtime) for days at a time (e.g., 4 to 8 days) (123). It is important to note that this data comes from small-scale *in situ* testing, and full-scale operation may likely see increased operation speeds and/or durations.
Relationship between stressors and receptors	The degree of environmental disturbance and impact to the seafloor is a compound of the weight of the net, forward momentum (i.e., towing speed), seafloor composition and substrate, and the strength of the tides and currents (21, 28, 62)	Environmental disturbance will likely correspond to the weight of vehicles and equipment, driving speed and path, seafloor composition and substrate, strength of the currents, and the method by which minerals are removed (e.g., picking up, fragmentation, vibration). Impacts will also depend on the method of dewatering and injection back into the water

	An increase in trawling frequency increases the likelihood of permanent damage to the seabed (62).	column; equipment details such as noise, light, and vibration; and the ecosystems which are targeted (e.g., biodiversity hotspots, breeding grounds, etc.).

Bottom trawling is currently the most pervasive development on the deep seafloor (126). DSBT remains more feasible than DSM because trawling on continental shelves and at bathyal depths is more accessible than the abyssal deep-sea. Once technology allows humans to progress deeper into the ocean, DSM may begin to rival the DSBT footprint.

Because trawling is well established, its equipment is well understood. The most distinctive feature of DSBT is the dragging of heavy nets along the seafloor, which is not a feature of DSM. On the other hand, DSM is likely to require more advanced technology able to withstand more extreme conditions (e.g., greater pressure) and that can maneuver in complex ways. The driving of remote-operated vehicles along the seafloor, which is virtually ubiquitous in DSM concepts, parallels the distinctive ‘plowing-like’ approach in trawling. While DSBT targets just marine fisheries species specifically (e.g., demersal fishes and invertebrates), other ecosystem components such as non-target species, corals and other structural components are often removed as well. In contrast, DSM does not target fauna, but instead aims to remove mineral features which can act as habitat structures. Benthic fauna may be removed in the process. Thus, both processes will remove biotic and abiotic ecosystem components resulting in marine organism fatalities and/or disposal elsewhere.

At present, it is difficult to compare equipment details as full-scale mining has not yet taken place. However, small-scale tests and preliminary development implies that size and weight of DSM equipment are likely to be large. Data on operation speed and duration is lacking as well, but additional *in situ* tests will provide supplementary information.

The relationship between stressors and receptors of DSM is less well-known than trawling but will likely mirror DSBT to some extent. In the case of DSBT, environmental disturbance is relative to the weight of the net, forward momentum of the vessel, seafloor composition and substrate, and current velocity (28, 62). For DSM, disturbance will likely correspond to similar factors, including vehicle and equipment weight, driving speed and path, seafloor composition, currents, and the methods by which mineral deposits are removed.

Furthermore, increases in trawling frequency increases the likelihood that there will be permanent damage to the seabed. This may hold true for DSM, though it is likely that areas that have been thoroughly mined once will not be mined again as deposits take millions of years to form (see Table 3) and initial harvesting excursions are unlikely to leave behind significant deposits (beyond what regulation requires in some cases). With continuing research and development for exploration and extraction, more information will become available on DSM equipment and its causal relationships with impacts on benthic ecosystems.

4.2 Abiotic Features

Abiotic features play a key role in how an environment reacts to different pressures. Depth, bathymetry, seafloor substrate and composition, deposition and sedimentation rates, currents, temperature, salinity, and pressure are compared. These results are detailed in Table 3.

Both the bathyal and abyssal zone are considered the deep-sea, but the abyssal seafloor is significantly more remote than the bathyal. Naturally, the abyssal seafloor experiences greater pressure and colder water temperatures (except around hydrothermal vents) than the bathyal seafloor, and neither experience any sunlight penetration. Salinity of the deep-sea is relatively constant.

Some mineral deposits (e.g., Co-FeMn crusts) can be found in shallower waters, but a large proportion can only be found in abyssal depths. Sedimentation occurs relatively slowly in the deep-sea, but it is much slower in the abyss than the bathyal zone. This is because sediment is less likely to eventually reach the seafloor at greater depths (i.e., more likely to be picked up by currents or deposit-feeders with increased travel along the water column). To compound this, deposition of nodules and crusts is even slower, with noticeable changes only on the scale of a million years. Similarly, the velocity of currents is much slower in the abyss, which plays a significant role in ecosystem functioning and biologic response to change.

General bathymetry is relatively similar between the bathyal and abyssal seafloors, characterized by consistent terrain and rolling hills occasionally transfigured by canyons, seamounts, and similar topological features. However, deeper seafloor is on average more homogenous, characterized by vast abyssal plains. Both the bathyal and abyssal seafloor contain areas of soft sediment and rocky substrate, with soft substrate being more predominant. Perhaps surprising is that in both bathyal and abyssal depths, more species live on hard-bottom substrate than soft-bottom, despite the more three-dimensional nature of soft-bottom habitats (10).

Table 3: Abiotic features of the bathyal and abyssal seafloor. Environmental parameters derived from the General Ocean Survey and Sampling Iterative Protocol (GOSSIP) (127).

	Bathyal seafloor	**Abyssal seafloor**
Depth	200-2,000m (44)	Fe-Mn nodules: >3,000m (37, 105) Co-FeMn crusts: 600m* - 7,000m (93)
Bathymetry	Sedimentary seafloor morphology can be highly heterogeneous, characterized by topographic features such as canyons, trenches, and ridges (45). In major ocean basins, topography is relatively continuous within isobaths (areas with similar depths), occasionally interrupted by small features (e.g., canyons) (10).	Vast plains and rolling hills, occasionally transfigured by seamounts, mid-ocean ridges, island arcs, and trenches (5). Below 3500m, topography mainly consists of isolated basins (10).
Seafloor composition and substrate	Predominantly covered by soft sediments. e.g., in the northern Mid-Atlantic Ridge (MAR) at bathyal depths, 100.0% of flat slopes (constituting 37.65% of MAR surface area) was covered in soft sediments, 98.4% of gentle slopes (constituting 55.79% of MAR surface area) were covered in soft sediments, and 33.1% of steep slopes (constituting 1.87% of MAR surface area) were covered in soft sediments (128). Rocky seafloor: Areas with steep slopes (e.g., ridges, canyons) have high	Predominantly covered by fine sediments of sands, soft clays, or carbonaceous oozes (5, 46). Soft biogenic sediments influenced by epifauna and infauna (129). Hard substrate in the form of FeMn nodules adds diminutive heterogeneity to the soft substrate (10, 83).

	proportions (70%) of hard substrate including bare cliffs and rock outcrops (128).	Rocky seafloor: Co-FeMn crusts, and other rocky substrates such as knolls, volcanoes, and ridges (107).
Sedimentation and deposition rates	On the scale of mm-cm/yr, e.g., continental slope regions in Blanes Canyon (300-2,200m) experience natural sedimentation rates of 0.08-0.20cm/yr, whereas other areas of the canyon experience increased rates due to bottom trawling, with the highest rate up to 2.1cm/yr (130). e.g., the southern-most part of the Okinawa Trough (560-1340m) experiences sedimentation at 0.1cm/yr (131). e.g., sedimentation in La Fonera submarine canyon (>1,750) has increased from around 0.25cm/yr in the 1970s to around 2.4cm/yr in 2015, suggesting that commercial bottom trawling significantly affects sediment dynamics, especially on continental margins (69).	<10mm/Ty[‡] (83); very slow in terms of sediment deposition, but significantly faster than nodule and crust mineral deposition (105). FeMn nodules: 250mm/My[†] (83, 105) Co-FeMn crusts: 1-5mm/My[†] (83, 105, 107)
Velocity	<10cm/s (10)	<4cm/s (10)
Water temperatures	4.0°C (47)	-0.5°C – 3.0°C (5)
Salinity	34 – 36ppt[§] (47)	34.6 – 35.0ppt[§] (132)
Pressure	20atm – 200atm (10)	200atm – 700atm (10)

**600m includes the bathyal zone*

[†] *millimeters per million years*

[‡] *millimeters per thousand years*

[§] *parts per thousand*

4.3 Fauna

The fauna of the deep-sea makes these environments distinct from shallower environments. Fauna is classified in different ways (Table 4), by type of organism (taxonomy), type of habitat, and size.

Table 4: Classifications of relevant fauna.

Subdivisions	Type of Class	Definition
Piscifauna* (or *ichthyofauna*)	Taxonomy	Fish fauna
Epifauna (or *epibenthos*)	Habitat	Aquatic benthic fauna living on top of the bottom substrate on the seafloor (133)
Infauna (or *endofauna*)	Habitat	Aquatic benthic fauna living within the bottom substrate of the seafloor (134)
Megafauna (or *megabenthos*)	Size	>5cm (79)
Macrofauna (or *macrobenthos*)	Size	0.5mm-5cm; deep-sea macrofauna sometimes include fauna retained on a 0.3mm sieve (135)
Meiofauna (or *meiobenthos*)	Size	63µm-0.5mm (136)
Microfauna (or *microbenthos*)	Size	<63µm (137)

1mm=1000µm; 1cm=10mm

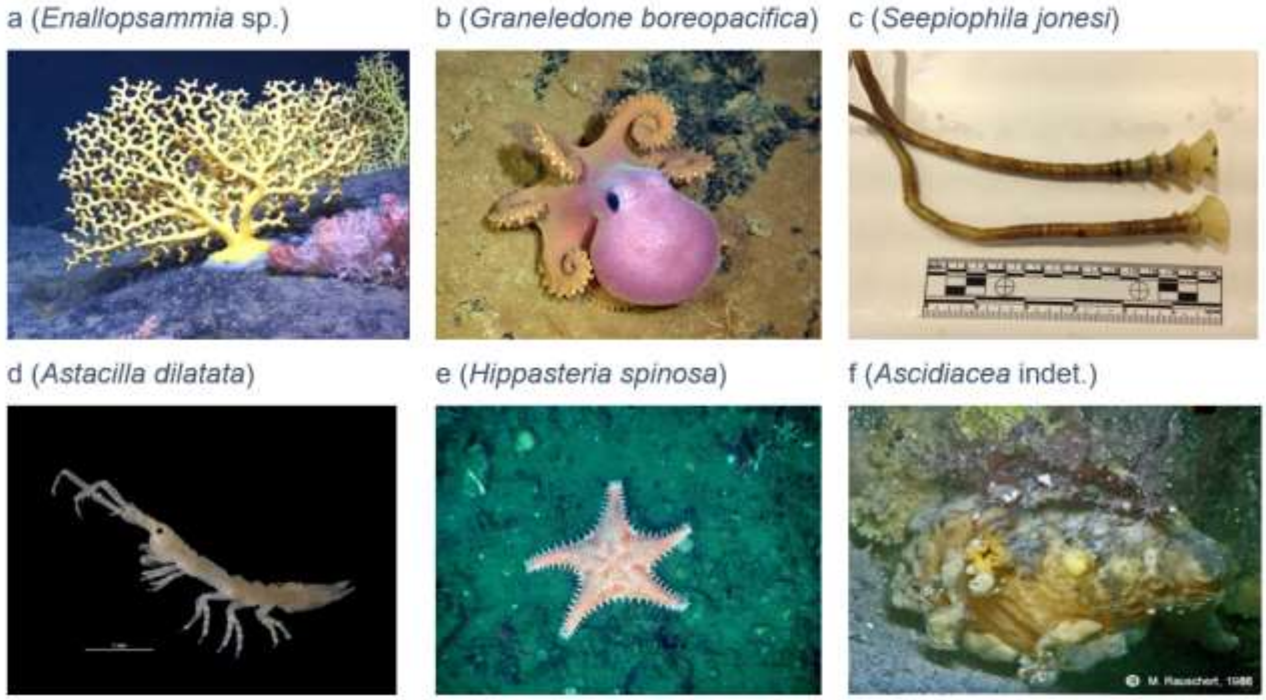
**hereafter included in megafauna*

Bathyal and abyssal fauna exhibit many similarities, predominantly because they are from the same major taxa. The six major phyla of both the bathyal and abyssal seafloors (Fig. 13) are Cnidaria, Mollusca, Annelida, Crustacea, Echinodermata, and Chordata (135). Over the last century, perceptions of the deep-sea have drastically changed, from the misconception that the deep is species-poor to realizing that it is rich in species (138). The bathyal zone contains several relict and primitive species, and it is thought that it may have acted as a species 'reserve' for recolonization during previous periods of natural global climate changes (139). This is likely due to the remote nature of the deep-sea. Additionally, deep-sea species are typically characterized by long life spans, low fecundity, and slow growth rates. This is especially true for abyssal organisms (32).

Despite containing analogous taxa, ecosystem influences cause relatively rapid faunal changes at lower taxonomic levels every 500m as the bathyal zone transitions into the abyss. The abundance of most types of fauna per unit area of seafloor decreases with depth as well (142). Species are more likely to have restricted distributions (i.e., increased likelihood of endemicity) at abyssal depths (10, 114).

Furthermore, taxa that have numerous shallow-water species are likely to have only a few species that inhabit the deep-sea at abyssal depths (10). For example, this occurs in Stomatopoda (Crustacea, Arthropoda) species and Eulamellibranchia (Bivalvia, Mollusca) (143, 144). In contrast, some taxa see the increase of species abundance with depth and in some cases inhabit only abyssal depths exclusively (10). This can be found in certain Asellota Isopoda (Malacostraca, Crustacea) and Xenophyophore protists (Foraminifera, Retaria) (145, 146).

Feeding methods of fauna that inhabit the bathyal and abyssal seafloors are relatively similar, likely due to sharing the same major phyla. Deposit feeding by ingesting sediments is the predominant feeding mode (147). Phyla that feed via this method include Echinodermata, Annelida, and Hemichordata (148). Other common feeding modes include suspension feeding and parcel-attending. Suspension feeders collect material from the water column (e.g., particles resuspended from the seabed) and parcel-attending species consume food fall (e.g., fish and whale carcasses) ‘raining down’ from shallower waters (10).Many parcel-attending species can go months between meals. The proportion of deep-sea carnivores is not well known, as prey can be rare and direct evidence of live carnivorous feeding can be hard to collect (10). Many deep-sea species are known “croppers,” meaning they ingest both live and dead prey as well as other inorganic material (149).



a (*Enallopsammia* sp.) b (*Graneledone boreopacifica*) c (*Seepiophila jonesi*)

d (*Astacilla dilatata*) e (*Hippasteria spinosa*) f (*Ascidiacea* indet.)

Figure 13: The six major phyla of the deep-sea are Cnidaria, Mollusca, Annelida, Crustacea, Echinodermata, and Chordata. Cnidaria (a) are cnidocyte-containing animals including jellyfish, coral, and sea anemones. Mollusca (b) includes snails, scallops, octopuses, clams, limpets, and other mollusks. Annelida (c) are ringed or segmented worms, for example ragworms and giant tube worms. Crustacea (d) are arthropods such as crabs, lobster, shrimp, and barnacles. Echinodermata (e) is an exclusively marina phylum with biota such as starfish and sea urchins. Lastly, Chordata (f) includes notochord-containing animals such as sea squirts, tunicates, and fish. Images (a)-(c) and (e)-(f) from (140) and image (d) from (141).

4.3.1 Epifauna and Infauna

At high taxonomic scales (i.e., phylum, class, order), deep-sea soft substrate epifauna mirrors shallow water epifauna. At lower taxonomic levels (i.e., family, genus, species), these similarities end (10). Organisms living in deeper waters need to be adapted to these extreme environments, and so specific species may not always be found in both bathyal and abyssal depths. Sponge-dominated (Anthozoa, Cnidaria) communities on soft substrate are common at mid-slope bathyal depths but less so in the abyss (150). Other common soft substrate mega epifauna include Ophiuroidea (Echinodermata), Nemertea, Polychaeta (Annelida), Bivalvia (Mollusca), and Decapoda (Crustacea) (55, 151).

At abyssal depths, epifauna is primarily meio- and microfauna. Hard substrate meio- and microfauna are much denser than soft substrate mega- and macrofauna. Up to 20% of exposed FeMn nodule surfaces are covered with epifauna (Fig. 14) and species richness generally increases with exposed surface, partly due to microhabitats created by knobby nodule surfaces (152, 153). However, soft substrate meio- and microfauna outnumber both groups (153). Foraminifera (Retaria) is a dominant taxonomic group of these smaller fauna in both number of individuals and percent coverage (153).

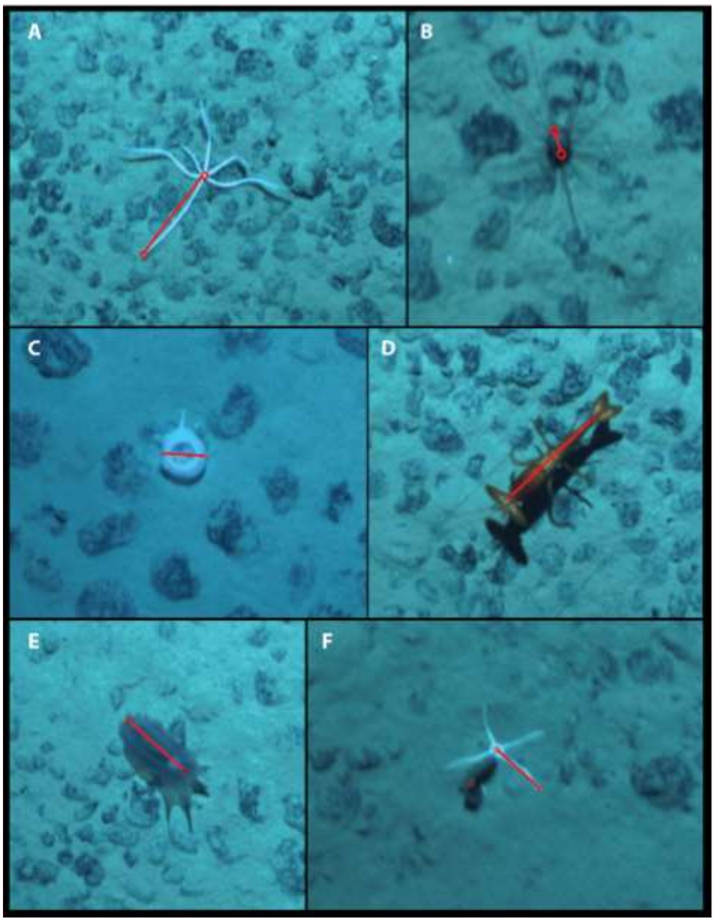


Figure 14: Nodule-associated mega-epifauna from the eastern CCZ:

(a) Echinodermata, Asteroidea;
(b) Echinodermata, Echinoidea;
(c) Porifera, Hexactinellida;
(d) Arthropoda, Decapoda;
(e) Echinodermata, Holothuroidea; (f) Echinodermata, Ophiuroidea (123).

Red lines are for measurement purposes from original study.

Soft substrate infauna is dominated by Polychaeta (Annelida), Foraminifera (Retaria), and Nematoda (10). Abundant microinfauna—representing a large proportion of total species abundance—in bathyal depths are Foraminifera (Retaria) and Nematoda, but these represent only a small amount of overall biomass due to their small sizes (Table 4) (151). Soft substrate macroinfauna is dominated by Polychaeta (Annelida) and Bivalvia (Mollusca), and these species account for a large amount of biomass (151). In abyssal depths, local (i.e., spatial scales of 0.1-1m^2) infauna biodiversity is moderate to high (138).

On the other hand, infauna is generally absent in hard substrates, simply due to the difficulty of living within rock and other hard surfaces. Hard substrate infauna can be found on the abyssal seafloor, though generally only present within the crevices of Fe-Mn nodules where sediment may accumulate (10).

4.3.3 Megafauna and Macrofauna

With mega- and macrofauna, taxonomic assemblage composition varies considerably between locations but in general shows no relation to depth. Species abundances tend to be lower at abyssal depths, but both bathyal and abyssal seafloors are commonly inhabited by Ophiuroidea (Echinodermata), Bivalvia (Mollusca), Polychaeta (Annelida), Asteroidea (Echinodermata), and Malacostraca (Crustacea) (10, 135). Ophiuroidea are abundant for both hard and soft substrates at these depths but tend to be more ecologically important at abyssal depths (135, 154). Additionally, Polychaeta (Annelida) are dominant in the abyssal Antarctic Weddell and Scotia Seas (155). For soft substrate macrofauna it has been shown that abundances increase up to depths of 2,000m but then decrease approaching abyssal depths (156). Often times, species richness is low but overall dominance and relative mass is high due to their size (156, 157).

Furthermore, the average size of individual mega- and macrofauna typically decreases with depth (i.e., dwarfism), but gigantism can also occur (10). For example, Ascidiacea (Chordata) typically decrease in size and mass with increased depth (158). In contrast, rare species of abyssal Ascidiacea (Chordata) can be up to 10 times larger than other members of their taxa (10).

Soft substrate megafauna is dominated by deposit and suspension feeders, including Ophiuroidea (Echinodermata), Foraminifera (Retaria), Cnidaria, and other Echinodermata (159). Hard substrate abyssal megafauna has high levels of diversity such as with Ophiuroidea (Echinodermata) in the eastern Pacific and various Echinodermata in the central Pacific (160, 161). Soft substrate macrofauna is dominated by detritovores and suspension-feeders including Polychaeta (Annelida), Mollusca, and Crustacea, and hard substrate macrofauna is dominated by Ascidiacea (Chordata) and Bryozoa (Tentaculata) (162).

4.3.4 Meiofauna and Microfauna

In general, both abundances and organismal density of meiofauna decreases from bathyal to abyssal depths—but this is not always true at higher taxa levels (163, 164). Common abyssal soft substrate meio- and microfauna taxa include Foraminifera (Retaria), Nematoda, and Harpacticoida Copepoda (Crustacea) (10). For example, nematodes constitute 84-94% of total meiofauna (followed by copepods constituting 2-8%) in abyssal Antarctic waters (163).

5. Discussion

The abyssal seafloor is characterized by extremes: slow to negligible currents, cold temperatures, and significant water pressure. These environmental components force extra constraints on technology intended to function at abyssal depths; however, they also separate the abyss from the bathyal zone. In shallower waters, strong currents and large temperature fluctuations create a relatively high degree of natural disturbance on environments (Fig. 15), which encourages natural adaptations (49).

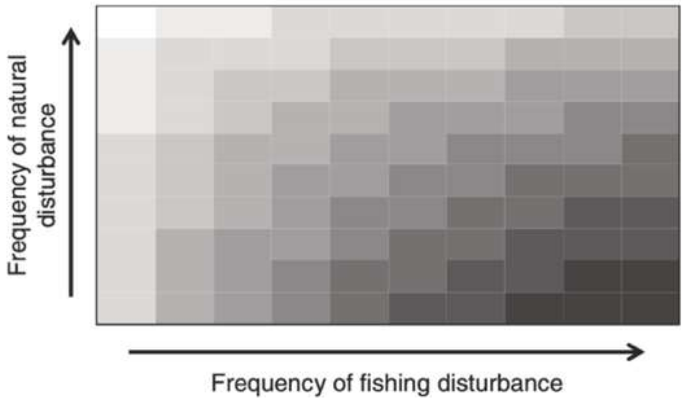


Figure 15: Conceptual model relating the impact of fishing pressure to benthic ecosystems (166). Disturbance level is represented by color, with white representing lowest impact and black representing highest impact. The impact of fishing also depends upon the degree and frequency of natural disturbances. In general, ecosystems experiencing low frequencies and magnitudes of natural disturbance (e.g., the deep-sea) will experience a disproportionally high impact from other types of disturbances (e.g., fishing). This can be extended to DSM.

With extremely slow currents and steady, cold temperatures, abyssal benthic environments are typically not exposed to this type of natural disturbance, implying lower resilience (165). Abyssal current velocities are too slow to even erode sediment or sessile benthic organisms, showing that introduced movement is not only unfamiliar, but potentially disruptive (10).

Similarly, reduced ecosystem resilience typically means fauna is also more affected by auxiliary disturbances; deep-sea fauna is customarily less adapted to recover from sudden changes than shallow water fauna. This means that effects from anthropogenic exploitation take longer to disappear—recovery time is often measured on the decadal scale (62). However, the abyssal seafloor being even deeper and more remote than the bathyal makes these effects and recovery times even more extreme.

Many studies support that marine species and habitats in the deep-sea require at least three decades to reach reference baseline data levels once a particular disturbance is removed

(167-169). Recovery times are longer for slow-growing taxa, of which many bathyal and abyssal species are (32, 170). This makes them vulnerable to anthropogenic impacts. Because deep-sea species have low abundances, recovery and repopulation cannot be guaranteed. Additionally, those organisms that do inhabit the abyssal zone tend to be more ecologically significant (135, 154). Ecological importance of a species can stem from their importance for other particular species, their influence on the whole ecosystem, and from their role as a source of energy and material (171).

Moreover, many deep-sea species are endemic, meaning that if a physical disturbance such as mining depletes the local population, the entire species could be wiped out (101). Having a low number of individuals combined with low distribution can be cause for insufficient recolonization and repopulation of an affected area (172). Environments hosting low abundance levels and ecologically significant species can be severely negatively impacted by the loss of even one species. This can have severe repercussions to marine biodiversity which helps maintain the health of the oceans.

While the specific methods of DSBT and DSM differ because of the different resources they target, the direct impact on the seabed will be similar. Trawling drags nets along the seabed to capture demersal fishes, invertebrates, and other fisheries targets while simultaneously capturing bycatch and other ecosystem components along the way. These structural components (e.g., corals) are critical habitat for benthic fauna, and their capture and/or damage results in the death of other living components as well. Additionally, the dragging of nets along soft substrates causes the resuspension of sandy particles, which can lead to the smothering of nearby filter feeders and the changing of natural sedimentation rates that have existed for ages.

DSM will cause similar impacts with the driving of heavy vehicles along the seafloor. Mining requires the retrieval of mineral deposits from the seafloor, and as studies have found, many of these deposits provide habitat to different epifauna and infauna. Mining will not only remove minerals, but will also remove ecosystem and habitat components, as well as species living in and around them—bycatch, as a convenient metaphor.

The weight and movements of mining vehicle operation will cause resuspension of sandy particles. Nodules exist on sandy abyssal plains and mining concepts include vehicles raking nodules into collection compartments as they move along. Sediment will inevitably be included in these plowing actions, in addition to the sediment that will be resuspended by wheel movement and forward momentum. In contrast, the forceful separation of mineral crusts from rock will cause significant vibrations and other physical alterations that influence seafloor composition and sedimentation. One effect of the resuspension of sandy particles on the bathyal seafloor from DSBT is the creation of plumes and the smothering of filter feeders. Studies have shown that resuspended sediment often has less organic matter and nutritional value, which can impair benthic fauna that derive nutrition from sediments (73). Because the predominant feeding methods of organisms found on or near the bathyal and abyssal seafloor are comparable, plumes caused by DSM will have similar deleterious effects on organisms living on the abyssal seafloor.

Ultimately, the degree of impact on the seabed from trawling is a relation of net weight, forward momentum, seafloor composition, and seafloor ocean current velocity, and it is likely to be similar for DSM. Since DSM technology is still being developed, there is no exact data on the weight and dimensions of equipment proposed to be used. Trawling nets are notably heavy and massive in size. Mining equipment is unlikely to be as massive but will require structures and frames that can withstand great pressures (Table 3). Thus, mining vehicles will be extremely heavy as evidenced by small-scale tests and preliminary developments by mining companies (Fig. 6). Additionally, as minerals are collected, the weight of the vehicle will increase, compounding its effect on the seafloor beyond its starting weight. As an example, the mass of wet nodules in the GSR small-scale tests was 3 tons for only $3m^3$ volume (123).

At an average of 4 knots, DSBT speeds remain faster than those of small-scale mining tests. Additional research and development may allow mining equipment to increase speeds, although the need for precise maneuvering and resource collection may not permit much increased speed. In contrast, the current state of development implies that mining may be able to operate for much longer durations than trawling, on the scale of days rather than hours. Thus, while mining speeds may be slower than trawling, they can operate more continually which can intensify overall impacts.

Aside from the presence of mineral deposits, the composition and substrate of the bathyal and abyssal seafloor are comparable, both largely characterized by vast soft sediments with areas of seamounts, ridges, and other rocky substrate. Thus, the deleterious effects from DSBT to the bathyal seabed are predictive of the effects from DSM to the abyssal seabed.

Because of their extremely slow deposition rates, FeMn nodules and Co-FeMn crusts can be considered finite resources, much like the species that inhabit them (33). Removing these mineral deposits from their environments is essentially removing their habitat from their ecosystems forever. Therefore, even if other ecosystem components eventually recover after several decades as suggested by some studies, these structural deposits will still be absent, ensuring that the habitat and structural damage persists indefinitely (81).

Benthic currents play a role in the residence time of sedimentary plumes and other suspended particles. With currents even slower in the abyss than the bathyal zone, plumes will take longer to disperse, compounding the pressure these plumes will put on benthic ecosystems and biota. A plume of the same size and density will take much longer to disperse in the abyss than in the bathyal zone. Because plumes and resuspended sediment can smother fauna as well as diminish the nutritional values of sediments food sources, the health and survival of seafloor fauna would be threatened, further impacting biodiversity. In addition to vehicle weight, forward momentum and path, seabed composition, and current velocity, there are likely to be other factors that impact the degree in which benthic ecosystems are affected by mining. This is likely to include the method of mineral dewatering, equipment light and noise, and the specific seafloor ecosystems that are targeted. However, until mining begins on a large-scale, these will be difficult to predict.

6. Conclusion

It is reasonable to assume that the environmental effects of bathyal bottom trawling can be used in predicting the environmental impacts of DSM. DSBT and DSM are vastly different processes, and they are used in different areas of the ocean, but their techniques and benthic environments remain comparable. Both DSBT and DSM directly and indirectly impact benthic ecosystems, extending as deep as the bathyal zone for DSBT and the abyss for DSM. In terms of methodology, both practices involve the dragging or driving of heavy equipment along the seafloor, removing and altering biotic and abiotic ecosystem aspects. The causal relationship between stressor and receptor in DSBT can be a helpful predictor for that of DSM.

Future DSM research should consider previous studies into DSBT. Trawling is much more established and so it is better studied. Insights from trawling research may be used to anticipate impacts from DSM that would otherwise go unpredicted due to challenges of studying mining in the abyss. As technology advances, research should prioritize *in situ* testing for DSM; however, in the meantime this comparison remains a good perspective through which to view the environmental impacts of DSM.

It is important to note that even though DSBT provides a good perspective with which to view DSM, it is likely that significant environmental impacts may arise unexpectedly. The abyssal seafloor is an extremely sensitive environment that is poorly understood by scientists. Any activity on this seafloor can potentially cause vast repercussions that will likely last for significant lengths of time, and in some cases cause permanent damage. Because full-scale mining has not yet occurred, there are no limits to what potential destruction may look like. Mining methods may be far more destructive than what current projections expect. Further, unseen difficulties in retrieving minerals from the seafloor may arise, thereby necessitating even more efforts that will harm the abyssal environment.

On the other hand, it is well established that bottom trawling exerts significant impacts on benthic environments and species. While it remains true that the extent of impacts of DSM are unknown, some scientists argue that the impacts of DSM will be negligible compared to DSBT. The footprint of DSBT is far greater than what is expected of DSM, and fished areas can be repeatedly trawled in a single season. Some marine mining companies such as The Metals Company are exploring nodule collector components that exert as little an impact on the seafloor as possible--for example, remote-operated vehicles that do not drive on the seabed, and instead ‘hover’ above while ‘sucking’ up nodules (174). This and other less ‘intrusive’ concepts may prove to reduce impacts of FeMn nodule mining.

It is also imperative to understand what recovery from mining may look like for the abyssal deep-sea. It is likely that environmental impacts will be permanent due to the extreme conditions of the abyss and the vulnerability of its ecosystems and fauna. Before DSM is allowed to commence, this should be better understood. The scientific community is at an unprecedented position in this development because DSM has not yet begun on the large-scale. Environmental scientists, marine biologists, oceanographers, and other experts have the opportunity to study the impacts of DSM before it is fully established—thus environmental impacts can still theoretically be predicted, regulated, mitigated, and prevented. Typically, deleterious environmental events are only to be studied and mitigated after the fact which can be less effective. However, because DSM is likely to commence in international waters within the decade, this research is needed as immediately as possible, as commercial mining companies are unlikely to wait for these scientific studies and their conclusions.

Not to be ignored though are the environmental and social impacts of the terrestrial mining industry as well as the ever-present need for countries to increase the security and supply of strategic critical minerals. Much of the world relies on only a few nations (e.g., China, Russia) for the majority of their critical mineral supply and these pathways can be volatile to disruptions (e.g., from pandemics, war, price fluctuations) (173). The urgent need for a LCE transition only highlights this issue. DSM, regardless of type or extent of marine environmental impact, may serve to alleviate this issue. It has also been argued that the DSM industry may be *essential* for the success of a low-carbon future. However, this has yet to be corroborated by renewable energy and electric vehicle/battery sectors (100). Many critical metals currently experience low levels of recycling (175). It is possible that an increase in the frequency and effectiveness of minerals recycling can support the LCE, rather than exploitation of sensitive abyssal environments via DSM. On the other hand, many experts claim that the dramatic increase in recycling rates to meet growing demand is not feasible on the required time scales. Some companies plan to explore and exploit marine minerals in the next few decades to meet immediate demand with the intention to slow production once recycling rates alone are able to meet this demand (174). This perspective from mining companies, if executed as such, may prove to be more environmentally sustainable than terrestrial mining

Finally, one should consider that fact that while DSBT and industrial fishing in general is definitively known to cause negative widespread impacts on the marine environment, this industry is prevailingly deemed as acceptable and necessary (notwithstanding unmistakable dissent from various environmental organizations and perspectives). Regardless of whether the DSM industry is proven to impact the environment more or less than DSBT, it follows that a similar sort of necessity can be argued for DSM for a transition to the LCE. If some level of environmental impact from the fishing industry is considered as a ‘necessary evil’ for the food provisioning it provides, the same could be said for the mineral provisioning from DSM.

The commencement of DSM ultimately means the onset of the environmental impacts described above. Impacts such as these put in jeopardy the many ecosystem services that the deep-sea and ocean provide for the planet such as oxygen production, climate regulation, and biodiversity. These ecosystem services play a significant role in the functioning of our planet and the quality of life on it—for not only plants and animals, but also for humans. For example, oceanic oxygen production provides the majority of oxygen utilized by humans for respiration; similarly, high levels of biodiversity help fight disease, provide food security, and protect human settlements from natural disasters. The hindering or loss of these services threatens the health of the earth and jeopardizes our survival.

The world’s oceans are currently facing more threats than ever before, creating extreme vulnerabilities for climate change resilience and the health of the planet. Even so, the nascent industry of DSM is beginning to exert even more pressure on the ocean. It is likely that there is no economically viable way to mine deep-sea minerals that is also environmentally friendly and sustainable. Knowledge about the biology, geochemistry, and other factors of the deep-sea makes it compelling to reassess the benefits of DSM. Choosing to exploit deep-sea minerals for the LCE is highly likely to be disastrous to both the seafloor and marine life at abyssal depths and will impact the overall health of our oceans; approaching forward using the precautionary principle will be essential. The likelihood that this environment may never recover from DSM impacts should be given due consideration.

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