MARINE MINING IN GREENLAND

A strategic assessment of potential impacts

Scientific Report from DCE – Danish Centre for Environment and Energy No. 640 2025

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Abstract: Aarhus University, DCE - Danish Centre for Environment and Energy, and Greenland Institute of Natural Resources (GINR) have prepared a report on the potential impacts related to marine mining in Greenland with a special focus on West Greenland. The report provides a basis for environmental assessments and regulation for authorities. It summarizes existing knowledge and highlights knowledge gaps, especially for sensitive areas and species in West Greenland. The report concludes that marine mining could potentially have significant impacts on biodiversity and the marine environment, with effects depending on location, timing, operation size, and technology.

Keywords: Greenland, marine mining, environmental impacts

Front page photo: The research vessel *Tajaroq* sampling sediment cores to gather data on marine sediments and enhance understanding of environmental conditions, photo by Christian Klindt Sølbeck.

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- Sumiiffiit akuersissuteqarnissamut ammatitat, norgemiut pisarnerattulli uumassusillit assigiinngissitaarnerat pillugu paasissutissanik katersisarnissamut piumasaqaatitalerlugit.

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- Sumiiffiit akuersissuteqarfigineqarsinnaasut sorliuneri paasiumallugit misissuinerit.

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Sammenfatning

Rapportens hovedformål er at styrke grundlaget for myndigheders miljøvurdering af marin minedrift i farvandene ved Grønland. Den samler eksisterende viden om marin minedrift og dens effekter på miljø, dyre- og plantelivet i havet. Desuden identificerer rapporten emner og områder, hvor der mangler viden og data, der kunne forbedre vurderingsgrundlaget for marin minedrift i grønlandske farvande.

Rapporten har fokus på marin minedrift inden for den Eksklusive Økonomiske Zone (EEZ) i Vestgrønland. I rapporten skelnes mellem minedrift på kontinentalsoklen (mindre end 200 meters vanddybde) og dybhavsminedrift (over 200 meters vanddybde). Rapporten giver en oversigt over forskellige mineralske ressourcer, der typisk udvindes fra havbunden. Viden om forskellige mineralske ressourcers specifikke forekomst i grønlandske farvande er stærkt begrænset. Forskellige indvindingsmetoder og deres mulige påvirkning af miljøet er beskrevet.

Rapporten indeholder en vurdering af den potentielle påvirkning af miljø og natur i grønlandske farvande, der kan forekomme som følge af marine minedriftsaktiviteter. Dette indebærer forstyrrelser af havbunden, spredning af sediment, frisættelse og udledning af forurenende stoffer samt støj-, vibration- og lysforurening. Derudover behandles utilsigtet introduktion af invasive arter og oliespild fra skibe i forbindelse med marin minedrift.

Forstyrrelser af havbunden og spredningen af sediment kan negativt påvirke bundlevende organismer og deres levesteder mens sedimentfaner kan reducere vandkvaliteten, hvilket kan påvirke organismer i vandsøjlen og filtrerende organismer på havbunden. Udledning af forurenende stoffer, herunder tungmetaller, kan medføre toksiske effekter og stofferne kan blive ophobet i organismer og fødekæder. Støj og vibrationer kan forstyrre kommunikation blandt havpattedyr, mens lysforurening kan forstyrre arters naturlige adfærd i mørke.

De marine økosystemer i Vestgrønland understøtter en bred vifte af arter, der kan være sårbare over for en række af de miljømæssige presfaktorer, der kan være tilknyttet marine minedrift. I rapporten identificeres sårbare arter på tværs af trofiske niveauer (alger, krebsdyr, fisk, havpattedyr, havfugle og hvaler).

Baseret på eksisterende viden og de identificerede følsomme arter, fremhæver rapporten områder i Vestgrønland, der rummer kritiske levesteder, samt regioner, hvor der er utilstrækkelige data. Desuden gives der oplysninger om specifikke områder i Vestgrønland, der er vigtige for bentiske og pelagiske arter, inklusive kort over arternes fordeling. Nordvandspolyniet Pikialasorsuaq og Store Hellefiskebanke fremhæves som marine områder, der har både international betydning og stor betydning for lokal fangst og fiskeri. Desuden omtaler rapporten, hvordan klimaforandringer kan forøge effekter af marin minedrift, fordi klimadrevne habitatændringer giver klimastress for de enkelte arter så de bliver mindre robuste overfor påvirkninger fra mineaktiviteter.

Rapporten skitserer flere afbødningsstrategier, der sigter mod at reducere de miljømæssige påvirkninger fra marin minedrift. Disse strategier inkluderer teknologiske fremskridt designet til bl.a. at minimere sedimentfaner og reducere støjforurening. Desuden fremlægger rapporten afbødningshierarkiet, et

rammeværk inden for miljøforvaltning og miljøbeskyttelse, der søger at minimere miljøpåvirkninger ved brug af fire nøgletilgange: undgåelse, reduktion, genopretning og kompensation. Desuden præsenterer rapporten erfaringer og reguleringsrammer fra Norge samt Den Internationale Havbundsmyndighed (ISA). Disse eksempler giver referencer til udviklingen af miljøregler.

Endelig konkluderer rapporten, at marin minedrift potentielt kan have betydelig indvirkning på biodiversitet og det marine miljø, afhængig af placering, timing, operationens størrelse og den anvendte teknologi. Mindre operationer uden for følsomme områder kan have begrænsede lokale virkninger. Rapporten opsummerer viden om følsomme marine områder i Vestgrønlands EEZ og fremhæver manglende data, især vedrørende biodiversitet og begrænset viden om modstandsdygtighed hos havpattedyr, havfugle og fisk over for påvirkninger fra minedrift i havet.

Baseret på rapporten kan det overvejes at regulere marin minedrift baseret på en rumlig analyse, således at der åbnes for efterforskningstilladelser, afhængigt af viden om et områdes økologiske, biodiversitetsmæssige og samfundsmæssige værdier og deres sårbarhed:

- Områder åbne for tilladelser med specifikke krav til miljøstudier for at adressere manglende data.

- Områder åbne for tilladelser, betinget af tidlig indsamling af biodiversitetsdata inspireret af norske praksisser

- Områder, der er lukkede for tilladelser, fordi der er dokumenteret store økologiske, biodiversitetsmæssige og/eller samfundsmæssige værdier der er sårbare.

- Områder der er midlertidigt lukkede for tilladelser fordi der ikke foreligger tilstrækkelig økologisk viden til at vurdere de potentielle langsigtede konsekvenser, og hvor der potentielt er store økologiske, biodiversitetsmæssige eller samfundsmæssige værdier der er sårbare.

Det anbefales at gennemføre udvidede overvågningsprogrammer for at forbedre både projektspecifik og generel viden om miljøpåvirkninger af marin minedrift, samt for ad hoc løbende at kunne regulere minedriftsaktiviteterne.

Summary

The report aims to strengthen the basis for environmental assessments of marine mining in West Greenland by the authorities. It summarizes existing knowledge on marine mining and its effects on the marine environment, as well as on marine flora and fauna. Additionally, the report highlights knowledge and data gaps, which could enhance the assessment basis for marine mining in Greenlandic waters.

The report focuses on marine mining within the Exclusive Economic Zone (EEZ) in West Greenland. It distinguishes between shallow-water mining (less than 200 meters depth) and deep-sea mining (greater than 200 meters depth). The report provides an overview of various mineral resources typically extracted from the seabed, though specific documentation on the occurrences of these resources in West Greenlandic marine environments is limited. Additionally, a range of extraction techniques and their potential pressures on the marine environment are examined.

The report includes an assessment of the potential environmental and ecological impacts in Greenlandic waters that may result from marine mining activities. These include seabed disturbance, sediment plume generation, pollutant discharge, noise, vibration, and light pollution. Additionally, it addresses the accidental introduction of invasive species and oil spills from vessels associated with marine mining.

Seabed disturbances can negatively affect benthic organisms and habitats, while sediment plumes can degrade water quality and thereby affect organisms in the water column and filter-feeding benthic species. Pollutant discharge, including heavy metals, can cause toxic effects and bioaccumulation in marine organisms and the food chain. Noise and vibrations may disrupt marine mammal communication and light pollution can interfere with the natural behavior of species in darkness.

The marine ecosystem in West Greenland supports a wide range of species, which may be sensitive to several environmental pressures from marine mining. The report identifies vulnerable species across trophic levels (algae, crustaceans, fish, marine mammals, seabirds)

Based on the existing knowledge and identified sensitive species, the report highlights areas in West Greenland containing critical habitats and regions with insufficient data. It also provides information on specific areas in West Greenland important for benthic and pelagic species, including maps of species distribution. The North Water Polynya (Pikialasorsuaq) and Store Hellefiskebanke are highlighted as marine areas of international significance and crucial for local hunting and fishery. Additionally, the report addresses how climate change may amplify the impacts of marine mining, as climate-driven habitat changes stress individual species, making them less resilient to mining activities.

The report outlines several mitigation strategies aimed at reducing the environmental impacts of marine mining. These strategies include technological advancements designed to minimize plume generation and reduce noise pollution. Additionally, the report presents the mitigation hierarchy, a framework within environmental management and conservation that seeks to minimize

negative impacts on ecosystems through four approaches: avoidance, minimization, restoration, and compensation. Furthermore, it draws on experiences and regulatory frameworks from Norway and the International Seabed Authority (ISA), providing references for developing environmental regulations.

In conclusion, the report finds that marine mining could potentially have significant impacts on biodiversity and the marine environment, with effects depending on location, timing, operation size, and technology. Smaller operations outside sensitive areas may have limited local impacts. The report summarizes knowledge of sensitive marine areas within West Greenland's EEZ and highlights data gaps, especially regarding benthic biodiversity and the level of resilience of marine mammals, seabirds, and fish to the impacts of marine mining.

Based on the report, it may be considered to regulate marine mining based on a spatial analysis, allowing exploration licenses depending on knowledge of an area's ecological, biodiversity, and societal values and vulnerability:

- Areas open for licenses with specific requirements for environmental studies to address data gaps.

- Areas open for licenses, conditional on early collection of biodiversity data inspired by Norwegian approaches.

- Areas closed for licenses due to their well-documented ecological, biodiversity, or societal values that are vulnerable.

- Temporary closure of areas where there is insufficient ecological knowledge to assess the potential long-term consequences and where there are potentially significant ecological, biodiversity, or societal values that are vulnerable.

Enhanced monitoring programs is recommended to improve both project specific and general knowledge of the environmental impacts of marine mining and allow for ad hoc regulation of mining activities.

1 Introduction

Objective and scope

This report deals with the potential environmental impacts of marine mining in the West Greenland Exclusive Economic Zone (EEZ) outside the straight territorial sea baseline. It primarily focuses on shallow-water seabed mining (less than 200 meters deep) but also considers deep-sea mining (greater than 200 meters) when it occurs within the EEZ.

The purpose of the report is to contribute to the basis for informed decision-making on marine mining in Greenland by presenting the best available information on biodiversity, ecosystems, their sensitivity, and the potential impacts of marine mining activities while identifying key information gaps. Commissioned by the Environmental Agency for Mineral Resources Activities in Greenland, the report examines key environmental concerns such as seabed disturbance, sediment plumes, and underwater noise, with particular attention to the identification of sensitive areas for biodiversity and human use in West Greenland.

Based on a comprehensive literature review, the report describes the potential impacts of marine mining and complements a recent brief published by DCE Rasmussen et al. (2024) on environmental issues related to Deep Sea Mining.

Overview of the report

Chapter 2 provides a **background of marine mining**, focusing on marine mineral extraction within the EEZ and distinguishing between shallow-water (less than 200 meters deep) and deep-sea mining (greater than 200 meters). It covers the extraction of typical marine mineral resources and different extraction techniques. Additionally, it highlights the legal aspects of marine mining within the EEZ.

Chapter 3 reviews the **potential environmental pressures and corresponding effects** of marine mining activities, especially focusing on seabed disturbance and sediment plumes. The chapter also addresses the potential release of metals and chemicals during mining, and underwater noise and vibration from mining equipment and vessels. Additionally, the chapter explores the effects of light pollution on the behaviour of marine organisms and seabirds as well as the potential risks associated with the introduction of invasive species and oil spills.

Chapter 4 identifies **sensitive species in West Greenland's marine ecosystems** vulnerable to disturbances from marine mining. It reports on the benthic communities, which can be significantly impacted by marine mining activities. Marine mammals such as narwhals, belugas, and bowhead whales, as well as seabirds, also face potential risks from noise and light pollution and habitat alteration. Additionally, the chapter also discusses the impacts on pelagic species, including fish and shellfish.

Chapter 5 identifies **key sensitive areas in West Greenland** crucial for marine ecosystem management and conservation. It highlights the dynamic marine environment influenced by Arctic and Atlantic processes, supporting high biodiversity and significant biological productivity. Key regions like Southwest Greenland, Davis Strait, Disko West, and Baffin Bay are outlined for their importance to various marine species, including commercially important fish, marine mammals, and seabirds. The chapter addresses the vulnerability of benthic communities, particularly those associated with complex substrates, along with the significance of primary production areas and polynyas, large open-water areas between sea ice being important for the Arctic food web. It finally touches upon the impacts of climate change on the marine environment when exposed to marine mining activities.

Chapter 6 addresses the possibilities for **mitigation and regulation** by identifying potential mitigation strategies to reduce the environmental impacts of marine mining. These include technological aspects, the application of the mitigation hierarchy, and insights drawn from the experience with marine mining in Norway and the International Seabed Authority.

Chapter 7 takes the findings from the preceding chapters to draw a **conclusion** on the potential environmental pressures and impacts, sensitive species, and areas of concern for marine mining operations in West Greenland. This provides a foundation for **recommendations** on planning and regulatory framework. Additionally, the chapter summarizes key areas of concern, data gaps for specific areas and species of concern in Greenland and outlines broader knowledge gaps regarding marine mining in the region.

2 Background

Definitions and general status of the industry

Marine mining is defined here as the extraction of mineral resources in marine areas within the Exclusive Economic Zone (EEZ). This zone extends from the coastal territorial baseline of Greenland out to 200 nautical miles or, where applicable, to the EEZ boundary shared with Canada (Figure 2.1 left). Mining in shallow water (<200 meters depth) is also termed **coastal, continental shelf mining,** or **shallow water seabed mining**. In the EEZ area, 87 % are deeper than 200m, and only 13 % are shallower than 200 m (Figure 2.1 right). The maximum depth of the EEZ reaches 3900 meters (in the southern region) (Figure 2.2).

Marine mining includes **deep-sea mining** at depths greater than 200 meters typically extracting minerals such as polymetallic nodules, sulfides, and cobalt-rich crusts from the ocean floor (Rasmussen et al., 2024). Deep sea mining is often discussed in international waters, however, it is also possible in the EEZ of countries, such as Norway where exploration activity has been approved, or the Cook Islands, which have granted three exploration licenses for polymetallic nodules within their EEZ.

Near-shore mining, occurring inside the territorial baseline, and **Offshore oil and gas extraction** can also be categorized as a marine mining activity but will not be discussed further in this report.

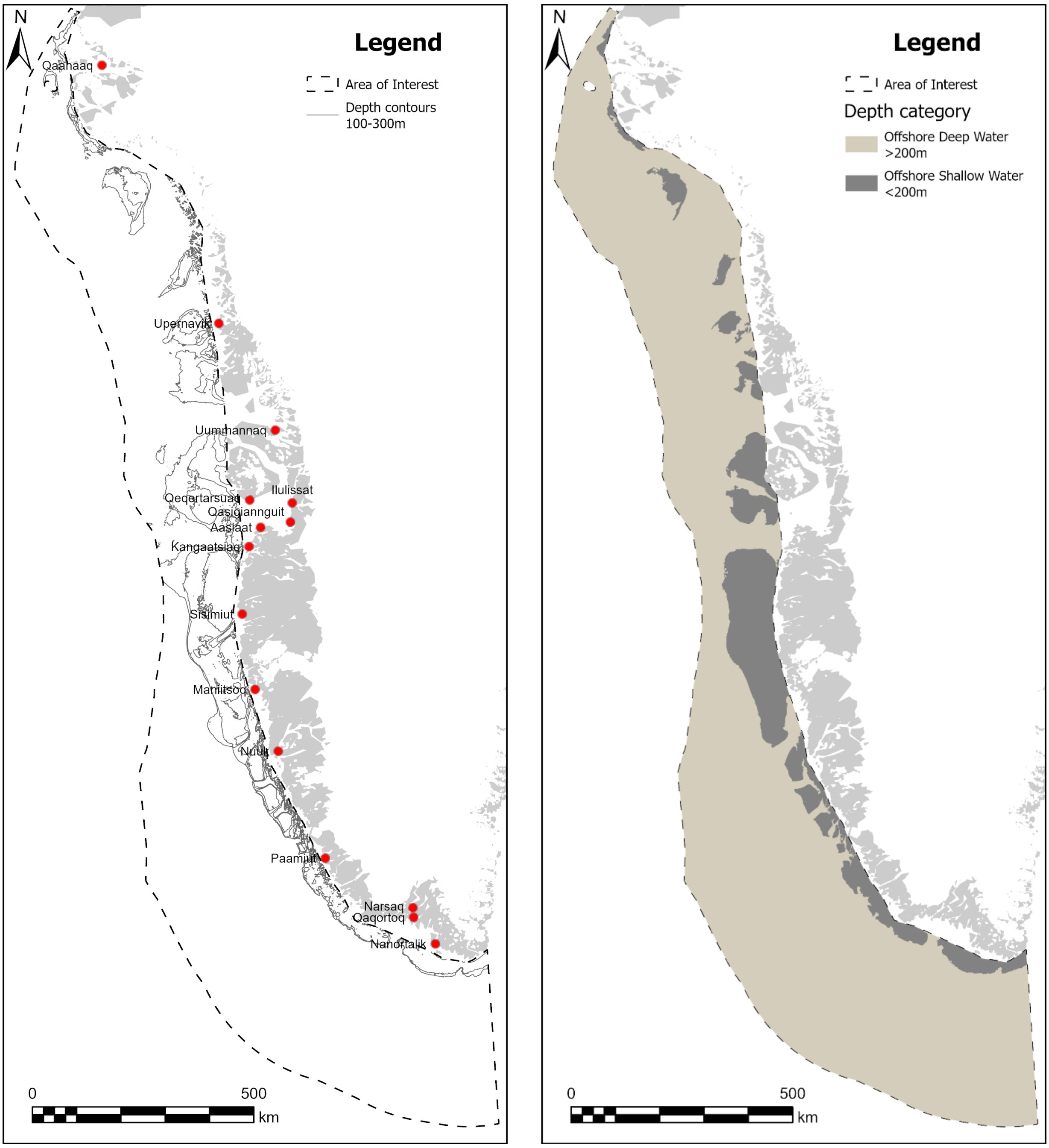


Figure 2.1. Left: Overview map of the West Greenland EEZ limited by the coastal terrestrial Greenland Baseline and the outermost EEZ border. Right: Depth of EEZ

Marine mining includes a variety of mineral resources and is conducted in various forms by different techniques, depending on the depth, seabed composition, and type of mineral targeted. Marine mining is a well-established practice in numerous countries (Hannington et al., 2017), where marine sand and gravel deposits in shelf seas are the most commonly mined. Additionally, the extraction of diamonds, gold, and tin from shallow marine environments has been ongoing for several decades in countries like Namibia, South Africa, and Southeast Asian countries of Thailand, Malaysia, and Indonesia.

In West Greenland, the dredging of sand and gravel is a well-established practice. Recently, the mining company De Beers commissioned a preliminary exploration survey of the ocean floor off Greenland's west coast to assess the potential for diamond deposits. However, this license has now been returned.

Potential marine mineral resources in West Greenland

Sand and gravel

The most recovered marine resources worldwide are sand and gravel from shallow water for use in the construction industry and the replenishment of beaches (Rona, 2008). Greenland has a long history of dredging, and the activity is regulated by the Mineral License and Safety Authority and EAMRA. The most used techniques include sand dredging with suction pumps and hoses, as well as the use of earth-moving machinery to excavate shallow sediments and transfer them into barges.

According to official statistics, Greenlandic sand and gravel dredging exceeded 60.000 metric tons in 2019. The materials are primarily utilized within the local industry. The Government of Greenland by the Ministry of Mineral Resources have also investigated the possibilities and profitability of exporting sand and gravel from Greenland (Blue Pelican Associates BV, 2021; Petersen & Læsøe, 2021), which identified five sites in West Greenland that could have the potential of being a sand or gravel deposit relevant for export. However, the feasibility study concluded that the export of aggregates from Greenland to the European market was currently not economically viable.

Placer deposits

Marine placer deposits are primarily composed of metallic heavy minerals, which have been eroded from exposed rocks on land and transported and concentrated on the continental shelves by flowing water due to their higher density compared to quartz and feldspar sediment particles. The resistance of a mineral particle in water dictates how far it can travel from its source without significant alteration (Rona, 2008) and includes:

Diamond deposits offshore occur in coastal waters associated with kimberlite pipes or alluvial deposits. Worldwide, diamond placer deposits are primarily found on the Atlantic coast of South Africa and Namibia, where large rivers transport diamond-bearing sediments to the sea. The diamond-bearing gravel deposits typically lie below a layer of sand or mud (Howard et al., 2020). In West Greenland, onshore kimberlite dykes are observed along with indicator minerals such as peridotite and eclogitic garnets (pyrope), chromite, ilmenite, and chrome-diopside from till and stream sediment samples which is evidence of a large onshore diamond potential (Secher & Jensen, 2004). The offshore potential is evidenced by environments affected by glacial weathering and the transportation of indicator minerals of diamond-hosting rocks to the sea (Hutchison, 2024).

The mining company De Beers conducted offshore surveys in 2021 led by GEUS near Maniitsoq on Greenland's west coast. This was a preliminary investigation of offshore topography to explore potential marine diamond deposits. However, the results remain unpublished (Hutchison, 2024).

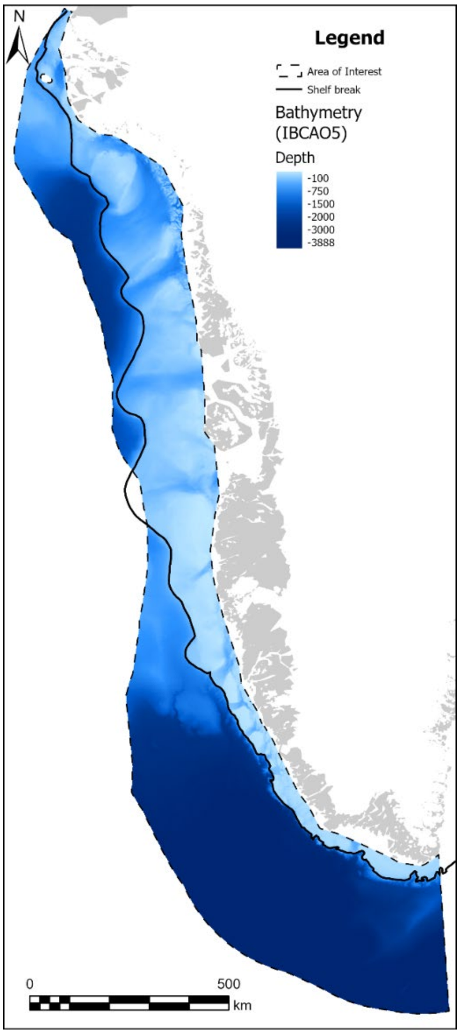
Mineral sand (contains titanium, iron, tin, zirconium, gold, and rare earth elements (REE)) is found in sedimentary deposits on the continental shelf, nearshore areas, and on land. Several onshore areas in West Greenland have known occurrences of titanium-vanadium potential (Sørensen et al., 2016). Beach sands along the shores of Steensby Land in North-West Greenland are very rich in ilmenite a source of titanium (https://eng.geus.dk/mineral-resources/mineralogy-and-petrology/origin-of-ilmenite-sands-in-the-thule-region) (onshore mining: Dundas ilmenite project). The deposits are expected to extend into the coastal waters. Commercially interesting mineral sand deposits can potentially exist in offshore areas in West Greenland where sedimentary processes have concentrated heavy minerals but have not been documented.

Polymetallic nodules

Polymetallic nodules (containing manganese, nickel, cobalt, copper, REE), also termed manganese nodules, are rock concretions formed of concentric layers of iron and manganese hydroxides. They are found in deep ocean basins on the abyssal plains away from active plate boundaries but also in shallow water on continental shelves (Kaikkonen & Virtanen, 2022; Rona, 2008).

At present, there are no surveys or studies indicating polymetallic nodule potential in West Greenland waters. Fact sheet by GEOMAR from 2020 showing a map with global nodule occurrences (for download at https://www.geomar.de/en/discover/marine-resources/manganese-nodules). Commercial abundances can only be found in four world regions to date.

Figure 2.2. The bathymetry (in meters depth) of the EEZ and the outline of the shelf break.



Phosphorite

Phosphorites are minerals that contain phosphor. They are sedimentary rocks or nodules formed on the continental shelf or slope. They are typically found along the western sides of continents, where they are associated with intense upwelling and an extensive oxygen-minimum zone beneath the highly fertile surface waters. Worldwide phosphate mining is currently limited to onshore operations, but several companies have applied for licenses to exploit marine phosphate reserves, including in Namibia, Mexico, and New Zealand (Kaikkonen & Virtanen, 2022; Rona, 2008; Sharma, 2018). No government has yet issued permits for marine phosphate mining due to environmental concerns and strong opposition from fishing industries.

West Greenland features a continental shelf that could contain sedimentary deposits suitable for phosphorite formation but phosphorite sedimentary minerals have not been documented.

Mining technology and environmental pressures

Marine mining technology is tailored to the specific type of deposit being extracted, influencing the design of mining operations and processing methods. These operations require specialized mining vehicles, launch and recovery systems, vessel conversions, ore processing facilities, transportation mechanisms, and ancillary equipment for ore handling. Transport vessels typically require 1 to 10 days of travel, plus additional time for loading, unloading, and resupplying. Helicopters may also service vessels when needed (Howard et al., 2020).

Dredging techniques

Most marine mining uses dredging systems to recover the target materials (Figure 2.3). Dredging involves removing sediments from the seabed in depths ranging from a few meters up to about 150 meters below the sea surface. Dredging systems can be shore-based systems (operate from land), barge-mounted (transported to specific locations by barges), and vessels-mounted (vessels designed specifically for dredging operations) using either hydraulic or mechanical dredging techniques. Dredging is commonly used for loose materials such as sand and gravel, while specific dredging types can operate on hard substrates.

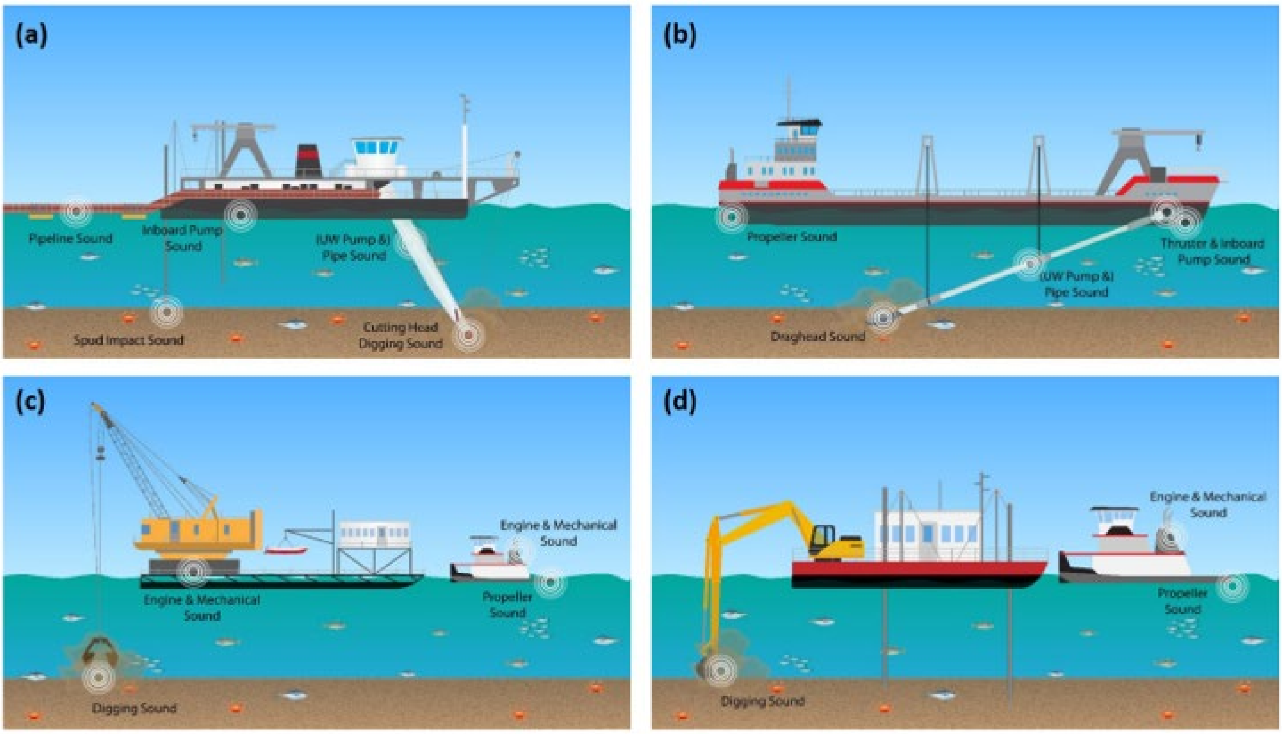


Figure 2.3. Examples of hydraulic (top) and mechanical (bottom) dredge types and potential sound sources (McQueen et al., 2019).

Mechanical dredging

Mechanical dredging involves the physical removal of sediment and debris from the seabed or waterway using mechanical equipment to dig or scoop loose substrate material from the bottom. It leaves cone-shaped holes in the substrate and is a relatively stationary operation held in place with spuds or anchors using barges to transport material to the placement site (Howard et al., 2020; McQueen et al., 2019).

It includes dredging techniques such as *grab dredgers/clamshell dredgers* (A crane-operated clamshell bucket that scoops up material from the seabed), *backhoe dredgers* (A hydraulic arm mounted at the rear of the vessel used to operate a bucket), and *bucket dredging* (a continuous chain of buckets rotating around a ladder, scoping up material from the seabed).

Hydraulic dredging

Hydraulic dredging involves the use of water in a drag head installed on the end of a pipe attached to the surface vessel. High-pressure water loosens the seabed material and creates a slurry. Due to a lower pressure in the pipe, the material is sucked up by a pipe to the surface vessel (the hopper). If in movement, the drag head produces long tracks on the seabed, typically 1.5 meters wide and up to 40 centimeters deep from the ship's movement (Howard et al., 2020; McQueen et al., 2019).

It includes specific dredging types such as *plain suction dredging* (A suction pipe used to remove loose material from the seabed without the use of any cutting or mechanical breaking devices), *cutter suction dredgers* (A rotating cutter head at the suction end of the intake pipe swinging laterally into the substrate surface, suitable for both loose and hard substrate), *trailing suction hopper dredgers* (Two trailing suction pipes, dragged behind the vessel to collect loose material from the seabed as the vessel moves), *auger suction dredgers* (A rotating auger mounted at the end of a suction pipe) and *hydrodynamic/water injection dredging* (high-pressure water or air injected into the seabed material, fluidizing it and allowing it to be carried away by natural currents).

Environmental pressures from dredging
Environmental pressures from dredging can be removal and disturbance of seafloor substrate occurring in specific areas or extending for a wider area depending on technique, which will generate a sediment plume. Mining machinery and vessels can cause noise, light, and vibration pollution over and under water during operations, and potential collision risks (Dargahi, 2023; Howard et al., 2020; Kaikkonen et al., 2018; Todd et al., 2015). Discharge of processing water (ballast water) can also cause the unwanted introduction of invasive species. It may also introduce harmful substances such as process chemicals or heavy metals from seabed extraction or accidental oil spills (Todd et al., 2015).

Unmanned underwater vehicles and machinery

Unmanned underwater vehicles are a range of uncrewed vehicles used at different stages in the marine mining process. They can vary significantly in their operational depths, depending on design and application, and range from shallow-water mining to deep-sea mining.

They include *autonomous underwater vehicles* (*AUVs*, self-guided vehicles preprogrammed to collect data or capture video and imagery mostly during the exploration process), *remotely operated vehicles* (ROVs) (remotely controlled vehicles tethered to a surface control station, they are equipped with cameras, sensors, and specialized tools for specific extraction operations). ROVs include *hydraulic mining vehicles/bottom crawlers*, which are designed for the extraction of a specific target metal. These seabed mining vehicles are surface vessel-towed or submersible platform-associated and equipped with specialized hydraulic extraction tools, that travel along the seabed and extract either accurately placed sediments (like diamond placer deposits) or spread deposits (like polymetallic nodules) on the seafloor. For diamond mining in Namibia (Figure 2.4), horizontal mining includes a crawler operating on up to 200 m water depth. Loose sea bottom material is sucked up by vacuum through a nozzle. Alternatively, for hard substrates, a large diameter drill on a drill string is employed for vertical mining (Frimanslund, 2016; Schneider, 2020). Extraction of polymetallic nodules in the Bothnian Bay, in the Baltic Sea is planned to take place at depths ranging from 60-120 meters using a suction nozzle sliding on skids sucking up loose material and transporting it to the surface (https://www.som-ab.se/en).

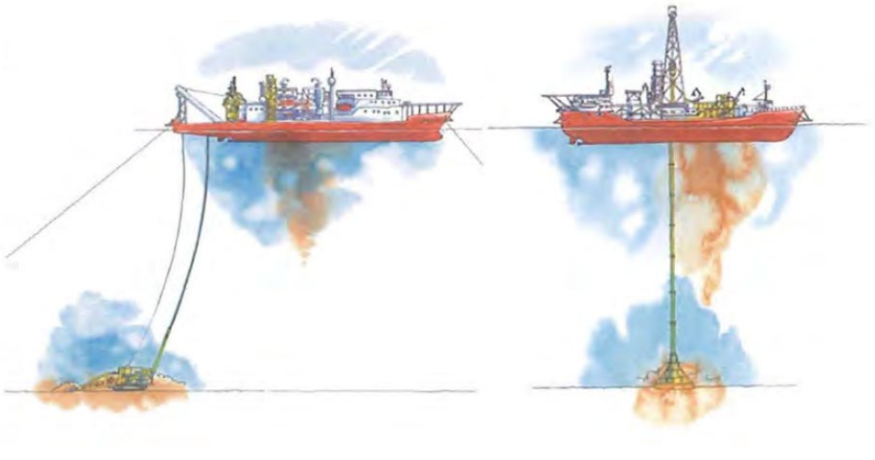


Figure 2.4 Illustrated Crawler and Large Diameter Drill concepts (Richardson, 2014).

For the extraction of polymetallic nodules (Figure 2.5), which employ crawlers with caterpillar wheels to extract the 1-20 cm surface sediment through mechanical or hydraulic means. Several crawlers have been developed or are currently under development (International Seabed Authorities, 2006; OSPAR Commission, 2021; Sitlhou & Chakraborty, 2024).

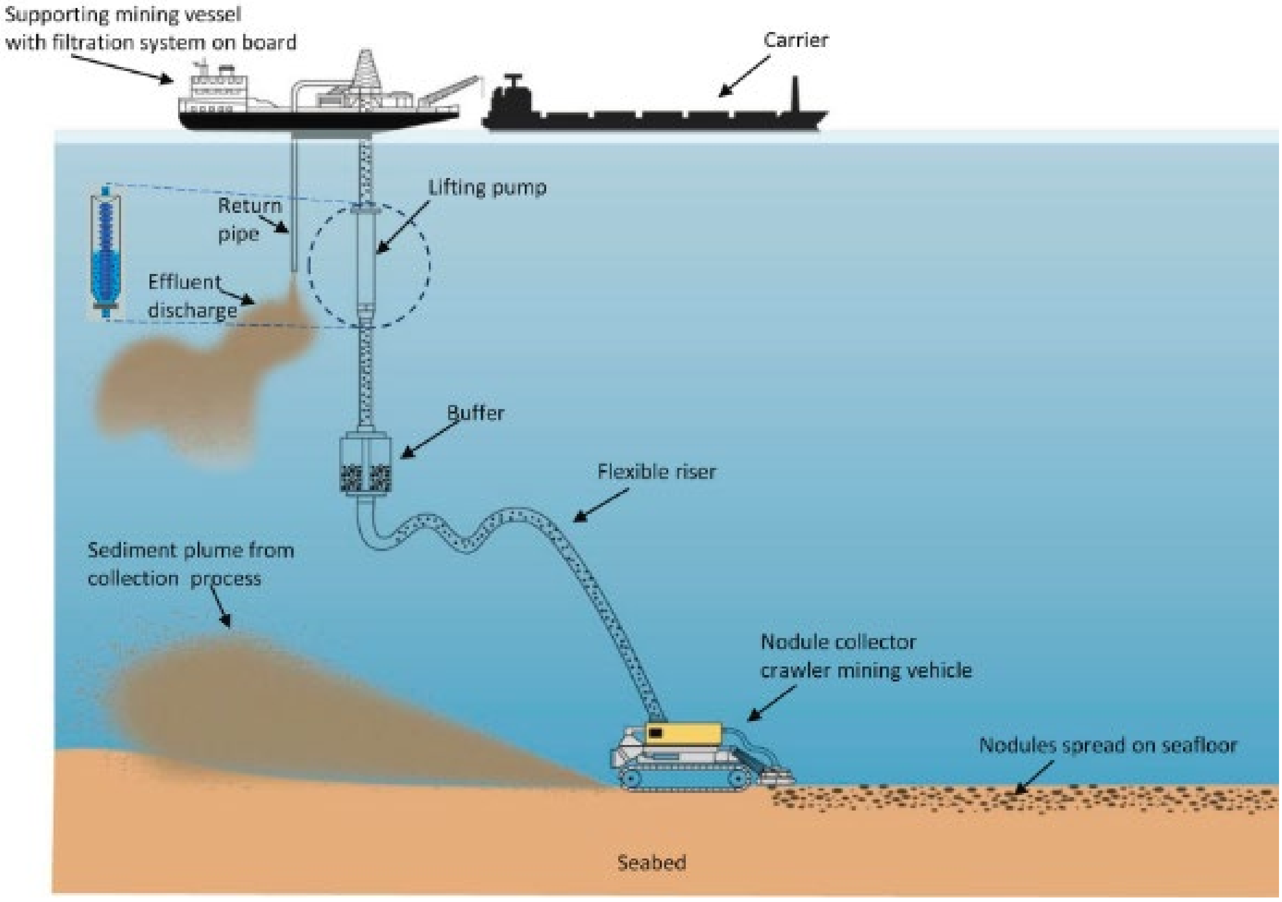


Figure 2.5. Schematic illustration of the general technological concept for Polymetallic nodule mining (Sitlhou & Chakraborty, 2024).

Depending on the type, the target material is either processed directly by the mining vehicle or transported in pipes to the surface vessel/platform for processing. Especially for diamond extraction, the on-board processing includes crushing and gravity separation, while the diamond concentrate is sent ashore via pipeline or transferred to barges or hoppers (Frimanslund, 2016; Howard et al., 2020).

Discharge techniques

The residual waste material is either stored, processed onboard the vessel, or can be discharged back into the ocean from a discharge outlet below the ship, releasing material to the water column or returned to the seabed through a sinker pipe (Howard et al., 2020; Sharma, 2018).

Environmental pressures

The environmental pressures from the operation of mining vehicles can lead to seabed disturbances including removal of substrate and dispersion of sediment plumes near the substrate or in the water column. The underwater vehicles' movement along the seabed can compress the sediment and cause noise, vibration, and light pollution. There is also potential for invasive species introduction with vehicles or as the material is lifted to the surface vessel. Vessel operations can also cause light and noise pollution above water. The processing and discharge of waste material can lead to increased sedimentation and the release of metals or industrial chemicals to the water column. The presence of surface vessels may present a collision risk for marine mammals (Howard et al., 2020; Olje- og energidepartementet, 2022; OSPAR Commission, 2021; Sitlhou & Chakraborty, 2024).

Legal aspects

Marine mining occurs in the EEZ (Figure 2.6). It is established under the United Nations Convention on the Law of the Sea (UNCLOS), granting a coastal state specific rights concerning the exploration and utilization of marine resources. It encompasses both the water column and the seabed beneath it.

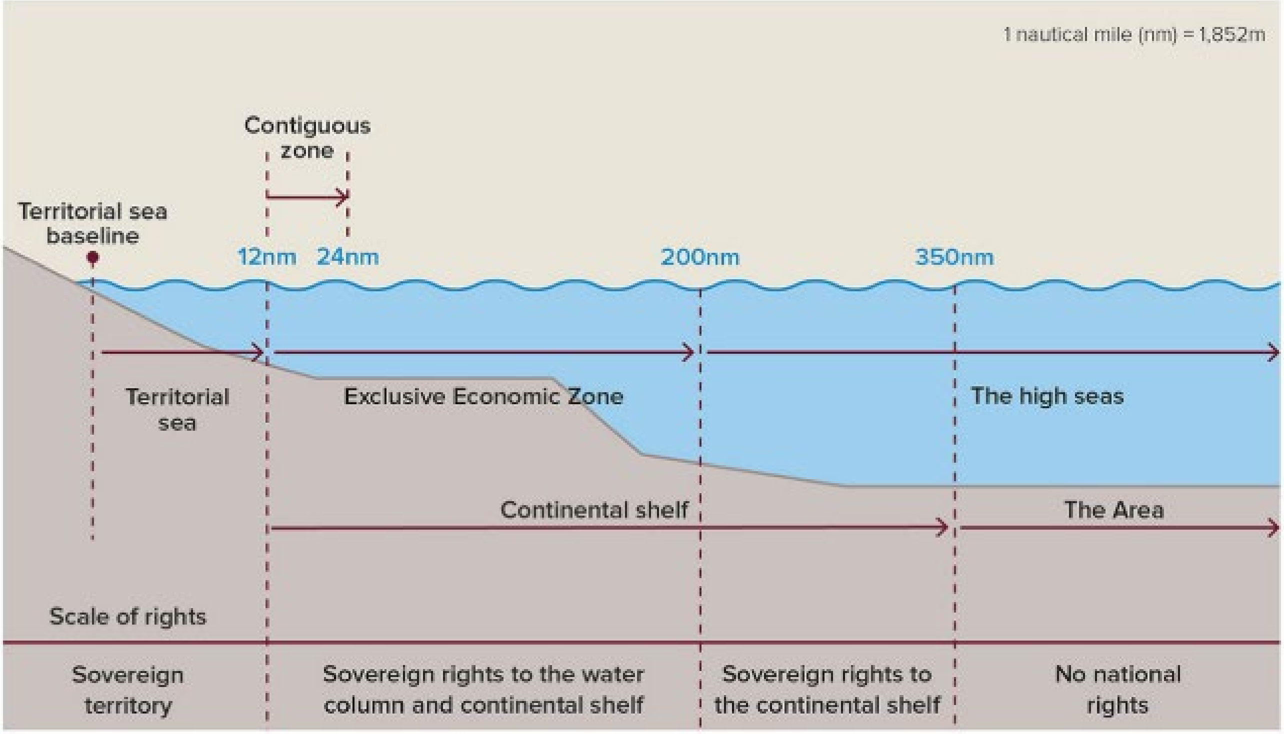


Figure 2.6. A schematic showing jurisdictional zones from a nation's coast (Miller et al., 2018).

The EEZ is legally defined in the Regulation on the Exclusive Economic Zone of Greenland (BEK nr 1020 af 20/10/2004) and environmentally protected and preserved by the Act on the Protection of the Marine Environment in the Exclusive Economic Zone of Greenland (LOV nr 1534 af 19/12/2017).

Additionally, under certain conditions, countries may claim continental shelf areas beyond this 200-nautical-mile limit (EEZ-zone), provided specific criteria are met, which gain extended rights to resources on and below the seabed. The Continental Shelf Project is a collaboration between Denmark, Greenland, and the Faroe Islands established in 2002. This cooperative effort has identified underwater areas surrounding Greenland and the Faroe Islands that qualify for an extension of the continental shelf beyond 200 nautical miles. One of three Greenlandic areas is located in the South to South-West area of Greenland on the border of Canada's 200-nautical-mile limit (Government of Denmark & Greenland, 2012). The project ended in 2014 with the submission of the last application to the United Nations Convention on the Sea and remains unanswered.

In the Greenlandic Standard conditions for the extraction of seabed materials (Grønlands selstyre – Råstofstyrelses, n.d.), commonly used for sand dredging activities, the holder of the extraction rights is responsible for any pollution related to extraction, storage, and transport of seabed materials and must conduct environmental measurements and submit annual reports to the Mineral Resources Authority. They must also actively protect the environment and respect important wildlife areas. However, no prior environmental impact assessment is required (as otherwise required in Danish waters, please see the Danish Regulation on the exploration and extraction of raw materials from the territorial sea and continental shelf (Miljøministeriet, 2024) applicable to Danish sand dredging activities).

Since marine mining has not been previously considered in many countries, its environmental regulation is inadequately reflected in many national legislations (Kaikkonen & Virtanen, 2022). In a case from New Zealand, the exploration application for iron sand rich in REE was not approved due to the uncertainty over the environmental effects (Anton & Kim, 2015; Kaikkonen & Virtanen, 2022). The company has since 2013 tried to get a permit to mine between 19-70 m depth (Corlett, 2024).

In contrast, deep-sea mining exploration and plans for exploitation most often occur at depths from 500 to 6000 m on the continental rise and the deep sea (abyssal plains) and are primarily discussed in relation to international waters outside the EEZ. It is regulated globally by the International Seabed Authority (ISA) under the framework of UNCLOS.

Examples of current global activities

Examples of global marine mining activities are given in Table 1.1 to provide a reference of current technologies and process stages.

Table 1.1. Examples of current global marine mining activities

Activity	Country	Description	Reference
Diamond mining (Figure 2.7)	Namibia	Since 2001, shallow seabed diamond mining in water depths up to 150 m has been taking place off the coast of Namibia. Early shallow water mining used digging-head and traversing digging-head dredging technologies while later deeper water mining used airlift, vertical drill or mechanical grab (crawler) dredging techniques. Mining usually only extracts the top 1 m of unconsolidated bottom sediment. The drill technology is mainly used in rugged terrain in which the crawler is unable to operate. The system sucks up gravel on the seabed through hoses or pipes, and pumps /airlifts the material up for further processing on a vessel, where material is screened,	(Erry, B., Johnston, P. & Santillo, 2000; Rogers & Li, 2002; Schneider, 2020)

		sized, processed using addition of ferrosilicon. 99.99% of the initially raised seabed material is then dumped overboard as waste.	
Tin mining	SE Asia (e.g. Thailand, Malaysia, Indonesia, Myanmar)	Tin dredging in Thailand offshore areas has occurred since 1907 in water depths up to 70 m. During the twentieth century operations in SE Asia yielded around 75% of the world's tin supply and is the largest marine metal mining operation in the world. The practice uses plain suction and cutter suction dredging. The dredgers preconcentrate the ore on board a small vessel and it is delivered to a processing plant on land. The ore is mostly dredged from shallow water.	(Erry, B., Johnston, P. & Santillo, 2000; Rona, 2008; Wang et al., 2023)
Polymetallic (manganese) nodules	Sweden, Bothnian Bay and Baltic Sea	An exploration permit was granted in July 2023 from the Swedish Ministry of Climate and Enterprise for depths of 60–120 m. Will use suction nozzle slides on skids to reduce compaction and pressure on the sea bottom.	Kaikkonen & Virtanen, 2022. In addition, a large number of countries and operators have exploration contracts with the ISA in the Pacific, see: https://www.isa.org.jm/exploration-contracts/polymetallic-nodules/

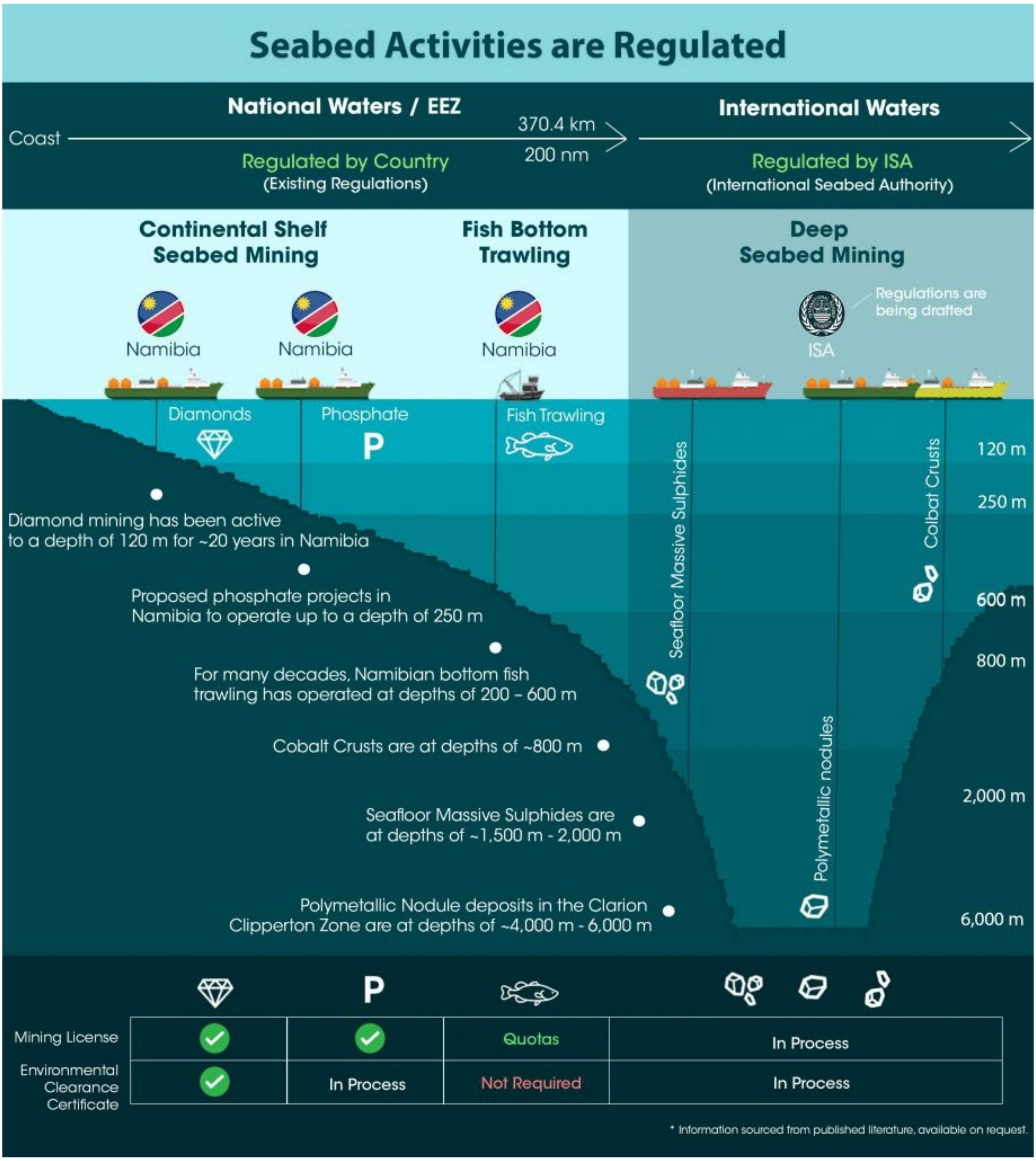


Figure 2.7. Current and Proposed Namibian Seabed Mining Projects are not the same as Deep-Sea Mining (https://chamber-ofmines.org.na/chamber-response-namibian-supplement-marine-phosphate-mining-fishing/).

3 A review of environmental pressures and effects of marine mining activities

The extraction of minerals from the seabed creates significant environmental challenges that affect marine ecosystems. This chapter reviews current knowledge of the various pressures associated with marine mining operations and their related effects on the marine environment. Key pressures on the marine environment include physical **disturbance of the seabed**, generation of **sediment plumes**, **discharge of pollutants**, creation of **noise**, **vibration**, and **light pollution** from mining equipment and vessels as well as the accidental introduction of **invasive species** and **oil spills**. Understanding and managing these impacts is crucial for developing sustainable marine mining practices.

Figure 3.1. summarizes the environmental pressures associated with deep-sea mining and the potential impacts these can cause. Although the figure focuses on deep-sea mining, it is broadly applicable to marine mining in general, as similar environmental pressures and impacts arise in both contexts.

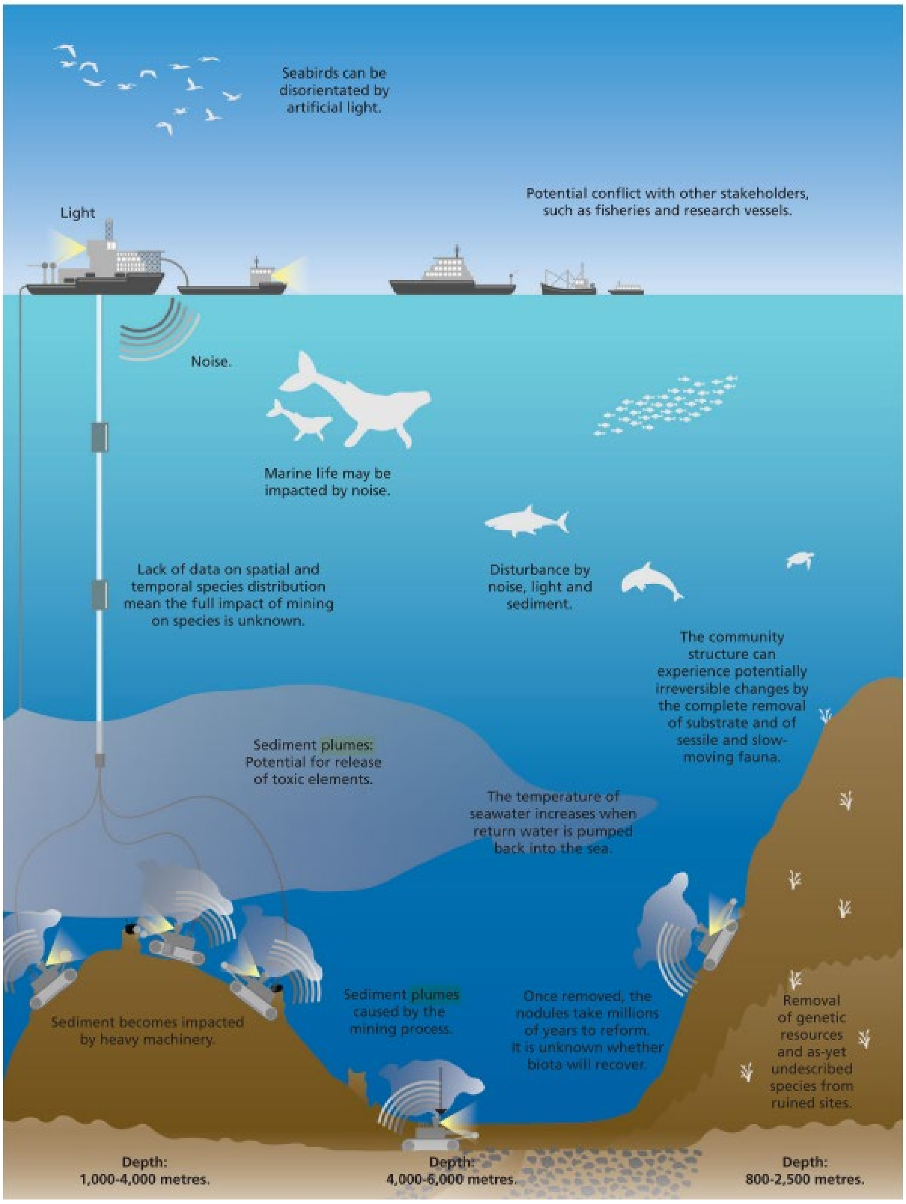


Figure 3.1. Figure 3.1. Primary impact mechanisms of deep-sea mining (European Academies Science Advisory Council, 2023).

Seabed disturbance

One of the most obvious pressures from marine mining is the physical disturbance and destruction of the seabed caused by the removal of the substrate to extract target materials. This disturbance can occur through dredging, which physically excavates the top layer in specific areas or along defined trails, or by the movement of mining vehicles (ROVs) across the seabed. As mining vehicles traverse the seabed, they create trails and compress the underlying sediment.

Seabed disturbance impacts the seabed by disturbing its natural structure and altering its physical composition. The extraction process physically removes the sediment and modifies topography by increasing shear stress on the substrate and changing the seabed levels (Dargahi, 2023). Shallow water dynamics can intensify the changed topography by increasing sediment resuspension and erosion due to stronger waves, tides, and current activity in the reduced water depths. Additionally, changes in water flow patterns can affect how sediments settle and accumulate, potentially leading to uneven sediment distribution in the altered area.

The sediment compaction caused by mining vehicles' movement along the seabed reduces permeability and porosity, altering its physical properties and restricting the natural exchange of gas and solute between the sediment and overlying water. Consequently, compacted sediment may become less suitable for benthic organisms, as it impedes their ability to burrow and diminishes overall habitat suitability.

These pressures overall impact habitat availability (Kaikkonen et al., 2018), potentially modifying existing environments or creating new ones that influence local species abundance and diversity (Kaikkonen & Virtanen, 2022). Marine mining can also disrupt homogenous habitats, such as sand flats, which might in turn create opportunities for new species to colonize, including non-native species.

Seabed disruption will most likely lead to habitat removal and degradation for a wide range of marine organisms, which may result in changes in the species composition or local extinctions (Jones et al., 2017; Kaikkonen & Virtanen, 2022). Benthic organisms living on or within the seabed that are removed will likely die (Boschen-Rose et al., 2021). Sessile organisms that are attached to hard substrate, such as bedrock, boulders, nodules or shells, are likely collected along with the target material. Mobile species living within sediments can move in response to disturbance, but their ability to escape is limited, leaving them vulnerable to the mechanical impacts of mining (Kaikkonen et al., 2018). Habitat removal is in many marine mining cases ranked as the highest risk for especially benthic habitats and the marine environment, followed by burial/smothering from sediment plume generation (Boschen-Rose et al., 2021; OSPAR Commission, 2021; Washburn et al., 2019).

Highly mobile species, such as fish or crustaceans living on the seafloor, may survive the immediate effects of mechanical disturbances and could even benefit from increased prey availability as mining exposes sediment-dwelling organisms (Todd et al., 2015). This represents one of the indirect effects of marine mining where organisms are impacted but not directly killed. Examples include disturbed sediment-living organisms, that may be dislodged from their burrows. Here, organisms will become more vulnerable to predation which reduces their survival rate (Richmond et al., 2018). Similarly, sessile organisms that cannot reattach after being dislodged may eventually die, even if not killed during the mining itself.

Even though the impacted area is concentrated on the specific mining site, the removal of the substrate and the death or extinction of species can have permanent or long-lasting effects (OSPAR Commission, 2021). The rate at which habitats can recover from such disturbances depends on the extent and duration of changes to the substrate by mining or other activities, including alteration in topography and the area affected (Van Dalfsen et al., 2000; van Dalfsen & Essink, 2001).

Sediment plumes

In marine mining, sediment plumes potentially represent one of the most significant pressures with severe impacts on the marine environment, occurring both near the seabed and within the water column (Helmons et al., 2022; Weaver et al., 2022), as illustrated in Figure 3.2. Near-bottom plumes are generated by the physical disturbance of the sediment by mining equipment, which removes or disturbs the top layer of sediment, resuspending surficial sediment and particles into the water column (Kaikkonen et al., 2018). The sediment plume generated from mining vehicles can for example extend far beyond the mining site. The generated sediment plumes might be lower near the disturbance source (>2 m) but tend to increase in height at greater distances from the source (Haalboom et al., 2023).

Additionally, local plumes on the seabed can form as the extracted material is transported or displaced. The other potential source of sediment plumes is the target material being transported to the mining platform (ship) at the ocean surface, where the extracted material may be separated from water, processed, and transferred to a transport vessel (Weaver et al., 2022).

The dewatering process, consisting of seawater with fine particles, can be returned near the seabed, mid-water, or at the surface (Muñoz-Royo et al., 2021; Washburn et al., 2019).

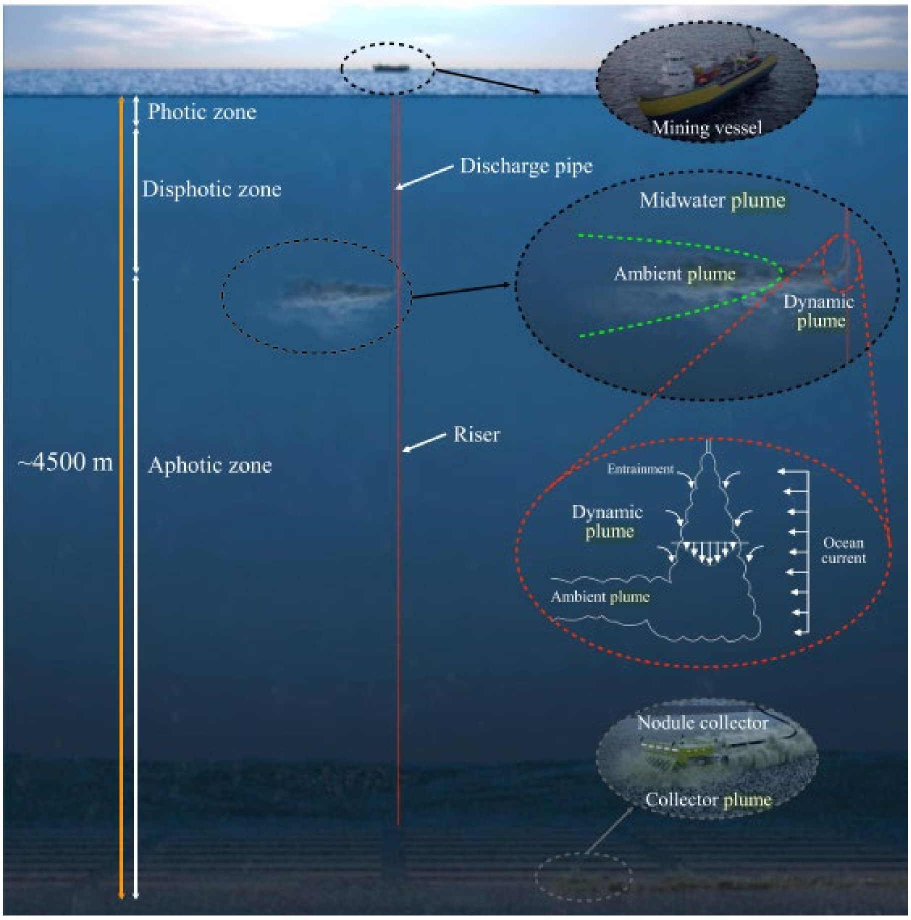


Figure 3.2. Schematic of a polymetallic nodule mining operation. The three panels illustrate the surface operation vessel, the midwater sediment plume, and the plume from the nodule collector operating on the seabed (Muñoz-Royo et al., 2021).

Sediment plume generation can lead to several environmental impacts. The increased turbidity from the particle suspension in the water column can affect both bottom-dwelling and pelagic species, and lead to immediate effects as the sediment eventually settles. Particularly immobile species such as cold-water corals and sponges may be vulnerable. Increased turbidity can reduce light penetration into the water at shallow water depths and reduce biological productivity for e.g. seagrasses and phytoplankton (Christiansen et al., 2020; Ellis, 2001; Washburn et al., 2019). Even though shallow coastal waters often experience natural turbidity, the additional, sustained turbidity from mining activities can pose challenges. Organisms present in these environments may be adapted to surviving periodic, rather than continuous, high turbidity, and may still require periods of clear water to survive. The increased turbidity can lead to clogging of suspension-feeding structures and respiratory organs (gills) (Washburn et al., 2019) and displacement of mobile species, as they flee the affected area, which temporarily alters the species distribution.

Suspended particles from the plume eventually settle out of the water column and onto the seabed. Immediate effects from the deposition involve the burial or smothering of habitats and bottom-dwelling organisms as well as effects on filter-feeding organisms, which may suffocate under the sediment load (Weaver et al 2022). Deep-sea benthos are typically exposed to very low natural sedimentation rates and may therefore be particularly susceptible to changes in turbidity. However, their ability to tolerate increased sediment deposition from marine mining, especially in terms of their ability to burrow upwards to avoid burial, remains uncertain (Smith et al., 2020). In contrast, shallow-water benthos may tolerate higher levels of sediment deposition, potentially several cm/year, due to their adaptability to more dynamic shallow-water environments (Ellis, 2001; Smith et al., 2020).

The behaviour of the redeposition of suspended particles depends on the mining process, sediment composition (fine or coarse particles), and water currents. Fine particles are often dispersed over a wide area (potentially extending tens of kilometers beyond the licensed boundaries) while coarse particles tend to settle more locally due to their higher mass density (Aleynik et al., 2017; Gillard et al., 2019; OSPAR Commission, 2021; Weaver et al., 2022). Sediment particles released at the surface or midwater into the water column such as those generated by the dewatering process can spread over vast areas (thousands of square kilometers) depending on factors like currents, particle size, and volume of material (OSPAR Commission, 2021). The redeposition of these particles can alter the size of the particle composition in the seabed and make the habitat less suitable for original living species that rely on the specific habitat conditions, ultimately leading to long-term effects on species abundance and diversity.

These immediate and long-term impacts from sediment plume generation significantly influence the recovery time of marine ecosystems (Ellis, 2001; Weaver et al., 2022). A previous study (Waye-Barker et al., 2015) found that benthic recovery from a high-intensity marine aggregate extraction site took 15–20 years to recover, primarily due to the change in the size of the particle composition caused by the plume generation. The recovery was further delayed when physical extraction continued. The physical and biological recovery may however be even slower in Arctic settings (Al-Habahbeh et al., 2020; Carey, 1991; Trannum et al., 2023).

Discharge of metals and chemicals

The physical disturbance of the seabed during mining extraction and the discharges of process water may release sediment containing nutrients or toxic substances like metals, organic contaminants, sulphides, or chemicals used in the mining processing (Kaikkonen et al., 2018).

The disturbance of seabed sediment can release naturally occurring components from the anoxic layers, such as Hydrogen sulphide (H_2S), formed in the dissimilatory reduction of sulphate by anaerobic bacterial respiration, abundant in sediments especially in coastal areas with a high organic matter content. The release of sulphides during sediment disturbance is a well-known concern related to dredging activities due to their toxicity to many organisms (Kaikkonen et al., 2018), and it must therefore be taken into consideration for mineral extraction activities in marine environments.

The generated sediment plumes can also contain harmful substances, including contaminants originating from the extracted target metal or minerals, such as heavy metals, or other associated substances released during the mining process. The release of these substances, such as heavy metals, can cause acute or chronic toxic effects on the marine environment (OSPAR Commission, 2021; Ramirez-Llodra et al., 2015). Once resuspended in the water column, these substances become bioavailable, leading to increased mortality, inhibition of growth, or lower reproductive rates in marine species (Anderson & Mackas, 1986; Fuchida et al., 2017). As these substances enter the food chain, they can bioaccumulate and bio-magnify, impacting marine organisms at the top of the food chain. Depending on particle structure, the suspension of fine sediment particles can also act as a carrier for contaminants, prolonging their suspension and extending their spread over large areas.

Metals released during mining will occur in different physical states and impacts. Metals may enter the solution/aqueous phase and be taken up across the gills, body walls, and digestive tracts of exposed animals. Alternatively, metals may adsorb onto sediment particles or flocculates and be ingested; this may be particularly the case for metals released during the dewatering of the ore slurry.

For mining projects where the exposure of organisms may be prolonged, sublethal impacts of chronic exposure should be considered. Lethal toxicity is conventionally assessed in terms of the '96-hour LC50': a measure that identifies the concentration of toxicant that kills 50% of the exposed organisms for 96 hours. However, 96-hour LC50 limits only indicate acute impacts. Mining within a license block will continue for prolonged periods of time, and organisms will be subject to chronic metal exposures that might be orders of magnitude lower than the lethal dose and at a considerable distance from the mined site. In addition, behavioural avoidance of organisms may indicate toxic impacts in real time and should also be considered. The Environmental Impact Assessment (EIA) for the project should be based on an assessment of organisms present and sensitive species in the license area.

Underwater noise and vibration

Marine mining activities generate underwater sound and vibrations that can impact marine ecosystems at the surface, midwater, and seabed level potentially operating 24 hours a day (Martin et al., 2021; OSPAR Commission, 2021; Thompson et al., 2023). Surface level noise primarily stems from vessel operations, platforms, and support traffic with significant contribution from engine operations and propeller cavitation. Additional machinery and onboard processing of the material is also contributing to surface-level noise. Surface vessels typically employ navigational echo sounders, while other acoustic tools are used for seabed exploration, equipment communication, and measurements with noise and vibration consequences. These activities extend beyond the mining industry, resulting in noise and vibrations generated by all forms of maritime traffic and operations such as oil and gas drilling (Duarte et al., 2021; McQueen et al., 2019). Midwater noise emissions arise from riser systems that transport material from the seabed to the surface via pipes. Seabed noise disturbances are mainly caused by dredging and excavation activities, where suction pumps and seabed-moving machinery disrupt the seabed and resuspend sediments. Additional seabed noise originates from acoustic exploration close to the seabed or other ROV or AUV operations exploring, sampling, monitoring, and excavating the seabed.

Noise and vibration from marine mining can affect organisms on all three levels given the many sources of noise as well as the ability of sound to travel three-dimensionally through the ocean (Martin et al., 2021) as illustrated in Figure 3.3. While high-frequency sounds tend to dissipate quickly and affect marine life primarily near the source (up to a few kilometers), low- and mid-frequency noise can travel, or propagate, over long distances (from tens to thousands of kilometers), potentially impacting marine species far from the mining site (Thompson et al., 2023; Williams et al., 2022). Even though dredging vessels are for example estimated to radiate low-frequency underwater noise (Kaikkonen et al., 2018; McQueen et al., 2019; Robinson et al., 2012), some species might be more vulnerable to the variability in noise emissions from these vessels and other noise-emitting activities than from constant noise emissions and specific frequencies (Nichols et al., 2015). Additionally, the cumulative effect of noise pollution from multiple sources could intensify the impacts, leading to broader disruptions in marine ecosystems.

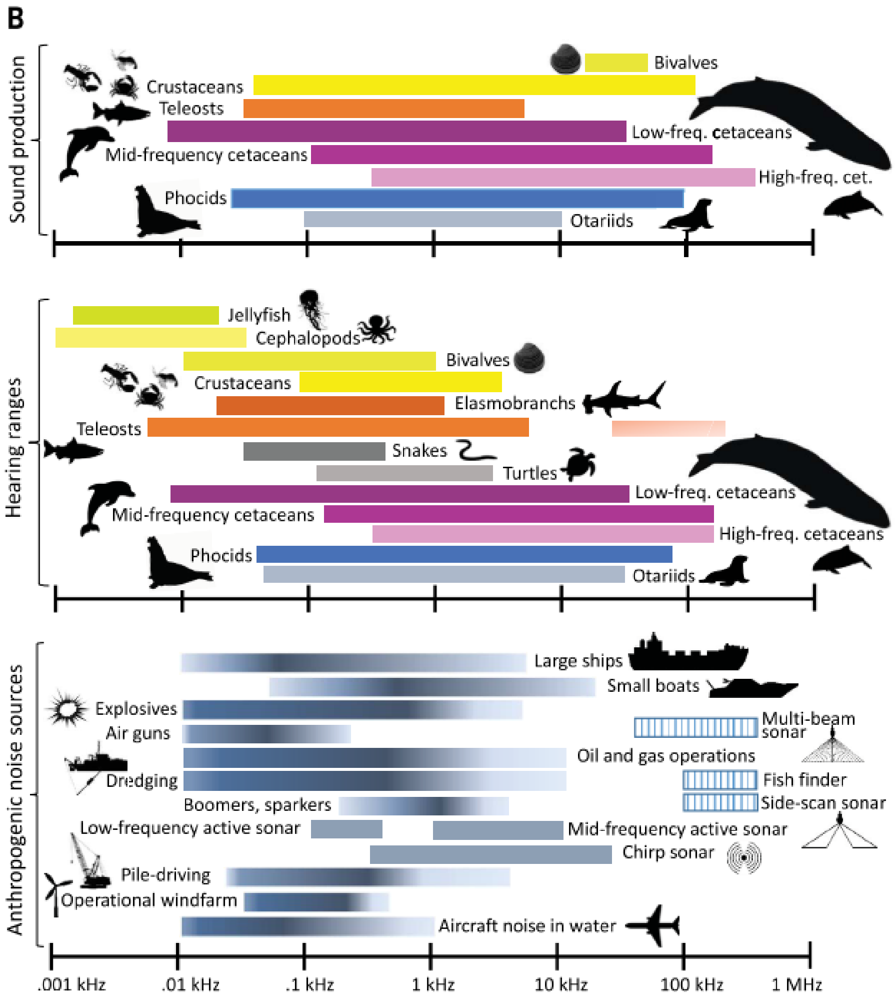


Figure 3.3. Approximate sound production and hearing ranges of marine species and frequency ranges of selected anthropogenic sound sources. These ranges represent the acoustic energy over the dominant frequency range of the sound source, and colour shading roughly corresponds to the dominant energy band of each source. Dashed lines represent sonars to depict the multifrequency nature of these sounds (Duarte et al., 2021).

This widespread noise and vibration can disrupt the behaviour of organisms across all trophic levels through mechanisms such as acoustic masking, behaviour, and migration disruption, stress, and hearing loss (Duarte et al., 2021; Martin et al., 2021; McQueen et al., 2019; Nichols et al., 2015). Highly vocal animals, such as many marine mammals, rely on sound to interact with each other and their environment. Acoustic masking refers to the fact that underwater noise can interfere with the whales' communication, navigation, and echolocation abilities to e.g. detect prey, impact reproductive success, and in turn affect populations (Thompson et al., 2023; Todd et al., 2015). Benthic species may use sensitive acoustic sensory systems to detect food falls up to 100 m away and constant noise will affect their natural soundscapes (Martin et al., 2021). Constant noise pollution has also been found to inhibit burying and bioirrigation (the exchange of solutes between overlying water and sediment by benthic organisms) among benthic species, including the water circulation within lobster burrows, which limits their movements. This reduction in burying, bioirrigation, and water circulation within the substrate can change the fluid and particle transport facilitated by these invertebrates, which plays a crucial role in nutrient and elemental cycling on the seabed.

Regarding vibration, marine invertebrates detect particle motion, using specialized sensory organs and mechanoreceptive hairs. For example, certain crabs, are known to detect substrate vibrations, allowing them to communicate and respond to environmental cues (Takeshita & Murai, 2016). Vibration from marine mining activities could disrupt these communication pathways and interfere with invertebrates' ability to detect essential signals, potentially impacting behaviours critical to survival and reproduction, including predator detection, mate selection, and territorial disputes (Lucke et al., 2016). Bivalves exposed to vibrations have also exhibited clear behavioural changes, impacting their overall fitness (Roberts et al., 2015) and even causing physical damage at high amplitudes (Roberts & Elliott, 2017).

Some species also move vertically through different ocean depths throughout their life stages and can hence be impacted by several sources from all three levels. For example, seabed-living larvae species rise to surface waters to be transported by currents, potentially exposing them to several stressors during their lifetime. These stressors have been shown to cause body malformations and developmental delays (Lin et al., 2019).

Intense noise from mining activities can also cause hearing loss or disorientation in marine species, impairing their ability to detect threats or navigate (Duarte et al., 2021; Martin et al., 2021; McQueen et al., 2019; Nichols et al., 2015). The effects are generally not considered to pose a direct risk of injury or mortality (McQueen et al., 2019) only indirectly as they become more vulnerable to predators (Simpson et al., 2016). Prolonged exposure to high noise levels can cause stress in marine organisms, affecting their immune response, reproduction, and overall health. Vibrations or noise can also disturb seabed communities, causing habitat avoidance and consequently, habitat loss or alteration, which may have long-term effects on seabed communities and marine species that depend on these environments. These effects can have severe immediate and long-term consequences on the structure and functioning of marine ecosystems, potentially reducing biodiversity and altering ecosystem dynamics (Martin et al., 2021).

Light

Artificial light pollution from marine mining activities can also pose significant environmental concerns (Figure 3.4). Light is a key structuring factor of the marine environment and can affect marine organisms individually, which potentially can cause changes at the population or ecosystem level (Miller & Rice, 2023). Many species rely on natural light cues (sun, moon, stars, aurora borealis) to migrate vertically in the water column or navigate across regions. Artificial light sources can interfere with these cycles, as well as animal foraging and breeding activities (Davies et al., 2014, 2020; Davies & Smyth, 2017; Marangoni et al., 2022). Also, artificial light in the sea emitted from e.g. mining vehicles on the seabed can interfere with the behaviour of marine organisms (European Academies Science Advisory Council, 2023; Ludvigsen et al., 2018) especially in deeper sea environments, where light is naturally absent. The introduction of artificial light in such dark ecosystems could disrupt feeding, spawning, and other critical behaviours, though the full extent of these impacts is not yet fully understood (OSPAR Commission, 2021).

Marine mining in Greenland will increase artificial light from vessel traffic and extraction machinery during darkness and may have local impacts on marine taxa and regional impacts on seabirds. Artificial light from fishing vessels (Figure 3.4) and stationary platforms are widely known to influence invertebrates and fishes (McConnell et al., 2010) and marine birds (Gjerdrum et al., 2021; Merkel & Johansen, 2011) but less is known about its impact on marine mammals.

Standard best practice guidelines to reduce the impacts of artificial light include (Australian Government - Department of the Environment and Energy, 2020; Marangoni et al., 2022): (i) Start with natural darkness and only add light for specific purposes; (ii) use adaptive light controls to manage light timing, intensity, and colour; (iii) light only the object or area intended, (iv) use the lowest intensity lighting appropriate for the task; (v) use non-reflective, dark-coloured surfaces; and (vi) use lights with reduced or filtered blue, violet, and ultraviolet wavelengths. Of these, the most important is avoiding short wavelength blue light due to its ubiquitous visibility across a wide range of taxa, as well as its higher capacity to penetrate the water column, shielding light to prevent light spill into the water or sky, and minimizing light intensity.

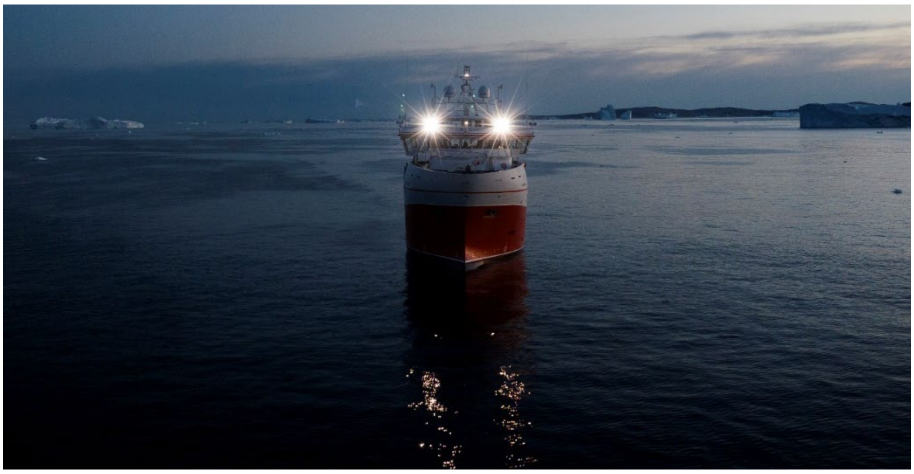


Figure 3.4. The main floodlight onboard R/V TARAJOQ used to detect icebergs or other navigational risks during sailing in ice-infested waters. Photo: Alex Rivest.

Artificial lights can attract and cause injury and death to marine birds, which are disoriented by lights and then fly into vessels (including those anchored), and offshore platforms, with numbers ranging from individual birds to hundreds in one incident. Secondary mortality occurs when birds have trouble taking off from the vessel and hide in deck spaces where they are exposed to oil contaminants, which soil feathers and thereby cause hypothermia (Merkel & Johansen, 2011; Ryan et al., 2021). Common factors associated with these events include time of year (newly fledged birds tend to be more susceptible), hours of darkness (especially with little or no moonlight), poor visibility (stormy or foggy weather), high winds, and high light radiance emanating from the vessel or platform (Gjerdrum et al., 2021; Merkel & Johansen, 2011; Ryan et al., 2021).

Invasive species

Marine mining activities can also lead to the introduction and spread of invasive species. The vessel transportation, discharge of process water (ballast water), and biofouling at various locations (Molnar et al., 2008), as well as seabed mining operations, such as relocating material or transporting sediments from the seabed to the surface, can all relocate organisms living in the sediment. All ships included in marine mining projects should follow the International Maritime Organization (IMO) regulation on ballast water (https://www.imo.org/en/MediaCentre/PressBriefings/Pages/21-BWM-EIF.aspx) and biofouling (IMO, 2023) to avoid the supply of potentially invasive and invasive alien species to the present mining area. Nevertheless, this relocation can potentially lead to the establishment of non-native species in previously uninhabited areas, potentially introducing invasive species into new habitats (Bailey et al., 2020; Christiansen et al., 2020; K. A. Miller et al., 2018).

Additionally, the physical disturbance caused by mining operations, such as dredging or the movement of mining vehicles, can create new or altered habitats that may be more suitable for non-native species. These invasive species can outcompete local fauna, disrupt existing ecosystems, and alter marine communities. This can have long-term effects on community structures (OSPAR Commission, 2021).

In relation to invasive species dispersal in marine waters, shipping remains the most prevalent pathway, primarily through the entrainment of organisms in ballast water and the accumulation of biofouling on hull surfaces (Molnar et al. 2008). Studies of Arctic shipping operations have demonstrated that the external hull and ballast tanks of vessels operating in ice-covered waters can support a wide variety of non-native marine organisms (Ware et al., 2014 and 2016, Chan et al., 2015 and 2019).

The spread of invasive species is of particular concern in fragile environments like the Arctic, where ecosystems are relatively undisturbed, and species are less adapted to cope with new competitors or predators. Once established, invasive species can rapidly colonize new areas, displace native species, and degrade biodiversity. While there are currently few known invasive non-native species in the Arctic, more are expected with climate change and increased human activity (Ware et al., 2014 and 2016), which alters temperature regimes and habitat availability, making some regions more vulnerable to the establishment of invasive species.

Accidental oil spills

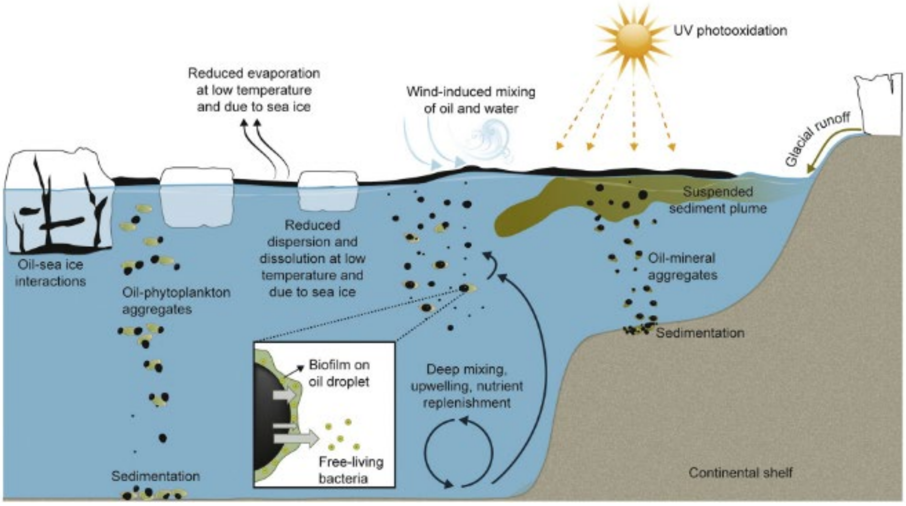
Marine mining operations carry the risk of accidental oil and hydraulic fluid spills and other unintended leakages. This can stem from the use of surface operation vessels, bottom vehicles, related heavy machinery and hydraulic systems, transport vessels, or other supportive activities and can pose a significant risk to marine and coastal environments (Mosbech, 2002).

Oil spills can occur due to various causes including vessel accidents or collisions, equipment failures, fuel or oil leaks for vessels and engines, respectively, pipeline ruptures or spills during operation or maintenance such as hydraulic leaks from underwater mining vehicles. This concern extends beyond the mining industry and is relevant to all forms of maritime traffic and activities, regardless of the purpose of the vessels involved, and is internationally regulated by The International Convention for the Prevention of Pollution from Ships (MARPOL Agreement: https://www.imo.org/en/about/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx).

Such incidents can result in severe environmental impacts such as the contamination of marine habitats and the degradation of water quality (Rasmussen et al., 2018; Sharma, 2018). Oil spills pose a significant environmental threat until the oil is either diluted or degraded (Vergeynst et al., 2018) as illustrated in Figure 3.5. The behaviour, spread, and effects of oil spills vary depending on the habitat. Marine spills can disperse over large distances on the water surface, potentially harming ecosystems and resources far from the spill's origin, whereas terrestrial spills typically have more confined, localized consequences (Mosbech, 2002). The impacts can include physical smothering, as oil coats feathers and furs of seabirds and marine mammals or toxicity, since oil contains hydrocarbons and other toxic substances that are harmful to fish, invertebrates, and plankton if ingested or absorbed.

Such spills pose significant threats to fragile environments like the Arctic (Brakstad et al., 2018; Rasmussen et al., 2018; Vergeynst et al., 2018). Here, the challenges posed by low temperatures, ice cover, and inadequate infrastructure often extend the duration of environmental damage as it represents a slow-recovering ecosystem, making the impacts more persistent than in lower-latitude regions. In marine areas dominated by sea ice, ice can trap and transport oil over long distances (Blanken et al., 2017) but may also limit its spread and protect shores. Nonetheless, biologically important areas such as ice edges and polynyas are highly vulnerable to spills. In general, oil spills in coastal areas are considered more harmful than those occurring in the open sea (Boertmann et al., 2009). The coastal zone's sensitivity is due to its rich biodiversity, including seabirds and Arctic char, and the risk of oil becoming trapped in bays, leading to toxic concentrations. Additionally, local fishermen and hunters rely heavily on these coastal areas (Boertmann et al., 2009).

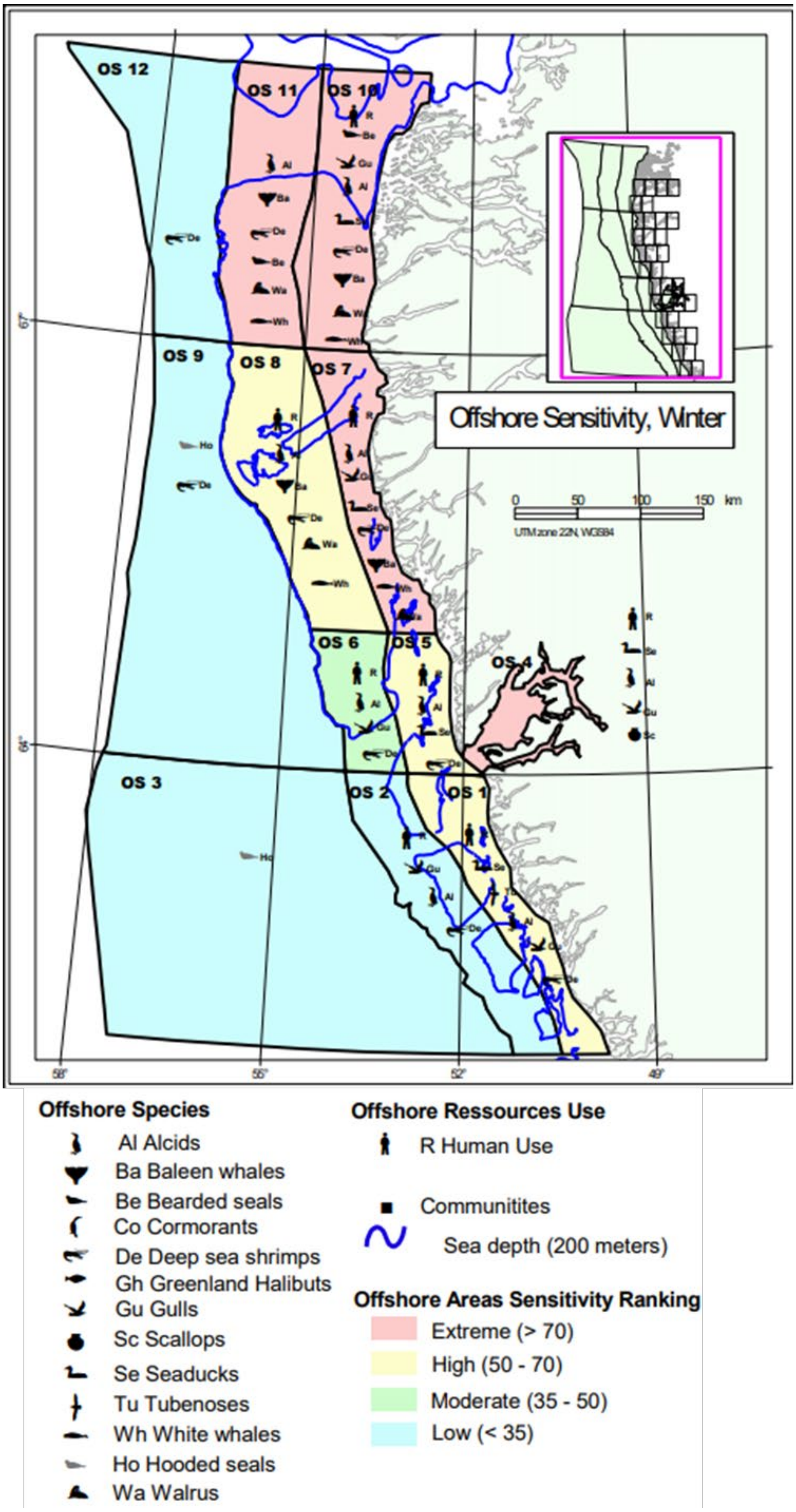
Figure 3.5. Schematic diagram of Arctic-specific conditions that affect oil biodegradation. UV photooxidation can be seasonally important. Sea ice and icebergs hamper wind/wave-induced mixing in the upper water column and cause a thicker oil slick, which, in combination with low temperature, reduces evaporation, dispersion, and dissolution. Oil-mineral and oil- phytoplankton aggregates are formed upon interaction with sediment plumes and phytoplankton blooms, respectively, which may enhance oil sedimentation. Deep mixing of the water column and upwelling cause nutrient replenishment. Biofilm-mediated hydrocarbon degradation model: biofilm-lifestyle enhances the bioavailability of water-insoluble hydrocarbons, whereas water-soluble hydrocarbons are bioavailable to both biofilm and free-living bacteria (Vergeynst et al., 2018).



The toxicity of oil impacts almost all organisms from lower (Rist et al., 2024) to higher (Fritt-Rasmussen et al., 2016) trophic levels, but the severity of these effects depends on the oil's composition and concentration, as well as the sensitivity of the affected species. Species with high individual sensitivity may not experience significant population impacts if they are widely distributed and possess high reproductive rates, which are characteristic of lower trophic levels such as copepods. Conversely, species at higher trophic levels, like king eiders on Store Hellefiskebanke, which tend to occur in dense concentrations and have slower reproduction rates, are more vulnerable to population-level impacts (see Chapter 6) (Mosbech, 2002). The limited natural dispersion of oils spilled on the surface into the water column suggests a relatively low exposure risk for organisms living in the water column in the event of a surface spill. However, there is a significant risk of physical smothering for seabirds, other surface-dwelling species, and marine organisms along the coastline (Fritt-Rasmussen et al., 2016; Rasmussen et al., 2018). Also emulsified oil with debris, special oil products, and new emergent alternative fuels can be heavier than water and sink into the water column with more risk of pollution in the water column and at the seafloor.

DCE and GINR have developed an Environmental Oil Spill Sensitivity Atlas covering West Greenland offshore waters and coastal areas, illustrated in Figure 3.6. The Atlas has been prepared to provide oil spill response planners and responders with tools to identify resources at risk, establish protection priorities, and identify appropriate response and clean-up strategies. The atlas enables companies and authorities to incorporate environmental considerations into exploration and contingency plans.

Figure 3.6. An example of an Environmental Oil Spill Sensitivity Atlas covering West Greenland offshore waters and coastal areas particularly sensitive to oil spills (Mosbech et al., 2000).



The atlas provides an overview of such aspects as the occurrence of wildlife, human resource use (fishing and hunting), and archaeological sites that are particularly sensitive to oil spills. Furthermore, it contains information regarding the physical environment – coastal types, oceanography – logistics, and oil spill response methods.

The information derives from numerous scientific studies and local knowledge collected from interviews with local fishermen and hunters in almost all settlements within the mapped region. The coast is divided into segments of approx. 50 km in length and each segment is classified according to its overall sensitivity to marine oil spills. The information is collected on two main sets of digital charts:

1) Shoreline sensitivity maps show index values for coastal sensitivity and symbols for the significant elements of the classification (hunting and fishing areas, fish, birds, marine mammals, and archaeological sites). Each map has a description of biological resources and human use of the area. 2) Physical environment and logistic maps show coast types, logistics, and proposed methods for oil spill response for each area.

4 Identification of sensitive species in West Greenland

The marine ecosystems of West Greenland are home to a diverse array of species that are highly sensitive to environmental disturbances. This chapter focuses on identifying the species that are most vulnerable to the marine mining pressures presented in Chapter 3. It provides an **introduction to the West Greenland marine fauna** and outlines the sensitivity of species across trophic levels, covering a range from **benthic** to **pelagic** species, including plankton, shellfish, fish, marine mammals, such as narwhale, beluga, bowhead whale, Atlantic walrus, and seabirds.

For each level, the following details are provided 1) the Red List status of affected species, 2) their sensitivity to noise exposure, particularly during preliminary investigations, and 3) their sensitivity to operations on the seabed, including the effects of sediment plumes and contamination. Not all possibly affected species are described.

Introduction to the West Greenland marine fauna

The arctic environment is variable and harsh, featuring low water temperatures, a yearly light regime ranging from total darkness to total light, regions covered by ice all year, and areas that shift from being ice-covered to being ice-free. These widely varying conditions require behavioural, physiological, and morphological adaptations that may affect the sensitivity of the organisms and species to the release and discharges of particles and different substances as well as to population dynamics during recovery. The Arctic has relatively short food webs, whose higher trophic levels are dominated by mammals and birds, of which many depend on rich populations of plankton that bloom heavily in spring in connection with ice break-up or upwelling (Woods et al., 2013).

Benthic epifauna species

Epifaunal communities (fauna living on top of the seabed) associated with hard, mixed, or muddy substrates are more vulnerable than those associated with high-energy environments (e.g. gravel and sandy substrates), to physical disturbance, such as bottom trawling, showing significant longer recovery times lasting up to 10-20 years after disturbance (Yesson et al., 2016). It should be noted, however, that Greenlandic epifaunal communities in soft sediments are sparsely studied, and although they may show quick recovery from marine mining-induced physical disturbance, their density and diversity may not recover for several decades (Jones et al., 2017). A study undertaken by Jones et al. (2017) demonstrated that mobile and small infauna (fauna living in the seabed) recover relatively fast compared to epifauna communities but that they do not completely regain their original distribution. Some vulnerable and long-living species like *Arctica islandica* are severely impacted by mechanical disturbance or smothering and exhibit slow recovery.

The taxa and communities most vulnerable to physical disturbance (e.g. coral and sponge gardens) were poorly represented in the dataset derived from drop camera surveys due to methodological limitations (Yesson et al., 2016), creating a data gap preventing accurate assessment of the extent of the impacts on these sensitive ecosystems. However, sponges and soft corals are regularly found in Greenland Institute of Natural Resources trawl surveys, suggesting that they are widely distributed across the benthic habitats of West Greenland and susceptible to marine mining impacts.

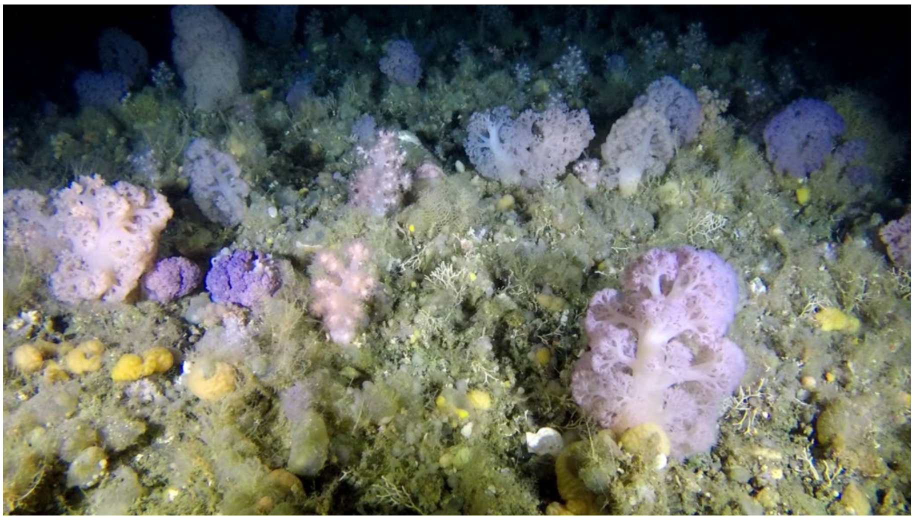


Figure 4.1. Undisturbed benthic environment in West Greenland waters with several vulnerable marine ecosystems (VME) species. Photo: Nadescha Zwerschke.

Sessile taxa forming three-dimensional structures provide habitats for other organisms, and they are often used to indicate Vulnerable Marine Ecosystems (VME) (Figure 4.1) and applied in the management of industrial bottom trawling fisheries in Greenland. According to the United Nation's Food and Agriculture Organization (FAO), VMEs include a set of specific species and ecosystems for the Northeast and Northwest Atlantic, of which some are slow-growing, long-living habitat builders such as coral sponges and erect bryozoans, which are widespread in large parts of the West Greenland shelf. When sessile taxa, primarily taxa associated with hard and mixed substratum types, are abundant, they foster biodiversity and create important habitats and nurseries for commercially important species (Mortensen & Buhl-Mortensen, 2004; Bryan & Metaxas, 2006). For Greenland, we focused on a subset of fairly well-documented taxa such as the classes Hexactinellida and Crinoidea, the orders Pennatulacea, Scleractinia, Antipatharia, and Tetractinellida, the families Capnellidae, and Gorgoniidae, and the genera Gersemia, Reteporella, and Hornera. These sessile filter-feeding organisms are directly affected by mechanical disturbance as well as by sediment plumes that clog their feeding apparatus and prevent larval settlement (Kutti et al., 2015 Richmond et al., 2018). Contamination by toxic compounds released during the mining process can further reduce their fitness, recruitment success, and survival (Richmond et al., 2018; Wurz et al., 2024).

Deep-sea muddy plains are characterized by a stable low energy environment, with continuous low sedimentation of fine organic material (Smith et al., 2008). Contrary to common belief, these deep-sea mud plains can feature high species diversity (Snelgrove & Smith, 2002) and are often home to long-living (50-128 years) bivalves such as *Serripes groenlandicus* and *Hiatella arctica* (Carrol et al., 2008). A relatively recent concern regarding low-energy soft substrate habitats is their potential for carbon storage (Burrows et al., 2024; Graves et al., 2022). Carbon that is captured at the ocean surface by primary producers and transported into the deep is locked away or sequestered in the anoxic layer of deep-sea muddy sediments, and mining activities could adversely affect these ecosystems. Thus, direct mechanical impact could crush and destroy long-lived organisms as well as reduce the biodiversity and abundance of taxa in the mudflats. The Greenland Institute of Natural Resources (GINR) only holds limited data on sediment-living taxa, whereas data is available on the taxa living on top of the muddy sediment, e.g. the sea cucumber *Laetmogone violacea* and these may be used as indicators for low-energy soft substratehabitats.

Pelagic and semi pelagic organisms

Marine mining can pose pressures to pelagic organisms such as plankton algae, zooplankton, crustaceans, and pelagic fish. Discharge of sediment plumes from surface vessels can shade the light and thus reduce plankton growth as well as smother pelagic organisms, impairing their ability to feed and reproduce. Additionally, the release of toxic substances during mining operations can contaminate the water column and consequently adversely affect the health of marine species. The cumulative impacts of these disturbances can lead to a decline in species populations and alter the structure of marine communities.

Plankton

The pelagic food web in high arctic waters (northwest Greenland waters) is controlled by light and the availability of nutrients. In early spring, increasing light and ice melting result in an increase in phytoplankton growth and some of the highest rates of growth in these marginal ice zones. The zooplankton community in northwest Greenland waters is dominated by large copepods, particularly *Calanus glacialis* and *C. hyperboreus* (Kellerup et al., 2015). These species convert low-energy sugars from the phytoplankton into a high-energy lipid reserve in the copepods. The combination of rich lipid reserves and large size makes *C. glacialis* and *C. hyperboreus* a key prey item for higher-level consumers: fish, seabirds, and whales (Figure 4.2). Arctic cod, Polar cod, and capelin represent a critical link between the zooplankton community and higher trophic levels (e.g. seals, toothed whales) (Geoffroy et al., 2023; Woods et al., 2013).

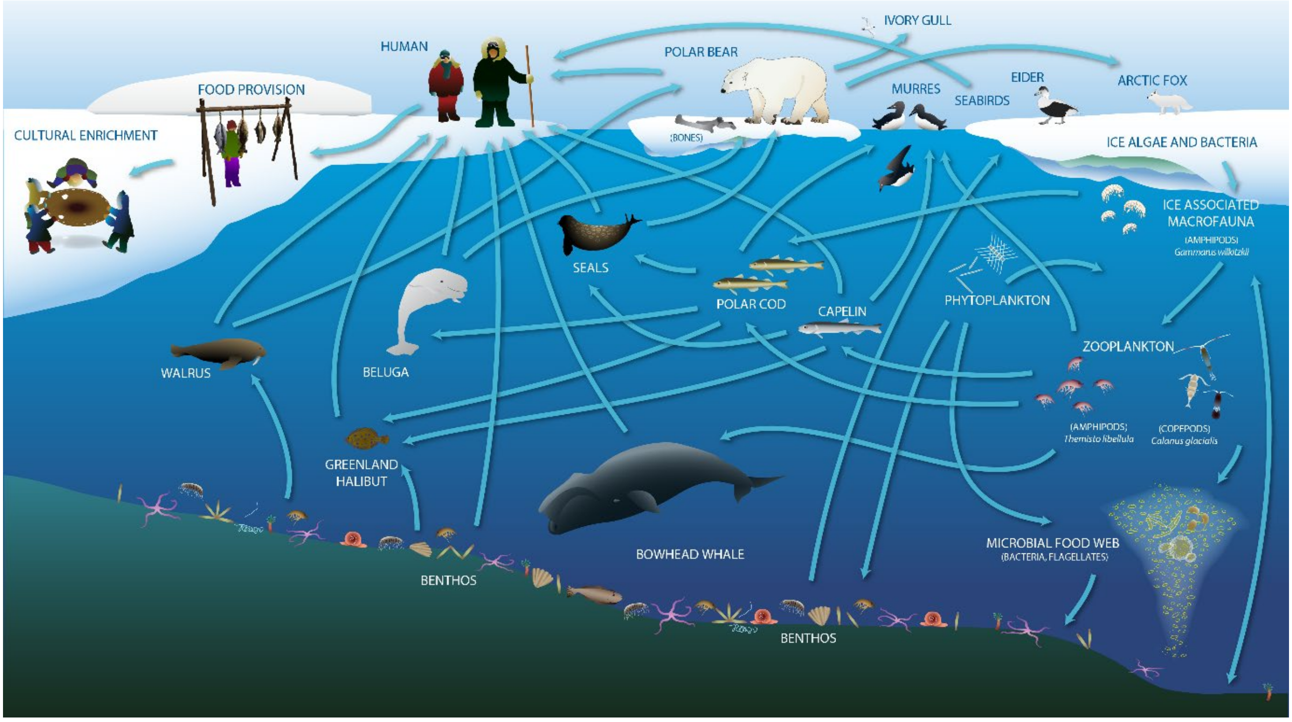


Figure 4.2. The energy flow and food web of the Arctic marine environment (CAFF, 2017).

In south-western areas, the size of the production of pelagic organisms is particularly determined by the supply of nutrient-rich bottom water, which typically takes place in upwelling zones at the large fish banks in southern Greenland. The dominating zooplankton in the southwestern waters of Greenland is the less lipid-rich, small-sized, *C. finmarchicus*, which is a valuable food resource for pelagic fish (Møller & Nielsen, 2020).

Egg and larval stages of fish and other organisms have been reported to be particularly vulnerable to suspended particles in the water body (Larsen et al., 2022). Suspended particles can impair the food intake and respiration by clogging the filtering apparatus of organisms that absorb nutrients by filtering small particles from the water bodies and/or sediment (Christiansen et al., 2020). Other negative effects of increased particle concentration in water bodies include food shortage, reduced buoyancy for fish eggs, masking of light signals, and disruption of avoidance behaviour, resulting in reduced survival against predators. Ingestion of particles with low nutritional value will result in increased metabolic energy consumption and may, over time, lead to starvation or reduced growth (Christiansen et al., 2020).

Several studies assess that the discharge of return water into the epipelagic (also called "photic" and "euphotic") zone (0-200 m) with subsequent increased turbidity and less light may harm the production of phytoplankton due to reduced photosynthesis (Christiansen et al., 2020).

Crustaceans

Shellfish, including species such as Northern shrimp (*Pandalus borealis*) (Figure 4.3), clam, and snow crab (C*hionoecetes opilio)*, could be affected by underwater noise. Knowledge is scarce on the specific impacts from noise and vibration on shellfish. Egg development among specific crustaceans may be retarded and noise could disrupt their feeding and reproductive behaviours. In the short term, the catch rates of snow crab fishery could potentially be affected negatively when snow crabs are exposed to noise > 165 dB and disappear from the area. However, whether seismic exposure has strong negative effects on catch rates in short or long term is uncertain (Christian et al., 2004, Morris et al, 2018, Morris et al., 2020) as the effect on snow crab catches due to disturbance caused by emission of seismic noise might be smaller than the changes related to natural spatial and temporal variations.

Crustaceans are likely to be highly affected by the physical processes of marine mining, which disturb or remove their habitat on the seafloor and change their access to nutrients from the upper water column. Although they migrate through the water column, Northern shrimps generally live in soft seabed habitats. Females start spawning during summer in offshore waters, and egg-carrying females migrate into shallower waters for egg hatching (Wieland, 2005). Their habitat could be affected by extraction activities, pumping, and dispersal of sediment from plumes on the seabed and in the water column. The commercial fishery of Greenland depends highly on Northern shrimp, and any negative changes to the health and size of the stock of Northern shrimp could affect the economy of Greenland.

Figure 4.3. Northern shrimp is an important resource in the commercial fishery of Greenland. Photo: Christian Sølbeck, GINR.

The mainly benthic species of snow crab (Chionoecetes opilio), and Islandic scallop (Chlamys islandica) or other crustaceans living directly on and in the seabed can be further affected by changes caused by marine mining. It has not been well studied if sediment plumes or deposits could deteriorate the food sources for snow crabs in a larger region, but, if so, individuals could die from starvation as was the case for snow crabs in the Bering Sea in 2018-2021, possibly due to changes in water properties, e.g. temperature and their limited range (Szuwalski et al., 2023).

Fish

Behavioural and physiological reactions to sounds from geophysical surveys among fish may vary between species, i.e. depending on whether they are territorial or pelagic, on their anatomy and physiology, and the seismic equipment applied. Generalizations should therefore be made with caution (Boertmann et al., 2021). Adult fish generally avoid sound waves with higher amplitudes by moving towards the bottom, thereby avoiding direct harm (Boertmann et al., 2021). Noise pollution can also lead the fish to abandon their habitats, which alters their distribution patterns and population dynamics (Lancaster et al., 2021).

In the Arctic, species such as Arctic cod, redfish, and capelin, use sound for various biological functions, including predator avoidance and mating. Noise pollution can interfere with these functions and lead to decreased survival rates. Research indicates that fish exposed to high levels of noise (above 150 dB) may suffer from hearing loss and exhibit altered behaviour, which can impact their ability to find food and avoid predators. For example, Arctic cod has shown a 50% reduction in foraging efficiency when exposed to continuous noise at 166-170 dB (Ivanova et al., 2020). Greenland halibut, on the other hand, is less affected by noise as it has no swim bladder and thus reduced hearing ability, and the fishery is conducted in deep waters, approximately 1000-1500 meters depth (Boertmann et al., 2021).

In general, fish stocks are particularly vulnerable if adult fish are deterred from local spawning grounds during their spawning season. Outside the spawning grounds, fish stocks are likely not disturbed to the same degree, but the fish can be displaced temporarily from important feeding grounds due to noise (Boertmann et al., 2021 Engås et al., 1996; Slotte et al., 2004). A review by Slabbekoorn et al. (2019) highlights the significant gaps in our understanding of how seismic surveys affect fish behaviour across species. The review emphasizes the need for further research into the long-term effects on behavioural changes, such as disruptions in time and energy budgets, missed feeding or mating opportunities, impaired predator-prey interactions, and chronic stress effects on growth, development, and reproduction. Moreover, noise effects on population levels remain to be elucidated (Boertmann et al., 2021).

Marine mammals

Marine mammals, including baleen whales, cetaceans (toothed whales, dolphins, and porpoises), and pinnipeds (seals, sea lions, and walruses), rely on acoustics as it is their primary sensory modality to gain information from their environment. Due to their limited vision underwater due to lack of light, sound is the most effective medium for these animals to detect, communicate, and interpret environmental cues. Marine mammals utilize sound for navigation, foraging, predator avoidance, and social interaction. Given their dependence on acoustic information, marine mammals are highly sensitive to alterations in the ambient noise level and noise type.

Industrial noise can disrupt communication and navigation behaviour due to masking, cause disruption of foraging behaviour, and alter migration routes due to displacement (Erbe et al., 2018). Chronic noise exposure has been linked to increased stress levels, impacts on the hearing capability, and behavioural changes, such as reduced feeding and mating success (Lancaster et al., 2021; Rolland et al., 2012).

Figure 4.4. Orca calf and mother near Nunap Isua, South Greenland. Photo: Karl Zinglersen

For cetaceans and pinnipeds, many species rely heavily on echolocation and vocalizations for hunting, navigation, and social interactions. Noise pollution can interfere with these critical behaviours, leading to reduced foraging efficiency (Wisniewska et al., 2018) and increased stress. For example, orcas (Figure 4.4) have been observed to increase the duration, amplitude, and frequency of their calls in response to elevated noise levels, which can lead to enhanced energy expenditure (Foote et al., 2004; Holt et al., 2009). Sperm whales, which use powerful clicks for echolocation, have been found to reduce their vocal activity in noisy environments, potentially impacting their ability to locate prey (Isojunno et al., 2016). Pilot whales have also been observed to exhibit avoidance behaviour and changes in group cohesion in response to noise pollution (Visser et al., 2016). Bearded seals (Figure 4.5) use vocalizations for courtship and territorial defense, and male bearded seals increase their call amplitudes in response to elevated ambient noise, but only up to a certain threshold. Beyond this threshold, their ability to compensate for noise is limited, rendering them vulnerable to acoustic masking and disruption of critical behaviours (Fournet et el., 2021).

Figure 4.5. Bearded seal resting on ice. Photo: Thomas W. Johansen, NASA Oceans Melting Greenland.

Marine mammals are often top predators at a high trophic level and contaminants from plumes or other sources during marine mining processes can bioaccumulate into the food chain and end in the individuals at the top. Already, there are high levels of contaminants (PCBs, POPs, DDEs, pesticides, etc.) in toothed whales and other marine mammals in Greenland (Pedersen et al., 2024; Dietz et al., 2019). Baleen whales feed on krill, small fish (herring, capelin, sand lance), and squid, and many species forage in Greenland during summer, and fast during winter at lower latitudes; consequently, their summer feeding grounds are important for their energy budgets.

Narwhal, beluga, bowhead whale, and Atlantic walrus are particularly sensitive to disturbances, and their vulnerability is described separately below.

Narwhal

Narwhals (*Monodon monoceros*) are found in the Atlantic sector of the Arctic where they occupy deep water areas during winter and coastal fjords during summer. The global population is divided into separate local populations with little or no connectivity (Heide-Jørgensen et al., 2013; Heide-Jørgensen et al., 2015). On the national Red List of Greenland, the Northwest Greenland stock of narwhals is 'Near Threatened' (NT), and the East Greenland stock is 'Endangered' (Boertmann & Bay, 2018).

Narwhals (Figure 4.6) are highly sensitive to noise, which can significantly disrupt their natural behaviour (Heide-Jørgensen et al., 2021; Tervo et al., 2021; Williams et al., 2022; Tervo et al., 2023). Studies have shown that narwhals exhibit strong physiological and behavioural responses to anthropogenic noise. These responses include changes in heart rate, reduced foraging behaviour, increased activity level, and changes in diving behaviour (Tervo et al., 2023 Williams et al., 2022). Narwhals also react by increasing their swim speed and by altering their avoidance behaviour when approaching the coast (Heide-Jørgensen et al., 2021; Williams et al., 2022). Although narwhals exhibit the strongest reactions in the vicinity of the noise source, they have been shown to react to noise at very low sound pressure levels below the ambient noise level several tens of kilometers away from the noise source, which further underlines their sensitivity to sound disturbance (Heide-Jørgensen et al., 2021; Tervo et al., 2021; Williams et al., 2022; Tervo et al., 2023; PAME, 2019). The increased energy expenditure due to higher activity levels and reduced foraging efficiency may have long-term impacts on their health and survival, particularly in the context of increasing industrial activities in the Arctic. Additionally, the avoidance behaviour exhibited by narwhals in response to noise (Heide-Jørgensen et al., 2021; Williams et al., 2022) can lead to habitat displacement and increased vulnerability to predators.

Due to the sensitivity of narwhals, there is a high probability that they will avoid areas where mining activities occur, and if these take place in key feeding, mating, or other critical habitats and periods, they can disrupt crucial behaviours.

Figure 4.6. Group of narwhals near the ice during the acoustic mapping operations of the Oceans Melting Greenland campaign in 2016. Photo: Thomas W Johansen, NASA Oceans Melting Greenland.

Narwhals primarily forage during winter and early spring before migrating to their summer breeding areas (Laidre & Heide-Jørgensen, 2005; Heide-Jørgensen et al., 2015). Therefore, offshore winter and spring habitats are crucial for the annual growth and life cycle of the narwhal. Here, narwhals perform long and deep dives and forage mainly on bottom-dwelling Greenland halibut (*Reinhardtius hippoglossoides*), squids (Gonatus spp.), and Polar cod (*Boreogadus saida*) (Laidre & Heide-Jørgensen, 2005; Hansen & Nielsen, 2022).

Although narwhals leave their winter and spring foraging habitats in late spring and early summer and move into coastal fjords, mining operations during ice-free periods in summer and fall can still indirectly impact their foraging success. Offshore mining activities can disturb the seabed, generate sediment plumes, and contaminate the water column and benthic environment, which may negatively affect narwhal prey species and, consequently, the overall health of the narwhals.

As sea ice breaks up in spring and summer, the narwhal populations migrate to their summer grounds in Northwest Greenland, East Greenland, and Northeast Canada. Their migration patterns vary in both timing and location, depending on the distribution of sea ice as they follow the opening of the fjords. Since their seasonal migrations between summer and winter habitats occur over large geographic areas and extended periods, influenced by shifting environmental conditions such as ice melt, the migration patterns are difficult to predict. Narwhals are susceptible to occasional entrapments in sea ice (in Greenlandic: *Sassat*), and anthropogenic disturbance might lead to an increase in such incidents.

The narwhale summer grounds are located in the fjords within the baseline maritime boundary; however, entrances to the summer grounds are often off the baseline and consequently of relevance to the report.

Beluga whale

Beluga whales are found in Arctic and sub-Arctic waters, including Greenland. During summer, beluga whales occupy coastal estuaries and shallow bays, and in winter they migrate to deeper, ice-covered regions, typically traveling with narwhals. Some populations are known to remain in specific areas year-round, while others undertake long-distance seasonal migrations (Citta et al., 2017). Beluga whales are social animals living in groups, and they feed on a variety of fish and squid (Marcoux et al., 2012). On the national Red List, the Greenland population of beluga whale (Delphinapterus leucas) is 'Vulnerable' (VU) (Boertmann & Bay, 2018).

Beluga whales are sensitive to anthropogenic disturbance of underwater noise (NAMMCO, 2022). Belugas are often referred to as the "canaries of the sea" due to their rich vocal repertoire. Noise from human activities can mask these vocalizations, making it difficult for belugas to communicate and forage. In the Cook Inlet, for example, the low-frequency noise of commercial ships has been found to partially or completely mask the most common calls made by belugas (Brewer et al., 2023). This can lead to increased stress and reduced reproductive success, further threatening the Cook Inlet population. Furthermore, belugas exposed to chronic noise pollution have shown elevated levels of stress hormones, which can impair their immune function and impact their overall health (Halliday et al., 2021).

Moreover, reduction or changes in sea ice cover and properties might affect the distribution and migration patterns of beluga whales. Assessment of activities in important migration corridors should incorporate information on the current sea ice situation in the delineation of the corridors. Akin to narwhals, belugas are susceptible to occasional entrapments in sea ice, and anthropogenic disturbance might lead to an increase in such incidents.

Bowhead whale

Bowhead whales (*Balaena mysticetus*) are large baleen whales found in the Arctic and sub-Arctic regions. Adult bowheads can reach lengths of up to 18 meters and can weigh as much as 100 tons. Bowhead whales are filter feeders and use their baleen plates to filter zooplankton from the water. They are known for their long lifespan, with some individuals living more than 200 years.

The species is divided into several populations, with the Bering-Chukchi-Beaufort (BCB) stock being the largest. In Greenlandic waters, bowhead whales are found both off the coasts of East Greenland and West Greenland. On the national Red List, the Spitsbergen population of bowhead whales in East Greenland is 'Vulnerable' (VU) and the Baffin Bay-Davis Strait population off the west coast is 'Near threatened' (NT) (Boertmann & Bay, 2018).

Bowhead whales are another species significantly impacted by underwater noise. These whales use low-frequency sounds for communication and navigation, and these can be easily masked by low-frequency noise from shipping and industrial activities. In response to increased ambient noise, whales tend to increase the frequency and volume of their calls to maintain communication (Thode et al., 2020; Clark et al., 2009). However, beyond certain noise thresholds, the call density declines sharply, and in some cases, calling ceases entirely. This behavioural shift has been documented in response to air gun pulses and vessel sounds, which are particularly impactful due to their strength (high amplitude) and propagation range (low-frequency signals) (Blackwell et al., 2015; Blackwell et al., 2017). The short-term effects of increased call density and source levels in response to noise include an increase in energetic cost, whereas reduced call density and communication cessation at high noise levels can obstruct important behaviours such as navigation and mating and cause displacement (Blackwell et al., 2015). The long-term consequences of noise exposure for bowhead whales are still uncertain, but chronic stress from noise could likely have significant biological effects. For instance, a study on North Atlantic right whales, a close relative of bowhead whales, showed reduced stress hormone levels when shipping noise temporarily decreased after 9/11, highlighting the potential physiological impacts of noise on whale populations (Rolland et al., 2012). Bowhead whales are baleen whales filtering large volumes of water for mainly krill and copepods. Plumes and contaminants of e.g. heavy metals in the ocean water can move up through the food chain and can accumulate in the blubber of the bowhead whales through their long lifespans.

Atlantic walrus

The Greenland population of Atlantic walrus (*Odobenus rosmarus*) is mainly assessed as 'Vulnerable' (VU) on the national Red List, with the Northeast Greenland population being 'Near Threatened' (NT) (Boertmann & Bay, 2018).

Activities in the wintering and spring areas involve feeding, mating, and giving birth. Walrus feed intensively on bivalves in shallow water at approximately 5-100 m depth on banks or in coastal areas (Garde et al., 2018).

Walrus can be disturbed by vessel traffic related to investigations before and during marine mining processes if hauling out (resting) on the ice and by deployment of underwater vehicles in the water column.

Mineral extraction activities on the seabed can disturb the habitat of walruses by physical presence and related noise, removal of mussel banks or other bivalves, and by smothering and contamination of mussels through sediment plumes. The plumes can also reduce the visibility of walruses when feeding on mussels on the banks. This main food source of the walruses can thus deteriorate or become polluted by materials from the plume filtered by the mussels. Contaminants can bioaccumulate from the mussels to the walrus.

Seabirds

Marine birds can be directly impacted by noise and light from marine mining operations causing disturbance and altered behaviour, and by sediment plumes disrupting visual foraging. Indirect impacts are mainly caused by reduced food abundance, caused by physical disturbance of the seabed for benthic-feeding marine birds and by sediment plumes, noise, and light for pelagic-feeding marine birds (Boertmann et al., 2021; Boertmann & Mosbech, 2017; Merkel et al., 2020; Merkel & Johansen, 2011).

All marine bird species (see Table 4.1) may be affected by marine mining and a potential population impact depends on the importance of the area for foraging and the specific mining activities taking place. Examples of bird species and their vulnerability to disturbance and pollution are described below.

All colonial marine birds depend on good foraging conditions within commuting range from their colony in the breeding season. In these areas, they will be sensitive to disturbance and mining activities that can hamper the feeding conditions both directly and indirectly. Large colonies include birds foraging at larger distances (e.g. 75 kilometers) from the colony, making large colonies of thick-billed murres, little auks, kittiwakes, and terns potentially sensitive to mining operations at some distance (Patterson et al., 2022). However, not all areas within a foraging range are important foraging areas, and a detailed gathering of data and analysis of each foraging range is therefore required to determine the important parts.

Sea ducks like common eider and king eider rely on benthic foraging and are especially sensitive to human disturbance during the moulting of flying feathers in August-September (Mosbech et al., 2007). Sediment plumes and sedimentation from extraction activities can impact benthic prey availability as well as their visual feeding capabilities.

Auks like thick-billed murre and most other seabirds breeding in large colonies rely on pelagic feeding, and sediment plumes can impact prey availability as well as their visual feeding capabilities. During breeding, seabirds are central-place foragers and loss of feeding grounds can impair the breeding success.

High levels of ship traffic and human activities in certain areas can disturb seabird populations, leading to potential declines in their numbers (Frederiksen et al., 2017; Merkel et al., 2023; Labansen et al., 2021). Keeping important foraging areas intact and minimizing human disturbances are essential for the conservation of seabird populations.

Table 4.1. Overview of selected seabird species occurring regularly in the West Greenland EEZ. b = breeding coastal, (b) = breeding inland, s = summering, w = wintering, mi = migrant visitor, c = coastal, o = offshore. Importance of study area to population (conservation value) indicates the significance of the population found in the assessment area in a national and international context. * indicates that the species are colonial breeders in the assessment area. (Table adapted from Boertmann et.al 2021). Especially seabirds with an offshore distribution (indicated with distribution=o) may occur in areas potentially impacted by marine mining.

Species	Feeding strategy	Occurrence		Distribution	Red-list status in Greenland	Importance of study area to population
Fulmar*	surface and shallow diver	b/s/w/mi	year round	c & o	Least concern (LC)	High
Great cormorant*	diver and feed in water column	b/s/w	year round	c	Least concern (LC)	High
Brent goose	grazing on salt marshes	mi	spring and autumn	c	Vulnerable (VU)	Medium
Mallard	surface	w/(b)	year round	c	Least concern (LC)	Medium
Common eider*	diver to seabed	b/s/mi/w	year round	c	Least concern (LC)	High
King eider	diver to seabed	mi	Aug.-Sept.	c	Least concern (LC)	High
		w	October-May	c & shallow banks o		
Long-tailed duck	diver to seabed	b/mi/w	year round, in winter only southern part	c & shallow banks o	Least concern (LC)	High
Red-breasted merganser	diver and feed in water column	b/mi/w	year round, in winter only southern part	c	Least concern (LC)	High

Harlequin duck	diver to seabed	mi/w/(b)	year round	c (rocky shores)	Least concern (LC)	High
Red-necked phalarope	surface	mi/(b)	spring and autumn	o	Least concern (LC)	Low
Grey phalarope	surface	mi/b	spring and autumn	c & o	Least concern (LC)	Low
Arctic skua	surface	b	summer	c	Least concern (LC)	Low
Black-legged kittiwake*	surface	b/s/w/mi	year round,	c & o	Vulnerable (VU)	High
Glaucous gull*	surface	b/s/w	year round	c & o	Least concern (LC)	Medium
Iceland gull*	surface	b/s/w	year round	c & o	Least concern (LC)	Medium
Great black-backed gull*	surface	b/s/w	year round	c & o	Least concern (LC)	Medium
Sabine's gull	surface	b	very localised	c	Near threatened (NT)	Low
		mi	August and May/June	o		
Ross' gull	surface	b	very localised	c	Vulnerable (VU)	Low
Ivory gull	surface	w/mi	October - May	o	Vulnerable (VU)	High
Arctic tern*	diver and feed in water column	b	May - September	c	Near threatened (NT)	High
Thick-billed murre*	diver and feed in water column	b/s/w/mi	year-round	c & o	Vulnerable (VU)	High
Razorbill*	diver and feed in water column	b/w	year-round	c & o	Least concern (LC)	High
Atlantic puffin*	diver and feed in water column	b/w/mi	year-round	c & o	Vulnerable (VU)	High
Black guillemot*	diver and feed in water column and in kelp forest	b/w	summer	c	Least concern (LC)	High
			winter	c & o		
Little auk*	diver and feed in water column	b	May - August	c & o	Least concern (LC)	High
		w/mi	September - May	o		
White-tailed eagle	surface	b/w	year round	c	Vulnerable (VU)	High

5 Identification of sensitive areas in West Greenland

Identifying valuable marine areas especially sensitive to marine mining is essential for effective management and conservation of marine ecosystems. By understanding species distribution and habitats, we can better protect biodiversity and ensure ecological sustainability. This chapter introduces the **West Greenland marine environment** followed by highlighting sensitive areas for **benthic** and **pelagic species**, including marine mammals, fish, and seabirds. The identification of areas is based on previously published reports and related data. It should be noted that the delineation of these areas evolves as new data from monitoring efforts, ecological trends, and climatic changes, emerge. Area definitions continually adapt to and reflect the latest knowledge and research advancements.

Introduction to the West Greenland marine environment

The marine environment off Greenland's west coast is a dynamic ecosystem influenced by a combination of Arctic and Atlantic oceanographic processes. The region is characterized by complex water masses, high biological productivity, and diverse marine life, providing vital ecosystem services to both people and businesses in Greenland (Straneo et al., 2022). The region can be subdivided into subregions with different properties that are governed by the subsea landscape, the degree of influx of warm and heavy Atlantic water, and a hydrographic overlay of cold water from melting sea ice, icebergs from large marine-terminating glaciers, freshwater inputs, and the high Arctic Ocean. The following descriptions of the properties of the different subregions are predominantly based on the Strategic Environmental Impact Assessment reports prepared over the years by DCE Aarhus University and Greenland Institute of Natural Resources (Boertmann & Mosbech, 2017; Frederiksen et al., 2012; Merkel et al., 2021).

Southwest Greenland

The offshore marine ecosystem of Southwest Greenland is influenced by the convergence of Arctic and Atlantic waters, creating a highly productive environment. The region (Figure 5.1) is characterized by deep-sea habitats that support a variety of marine life, including commercially important fish species such as Atlantic cod. The nutrient-rich waters offshore, driven by upwelling and ocean currents, enhance primary productivity and thus support a complex food web. Studies have highlighted the importance of these offshore areas for the feeding and breeding of marine mammals, including seals and whales (Laidre et al., 2010; Rysgaard et al., 2012).

The area is in the sub-Arctic sector of the Northwest Atlantic, covering the north-eastern Labrador Sea and south-eastern Davis Strait, off the South Greenland coastline from Cape Farewell to Paamiut. The continental shelf is narrow (60-80 kilometers) with a well-defined shelf break, and the area features deep waters exceeding 2,000 meters, reaching a maximum depth of around 3,700 meters. The coastal topography is complex, with many archipelagos, fjords, and rocky shorelines with a large tidal range. The major current systems are the cold East Greenland Current and the warm Irminger Current, which meet around Cape Farewell. Sea ice is relatively sparse, but the East Greenland Current carries significant amounts of drift ice and icebergs, affecting ship access in late winter, spring, and early summer (Frederiksen et al., 2012).

Primary production peaks in spring with the stabilization of the water column and declines in summer due to nutrient depletion. The highest productivity is expected where upwelling or hydrographic fronts bring nutrient-rich water to the surface. The spring phytoplankton bloom is dominated by diatoms, which are grazed by zooplankton, mainly copepods. *Calanus finmarchicus* is the most abundant copepod species and constitutes a vital food source for small pelagic fish and the juvenile stages of larger demersal fish.

The coastline of Southwest Greenland has many fjords with steep continental slopes close to the coastline (<100 kilometers). The shallow benthic environment is greatly affected by ice scour, either transported with ocean currents from East Greenland or the numerous local glaciers, causing disturbance of benthic communities. The benthic environment of South Greenland is poorly studied which limits our understanding of these communities, especially in the deeper offshore areas. The benthic habitats of the narrow continental shelf of Southwest Greenland are heterogeneous, consisting of sandy and rocky habitats with fast currents over their surface (Gougeon et al., 2017). The rocky substrata and fast current favor sessile and mobile filter-feeding invertebrates such as sponges, anemones, bryozoans, and sea cucumbers contributing to high biomass and biodiversity (Yesson et al., 2015; Maier et al., 2024).

The area is crucial for the critically endangered harbor seal, which has an important haul-out (resting) site near Cape Farewell. A whelping area for harp seals is in the drift ice off the South Greenland coast, and large numbers of hooded seals migrate through the area. The continental shelf and shelf break are important summer foraging areas for baleen whales, particularly humpback, minke, and fin whales. Sperm whales and other toothed whales are also common, though data is limited. The northern right whale, critically endangered worldwide, may also pass through the area.

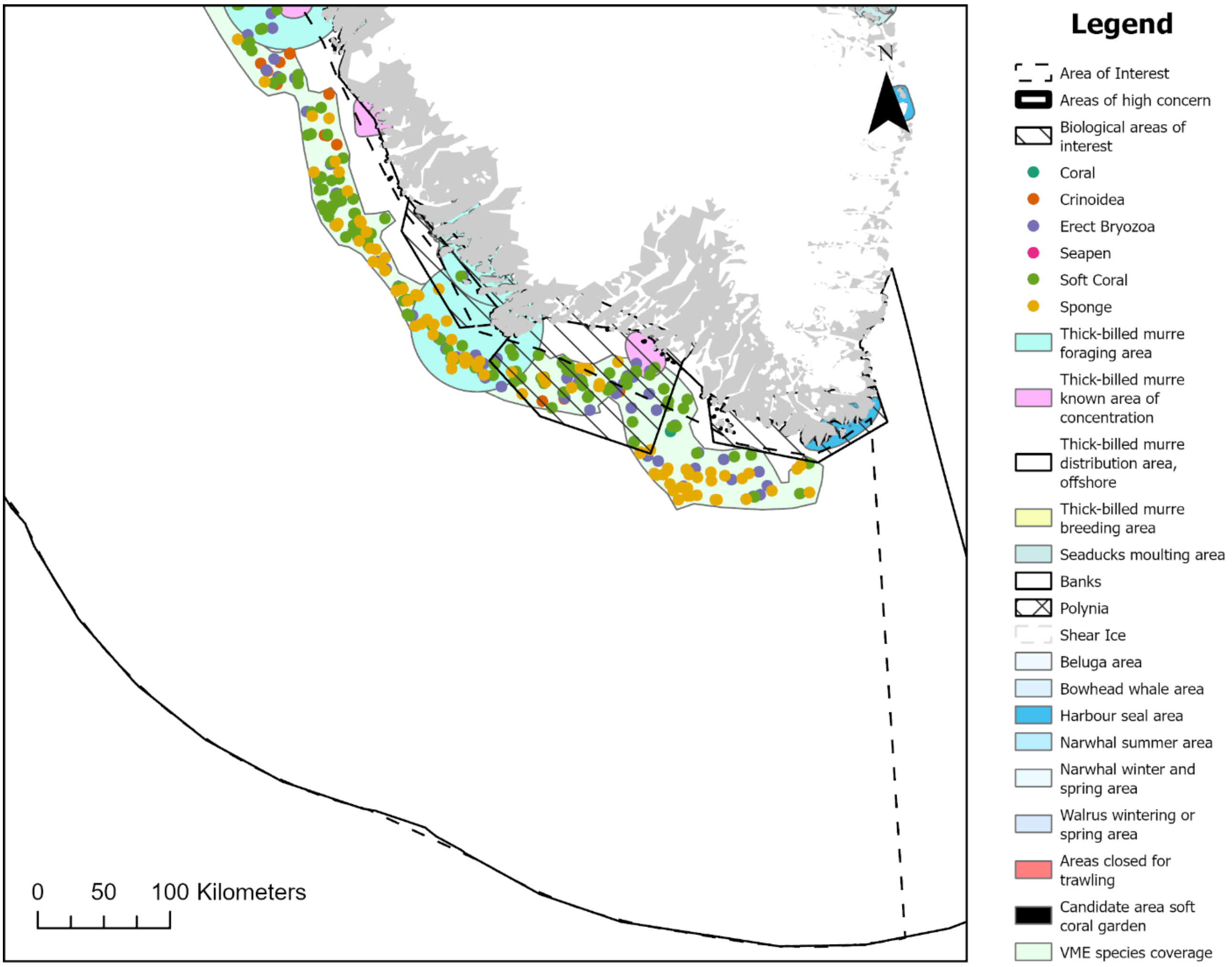


Figure 5.1. Map of the Southwest Greenland area of interest with information on sensitive areas.

Breeding seabird populations are relatively small but diverse. The most important colony is Ydre Kitsissut, home to the largest population of common murre in Greenland and significant populations of thick-billed murre and razorbill. The coastal part of the region is also important for moulting harlequin ducks, wintering common eiders, and migrating and wintering seabirds like thick-billed murres, black-legged kittiwakes, Atlantic puffins, and ivory gulls. Non-breeding great shearwaters from the South Atlantic also occur in large numbers during the northern summer.

Most commercially important fish species are demersal, such as northern shrimp, snow crab, and Greenland halibut. The largest populations of Atlantic cod in West Greenland are found in the assessment area, while redfish occur in deep offshore areas. The coastal zone is crucial for spawning capelin and lumpsucker. Ecologically important species include benthopelagic schooling fish like capelin and sand eel, which are key prey for larger predators, including large fish, marine mammals, and seabirds.

Davis Strait

The Davis Strait, situated between Greenland and Canada, is an offshore marine region characterized by its deep waters to the south from the Labrador Sea and north to the Baffin Bay, and in between a broad subsea ridge formed in front of a previous glacier bridging Canada and Greenland. To the east, there are large banks with shallow waters (approximately 50 m depth), and towards the fjords at the coast, deep troughs are running (Figure 5.2).

The hydrographic conditions involve a strong current of warm saline water from the Atlantic along the coast and cold water of lower salinity from the north as well as from the fjords having outlet glaciers and rivers. The southern part of the area generally has open water year-round, while the northwestern part experiences sea ice from February to May. The tides in the region are large, decreasing to the north.

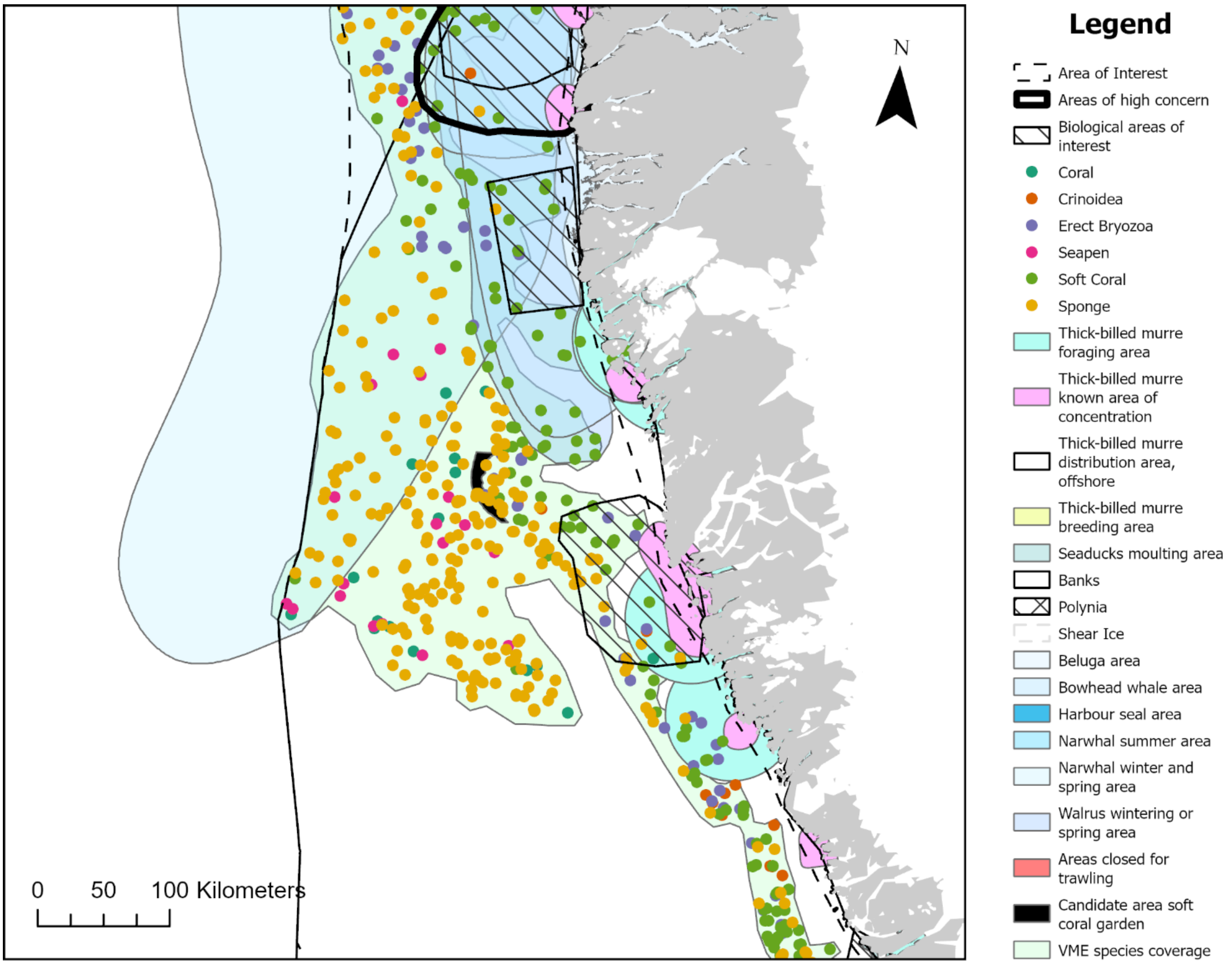


Figure 5.2. Map of the Davis Strait area of interest with information on sensitive areas

The Arctic and Atlantic waters are mixed, creating an environment that supports high biodiversity. Research indicates that the productivity of the region is influenced by the seasonal influx of nutrient-rich Arctic waters (Laidre et al., 2010; Rysgaard et al., 2012). Shallow-water banks along the west coast of Greenland are crucial for high primary productivity due to strong upwelling. The pelagic environment is characterized by low biodiversity but high animal population density, with key species of copepods (*Calanus finmarchicus and Calanus hyperboreus*) playing a significant role. The spring bloom of phytoplankton is a major ecological event, supporting higher trophic levels. Sea ice ecology is dynamic, supporting various microorganisms and influencing higher trophic levels.

The seabed macrofauna (benthos) play a crucial role in the ecosystem by consuming a significant proportion of the available production and serving as a vital food source for fish, seabirds, and mammals. The benthic communities in the Davis Strait are diverse, with significant populations of benthic invertebrates such as sea stars, sponges, and molluscs. The area boasts the highest number of historical sampling stations and contains over 1000 registered species of benthic invertebrates. Recent studies have shown a highly heterogeneous substrate composition and local species richness of soft bottom infauna, with more than 80 species/taxa per 0.1m^2 grab sample. Several species that characterize benthic Vulnerable Marine Ecosystems (VMEs) have been identified multiple times. Additionally, Greenland's first soft coral garden habitat, covering 486 km^2 and spanning approximately 60 km of the continental slope, has been discovered within the area, representing a VME candidate (Long et al., 2020).

This offshore area is a critical habitat for several species of marine mammals, including being the main distribution area in Greenland for harbor porpoises, the primary wintering area for Atlantic walrus hauling out on sea ice, the mating area for bearded seal (*Erignathus barbatus*), migration route for bowhead whale, important region for minke whale (*Balaenoptera acutorostrata*), and a generally a migration route between north and south, and east and west for many species foraging in the area and north hereof during summer relying on the rich feeding grounds. The southern wintering grounds of beluga whales and narwhals extend into the northern part of the area. Polar bears are present during winter and spring, associated with sea ice cover.

The seabird colonies in the area are numerous but generally smaller than those in more northern regions of West Greenland. There are 20 regular breeding species, with the highest colony density in the archipelago between 63° and 66°. Notably, the Atlantic puffin and common murre, both listed as vulnerable and endangered, respectively, breed here. The area is crucial for 13 bird species on a national or international scale, particularly as a wintering ground. Over 3.5 million birds, including thick-billed murre, common eider, king eider, and little auk, winter in the coastal areas. Additionally, many seabirds migrate through or winter in the offshore areas.

The fish fauna is dominated by demersal species, with Greenland halibut being commercially significant. The coastal zone supports important spawning species like Atlantic cod and capelin. The region is important to commercial fisheries of shrimp and snow crab in the throughs between fjords and continental slopes, e.g. the Holsteinsborg Deep, and for Greenland halibut the upwelling area in the southern part of the strait, where the continental slopes of Canada and Greenland connect. Consequently, these areas are also heavily impacted by bottom trawling.

Disko West

The Disko West offshore marine region forms the northern part of the Davis Strait and the southern part of the Baffin Bay (Figure 5.3). The large bank Store Hellefiske Banke has its northern end in the region, bordered by a broad trough connecting a system of a deep trench and subsea channels connecting the Ilulissat Icefjord through Disko Bay with the continental shelf.

The physical conditions include extensive ice cover in winter and spring, with numerous icebergs, primarily arriving from Disko Bay. Open water areas along the coast, caused by strong tidal currents, are biologically significant. The wide continental shelf and deep ocean troughs facilitate strong upwelling and mixing between cold and warm water, supporting high primary production.

The primary production is high in spring, particularly along the marginal ice zone and shelf break. Zooplankton, especially Calanus species, are abundant and crucial for the ecosystem with their high lipid content as key food sources for larger organisms, serving as energy reserves. A higher level of contaminants in the Calanus species will further accumulate into the marine food web.

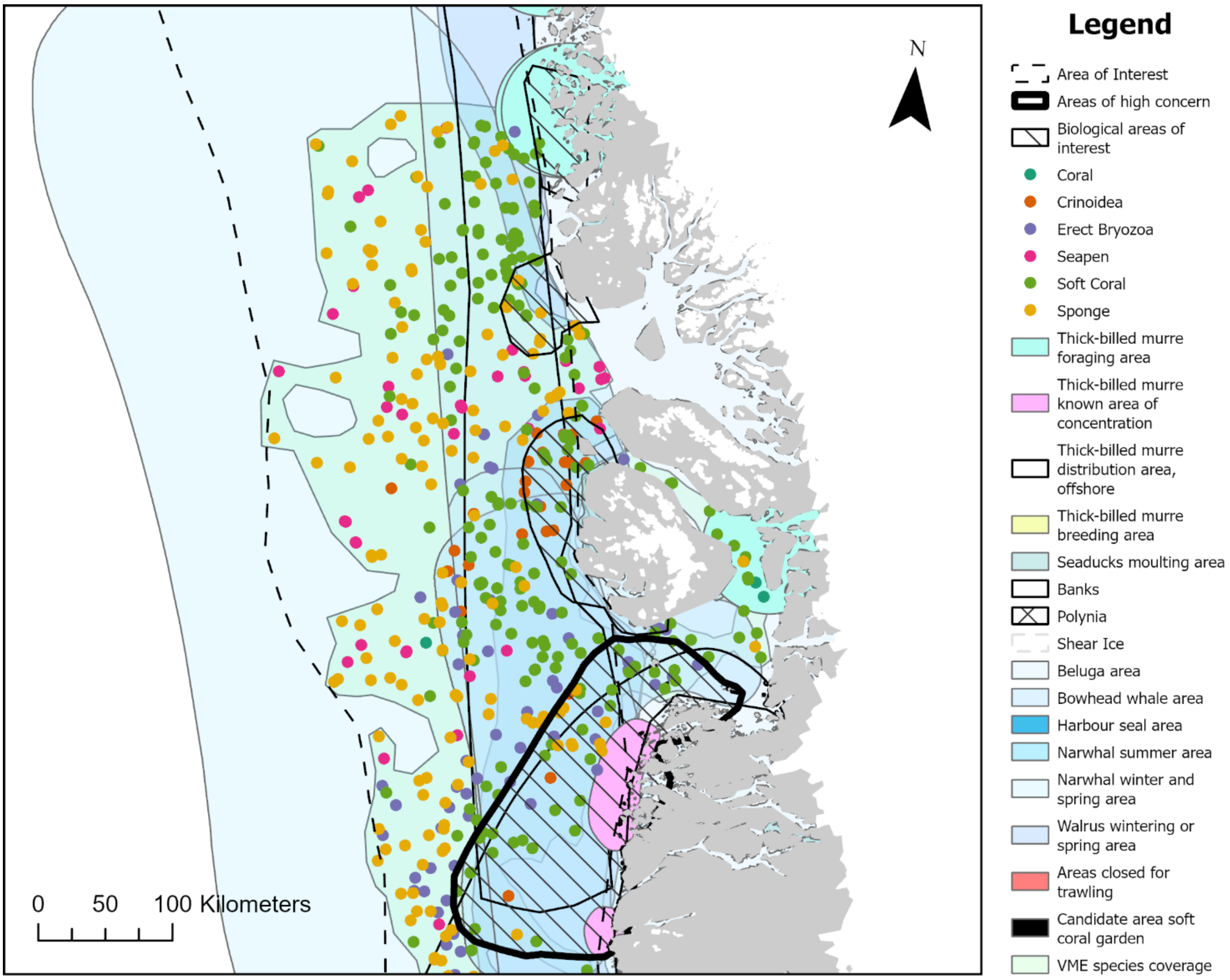


Figure 5.3. Map of the Disko West area of interest with information on sensitive areas.

The benthos communities display high biodiversity. The seabed fauna is diverse, with over 900 species identified. VMEs have been found, as well as a candidate VME area south of the area. Along the trench from Disko Bay, almost vertical walls with rich and unspoiled benthic ecosystems occur.

The fish fauna is dominated by demersal species, with the great commercial important Greenland halibut being significant along the shelf break.

Seabirds are numerous, with 16 breeding species, including thick-billed murres and Arctic terns. The area is also important for non-breeding seabirds in summer and fall and for wintering seabirds, particularly king eiders.

Marine mammals, including five seal species, walrus, 14 whale species, and polar bears, are significant components of the ecosystem. Recent studies have provided new data on population sizes and the habitat use of several species.

The region is important to commercial fisheries of shrimp and Greenland halibut. It is unknown if the area also serves as a nursery area for shrimp.

Baffin Bay

Baffin Bay, located to the north of the Disko West region, is a large, deep basin (Figure 5.4). Towards the west and north, it is bordered by the archipelago of the Upernavik region and Melville Bay, and further to the north by the Avannaata high polar region with channels to the Canadian Arctic Archipelago and the Arctic Ocean via Kane Basin. Very wide troughs lead from the fjords in Uummannaq, Upernavik, and Savissivik region to the continental shelf and the central basin. Between those are banks, and slopes, which have a potential for fishery, yet are little exploited.

The hydrographic conditions include a strong presence of cold Arctic waters from the north as well as outlet glaciers and meltwater, seasonal sea ice cover, icebergs arriving from Disko Bay, Uummannaq Bay, and the Upernavik region, lower tide system, and a more limited influx of warm Atlantic water. Despite this, waters are nutrient-rich, creating a unique Arctic environment supporting high biodiversity. Research has highlighted the importance of Baffin Bay’s offshore areas for the feeding and migration of marine mammals (Laidre et al., 2010; Rysgaard et al., 2012).

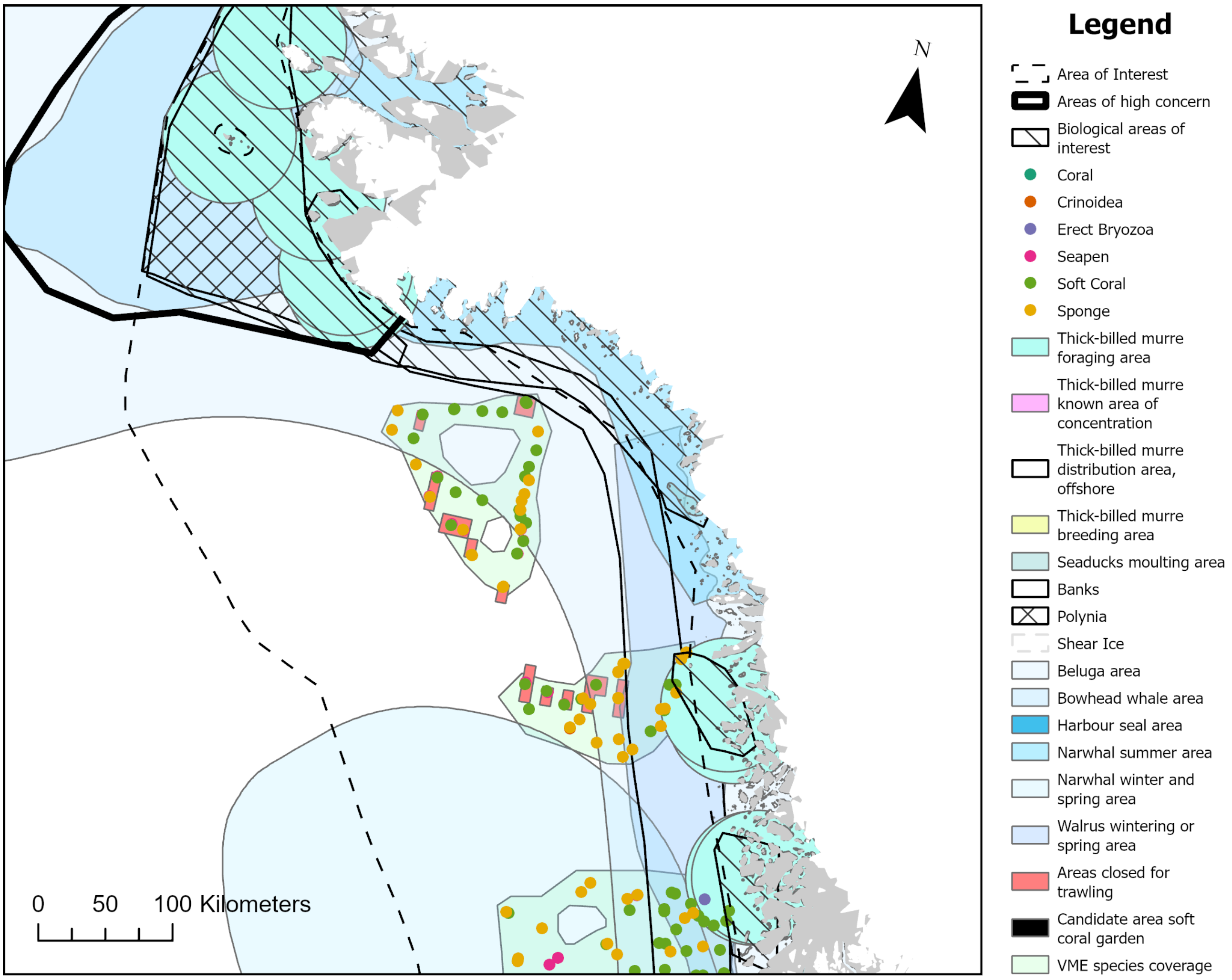


Figure 5.4. Map of the Baffin Bay area of interest with information on sensitive areas.

The ecosystem, existing in and on the sea ice, includes algae grazed by small crustaceans, which sustain populations of polar cod, an important food source for ringed seals and seabirds. There is a high level of primary productivity in the coastal region and to the north, while the central bay is of lower productivity.

One of the most significant ecoregions is the North Water Polynya between Greenland and Ellesmere Island, where sparse winter ice and early spring open waters facilitate early primary production. Other important ecological hotspots include Melville Bay and the coasts of the Upernavik district, which are crucial for breeding seabirds and migrating marine mammals. These areas are designated as ecologically valuable and sensitive marine areas, highlighting their importance for conservation and management efforts.

The benthic communities in Baffin Bay are diverse, with significant populations of benthic invertebrates such as sea stars, sponges, and molluscs. The benthos, or seabed fauna, are vital components of coastal and offshore ecosystems, consuming a significant fraction of available production and serving as important food sources for fish, seabirds, and mammals.

Seabirds are abundant, with several species breeding in dense colonies and millions migrating through the area. Key species include the common eider, thick-billed murre, and little auk, some of which are threatened and of national responsibility.

Baffin Bay is an important habitat for several species of marine mammals, including polar bear, narwhal, beluga, walrus, bowhead whale, and various species of seal, particularly in winter and spring with migration routes through and along the region. These are significant components of the ecosystem and of cultural importance to the Indigenous Inuit population, who particularly in the northern part of the Upernavik region, near Savissivik and, to some extent, in the Qaanaaq region still practice traditional hunting methods.

The region is important to commercial fisheries of shrimp and Greenland halibut in both inshore and offshore regions. It is unknown if the area also serves as a nursery area for shrimp.

Areas important for benthic species

Benthic fauna is found in different substrata and habitats throughout the depth range of West Greenland, from the shallow tidal zone, across the continental shelf, and down the shelf break to deep waters (Blicher & Arboe, in Boertmann et al., 2021). Benthic communities can be very species-rich with surveys finding more than 100 different macroinvertebrate species of infauna per m^2 in undisturbed soft sediments (Sejr et al., 2010b). On hard substrates, large epifauna can contribute to the structural complexity of habitats and support a rich associated fauna.

The benthic fauna community is affected by a multitude of different biological and physical parameters; with depth, temperature, food input, substrate composition, particle load, disturbance level (e.g. ice scouring, trawling), and hydrographical regime being the most prominent (e.g. Gray, 2002; Wlodarska-Kowalczuk et al., 2004; Piepenburg, 2005). Therefore, the benthic community is often extremely heterogeneous on both local and regional scales (Sejr et al., 2010a; Yesson et al., 2016; Blicher & Arboe, 2017).

The complex topography and hydrography of the assessment area also result in a highly heterogeneous substrate composition. A study of the Greenland shelf has documented a mix of seven different main surface substrate categories covering the entire spectrum from soft clay and mud to sand, gravel, and solid rock (Figure 5.5). A classification model was developed using environmental proxies to make habitat predictions for the West Greenland shelf (200-700 meters depth, up to 72°N) (Gougeon et al., 2017). The resolution and quality of environmental variables limited predictions to single habitat classes in 3.5x3.5-kilometer grid cells, which are likely to encompass multiple habitats. Still, the model underlines the heterogeneity of the seabed.

A very general indicator for the location of taxa indicating a VME is substratum types found on the seabed. A VME area constitutes an area in the benthic environment that may be vulnerable to impacts from fishing activities according to the Food and Agriculture Organization of the United Nations (FAO). Most VME indicator taxa often have an affinity for hard substrates, especially rock and drop stones. According to Gougeon et al. (2017), the distribution of substratum types depends on geological and oceanographic factors: the geological setting and history, the glacial history, erosion, and currents. The subsea landscape has some general patterns and large-scale landforms related to these factors: Deep channels and basins are dominated by muddy sediments, while shallow banks and shelves have a mix of substrate. To the north, sedimentation is more dominant due to materials from the Greenland Ice Sheet and weaker currents, while at the south there is a higher proportion of rocky habitats with less distribution of materials from outlet glaciers and stronger current speeds.

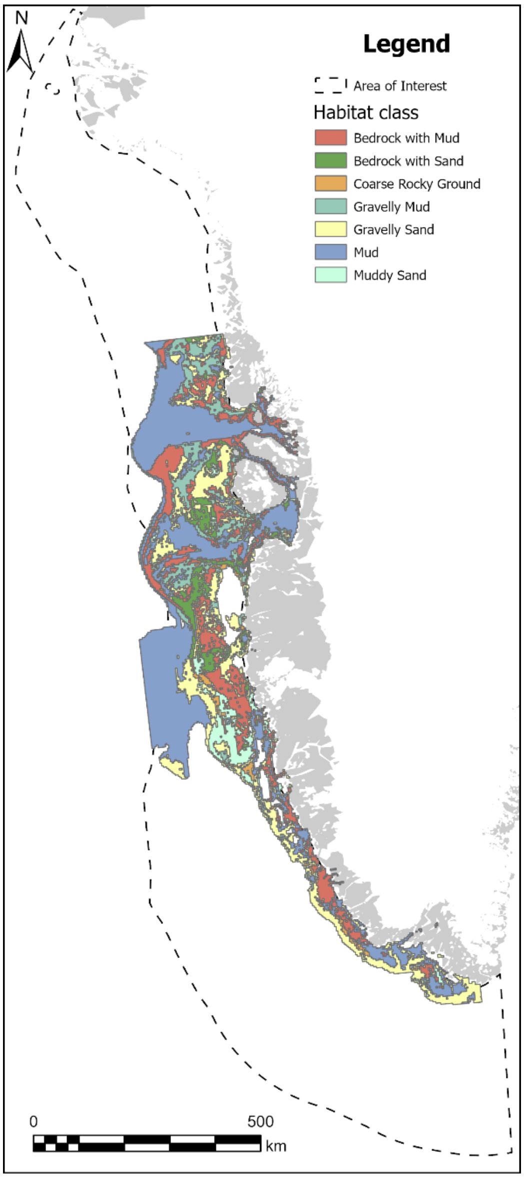
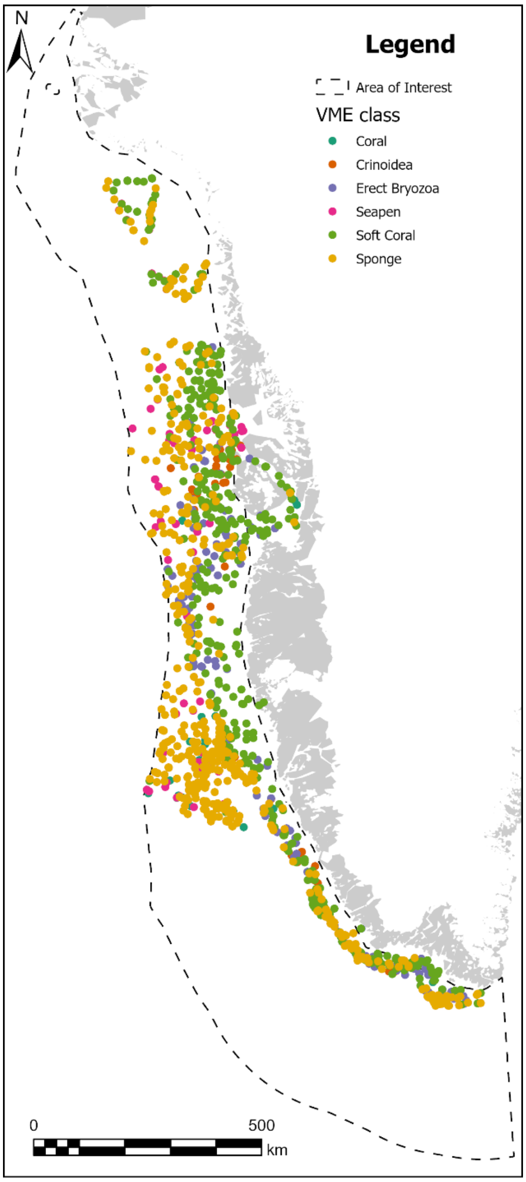


Figure 5.5. Seabed surface geology physical habitat classes relevant for benthic species. Data from Gougeon et al., (2017).

However, across the West Greenland Shelf, there is no clear spatial clustering of benthic community types (Figure 5.6). Instead, the most dominant taxa can be found across large latitudinal and depth gradients. This is most likely caused by the great geomorphological heterogeneity of the Greenland shelf as well as by the abundance of microhabitats, such as boulders and drop stones within soft sediments. The Davis Strait and the southwest continental shelf edge, which are predominantly rocky are particularly taxon rich > 200 taxa/50km^2. This is also where a greater abundance of VME taxa has been observed. (Richness decreases towards the North, with a stronger presence of truly Arctic species found in Baffin Bay (Maier et al., 2024).

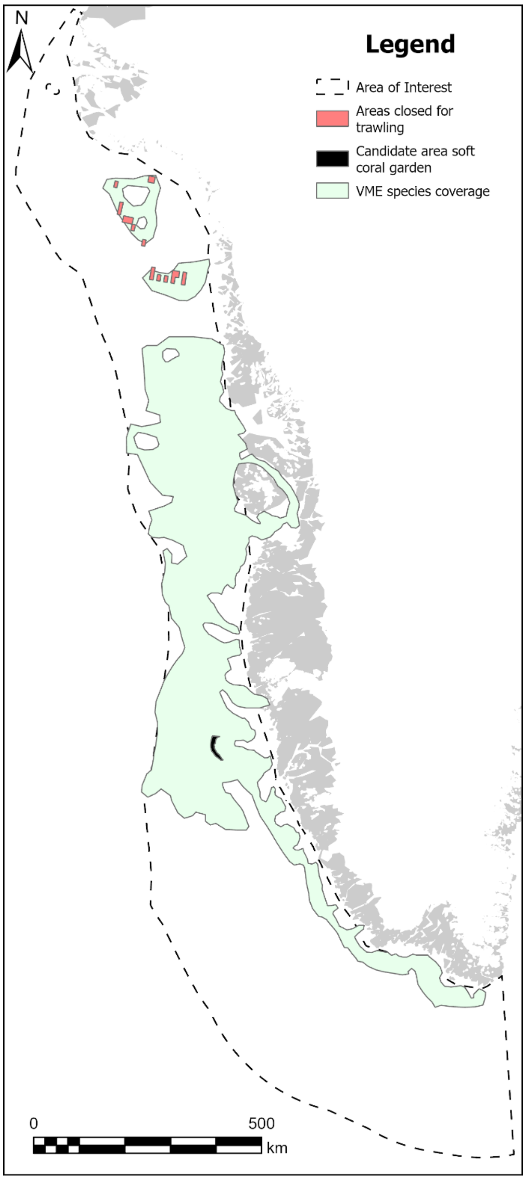
Data have primarily been collected within the distributional range of commercially harvested fish and shellfish species, which has resulted in a data paucity for the more northern regions of the Greenland shelf. This may cause an underrepresentation of diversity and VME abundance in the affected regions (Figure 5.8).

Figure 5.6. Observations through the benthic program and related projects of the Greenland Institute of Natural Resources of species classes indicating Vulnerable Marine Ecosystems for the benthic environment. Source: Nadescha Zwerschke, unpubl. data.



So far, no VME areas are designated in Greenland waters, although several small areas in Melville Bay have been protected from bottom trawling because of the presence of sea pens. There is, however, at least one area that has been identified as a strong candidate on the top of the continental shelf slope at the Toqqusaq Bank off Nuuk. The area is located between two trawling areas and holds a high density of cauliflower corals (*Nephtheidae*) and other VME indicator species often occurring on rocky or mixed substrates (Figure 5.7). However, given the diversity of the benthic species, there are likely to be many other VME-candidate areas in Greenland waters (Long et al., 2020).

Figure 5.7. Areas with a probability of species relevant for Vulnerable Marine Ecosystems (source: Nadescha Zwerschke), areas currently closed for bottom trawling activities by the Government of Greenland, and the VME-candidate area with a soft coral garden (Long et al., 2020).



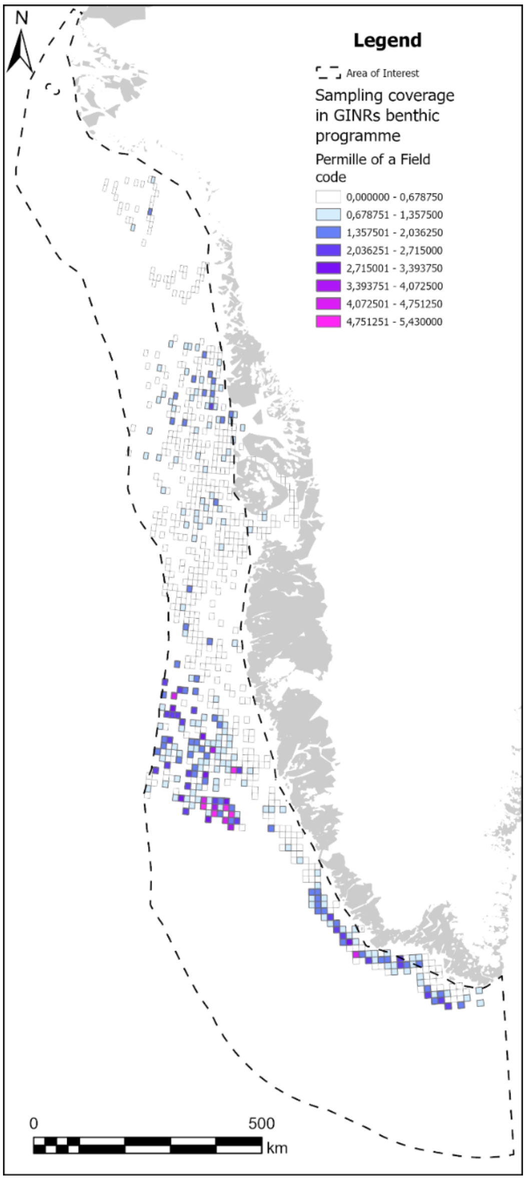


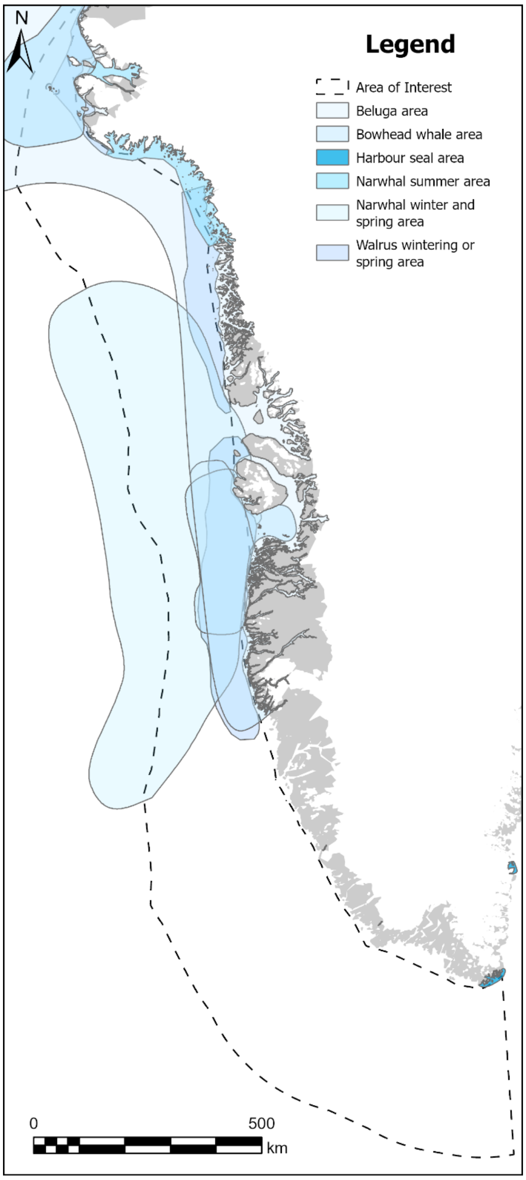
Figure 5.8. The sampling coverage in permille of the area of each fishery Field Code. Sampling achieved during fishery and benthic surveys conducted by the Greenland Institute of Natural Resources. The map shows the investigated Field Codes and that the regions offshore in the Davis Strait and along the continental shelf in Southwest Greenland were investigated more intensely than in the northern part of the Davis Strait, Disko Bay, and Baffin Bay.

Areas important for pelagic species

For the identification of areas important to the pelagic species, we draw on reports from DCE Aarhus University and Greenland Institute of Natural Resources on areas of biological interest (Christensen et al., 2016), Strategic Environmental Impact Assessments of Baffin Bay (Boertmann et al., 2017), Disko West (Boertmann et al., 2021), and Davis Strait (Merkel et al., 2021). For important areas for specific species being of the more serious categories of the national Red List, we draw on the recent scientific notes from the Greenland Institute of Natural Resources on narwhal (Hansen et al., 2023; Hansen et al., 2024), beluga (Hansen et al., 2024b), bowhead whale (Hansen et al., 2024c), and Atlantic walrus (Hansen et al., 2022) (Figure 5.9). For wintering seabirds, we draw on a survey from 2017 (Merkel et al., 2019).

In some cases, the information available to strictly delineate important areas can be very vague depending on factors such as the frequency of biological surveys, seasonality, and annual changes, and often it is only possible to broadly display a distribution area, and the definition of different areas will likely change when updated reviews become available.

Figure 5.9. Areas important to marine mammals in NatureMap. Source: NatureMap and supporting scientific notes by GINR and DCE/AU



Primary production and polynyas

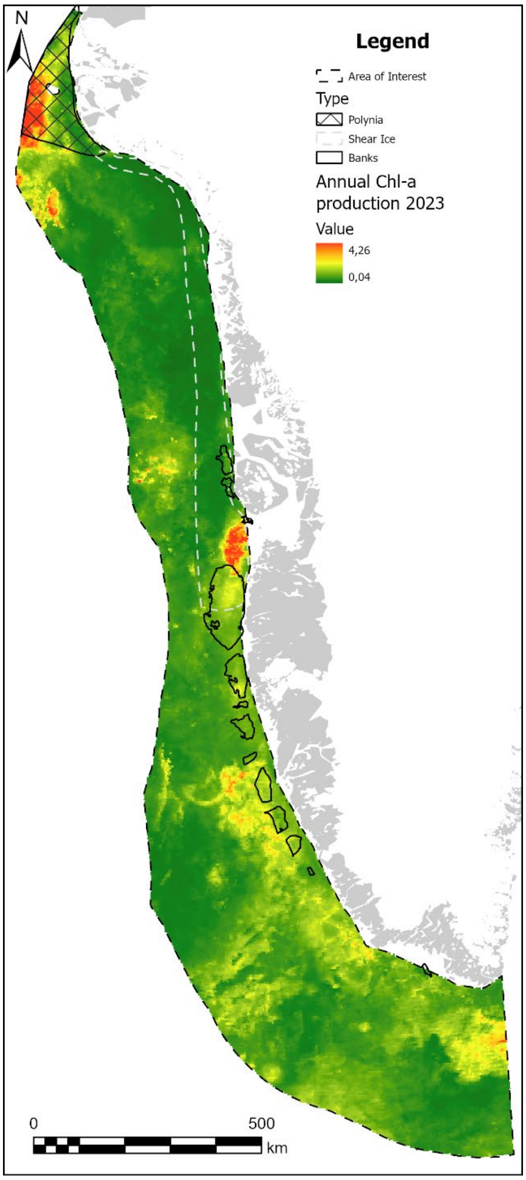
A high primary production of plankton in the water column is essential for several species in the Arctic food web and is the main driver for their foraging activities and locations over different seasons, following the bloom seasons.

For a spatial and temporal overview of primary production, observations from satellites (MODIS and Sentinel-3) and calculations are regularly used to detect chlorophyll-a values in the uppermost water column (Figure 5.10). For deeper water layers, methods of sampling or acoustic observations are used.

The biomass is generally high for the West Greenland waters, particularly along the banks and in many fjords such as Nuup Kangerlua, Disko Bay, Uummannaq Bay, and fjords in the Upernavik and Qaanaaq regions.

A polynya is a significant, recurring open-water area within an otherwise ice-covered ocean (Vincent, 2019). It remains open due to a combination of wind, currents, and potentially the upwelling of warmer water from deep below. Its biological significance lies in the fact that primary production starts much earlier here than in the surrounding waters, attracting seabirds and marine mammals. In the region of interest, the North Water Polynya is recognized as a large recurring polynya, although its exact boundaries change annually.

Figure 5.10. The annual biological production of chlorophyll-a in 2023, mark of the North Water Polynya, shear ice zone along the coast west off Disko Bay, Upernavik and Melville Bay, and shallow water banks.



Fish and crustaceans

Areas important to fish and crustaceans vary according to the species and their lifecycle. To consider the commercially important species in the region of interest, the focus could be on demersal species such as Greenland halibut, Northern shrimp, Atlantic cod, and Snow crab, including areas of active fishery as well as spawning grounds and regeneration areas for juvenile fish and crustaceans. However, other species should also be considered as being important in the food web and general ecosystem.

Baleen whales

Among the baleen whale species, the bowhead whale is the most vulnerable as its distribution area is limited to the Arctic region, with a strong presence in Greenland waters during summer, and has a sensitive vocality. Thus, special consideration must be given to this species. Into consideration are important areas for whales, minke whales, humpback whales, and blue whales in the region of interest.

Toothed whales

For narwhals, important winter and spring areas in the region are the North Water Polynya, the Davis Strait, and the Baffin Bay. They spend summer in the fjords outside the area of interest to the report, but the migration routes between wintering and spring areas to summer grounds are of importance. However, spatial and temporal identification of the areas depends on the ice conditions and movements.

For beluga, the North Water Polynya is similarly of great importance all year, and the West Greenland inshore and offshore waters between Maniitsoq and Disko Island during winter and spring. Also, of significance are the migration routes from the coast to 100 kilometers offshore between these two regions in Baffin Bay and along Melville Bay, defined very broadly in time and space.

Areas important to the other toothed whale species, sperm whale, Pilot whale, Northern bottlenose dolphin, Harbour porpoise, and Killer whale, also occur in the region of investigation.

Atlantic walrus and seals

Among the seal species, the Atlantic walrus stock is the most vulnerable in terms of important wintering areas offshore West Greenland, a limited number of areas in Greenland, dependence on sea ice for haul out and on shallow banks for feeding on molluscs and other bivalves. Areas important for bearded seal, ringed seal, and spotted seal are also found in the region of interest.

Seabirds

Areas important to seabirds in the area of interest include offshore foraging grounds connected to marine seabird colonies, moulting areas for seaducks, and feeding grounds for wintering birds offshore and along the coast.

Large seabird colonies are concentrated in the northern part of western Greenland (Egevang et al., 2024) and the southern western Greenland area is important internationally for wintering seabirds (Merkel et al., 2019 and 2021); see Figures 5.11 and 5.16.

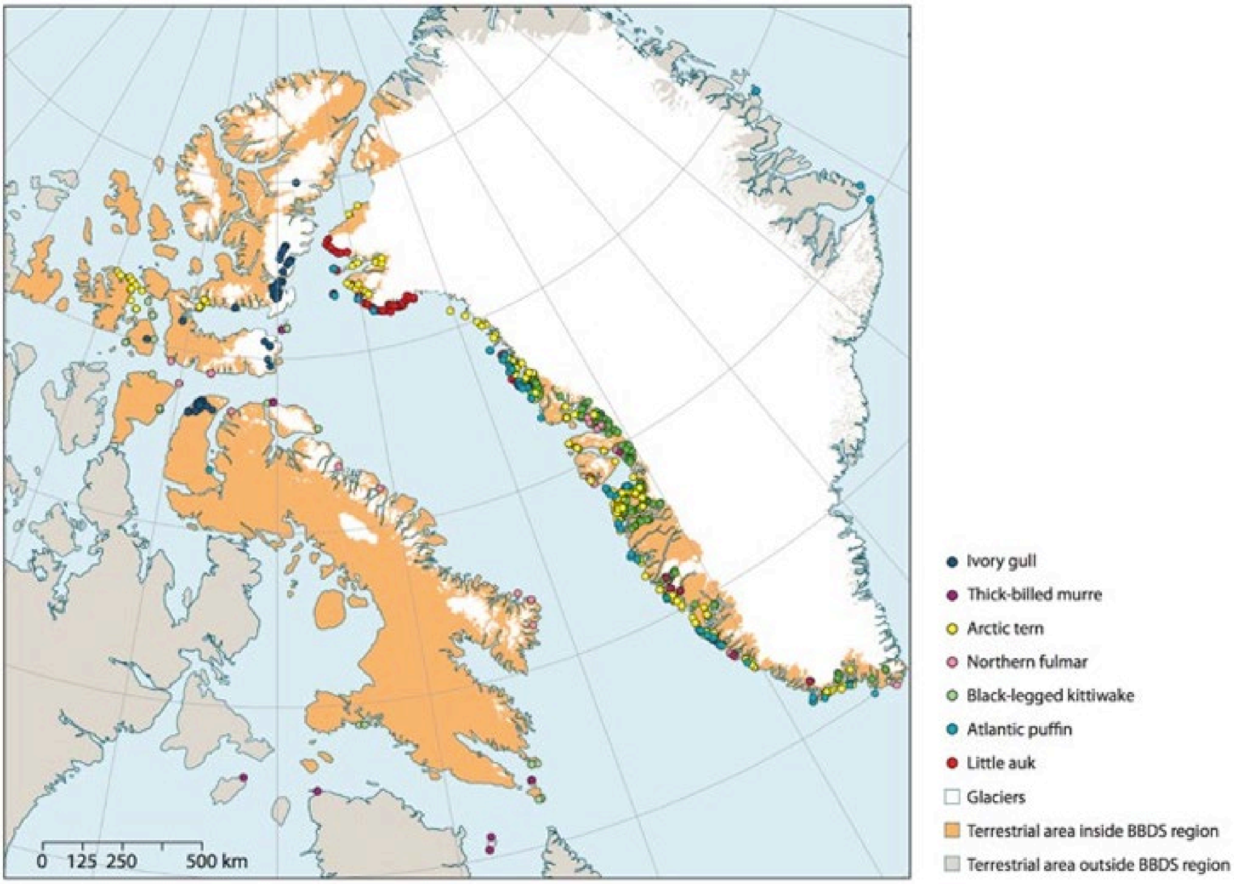
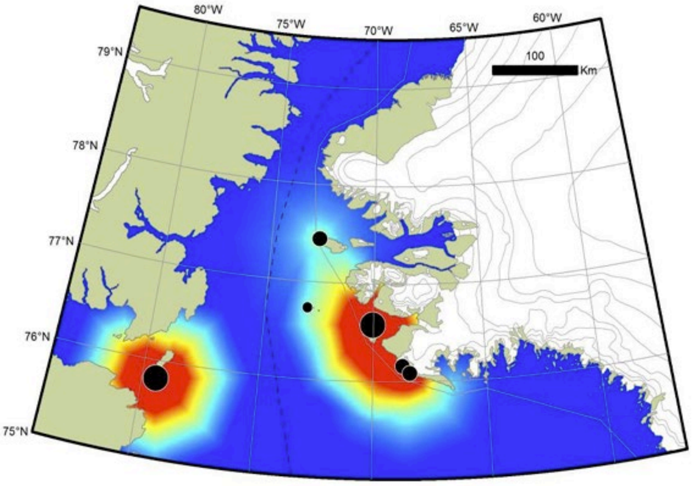


Figure 5.11. Distribution of breeding colonies of key bird species in the Baffin Bay-Davis Strait and the North Water region. Note the high density of Little Auk (Dovekie) colonies along the northwest Greenland coast adjacent to the area of the North Water (data from the Greenland Seabird Colony Register and Seabirds.net: Circumpolar Seabird Data Portal) (Source: AMAP, 2018; from Hornby et al., 2021).

From the large colonies, seabirds commute to foraging areas offshore; see examples in Figure 5.12-13.

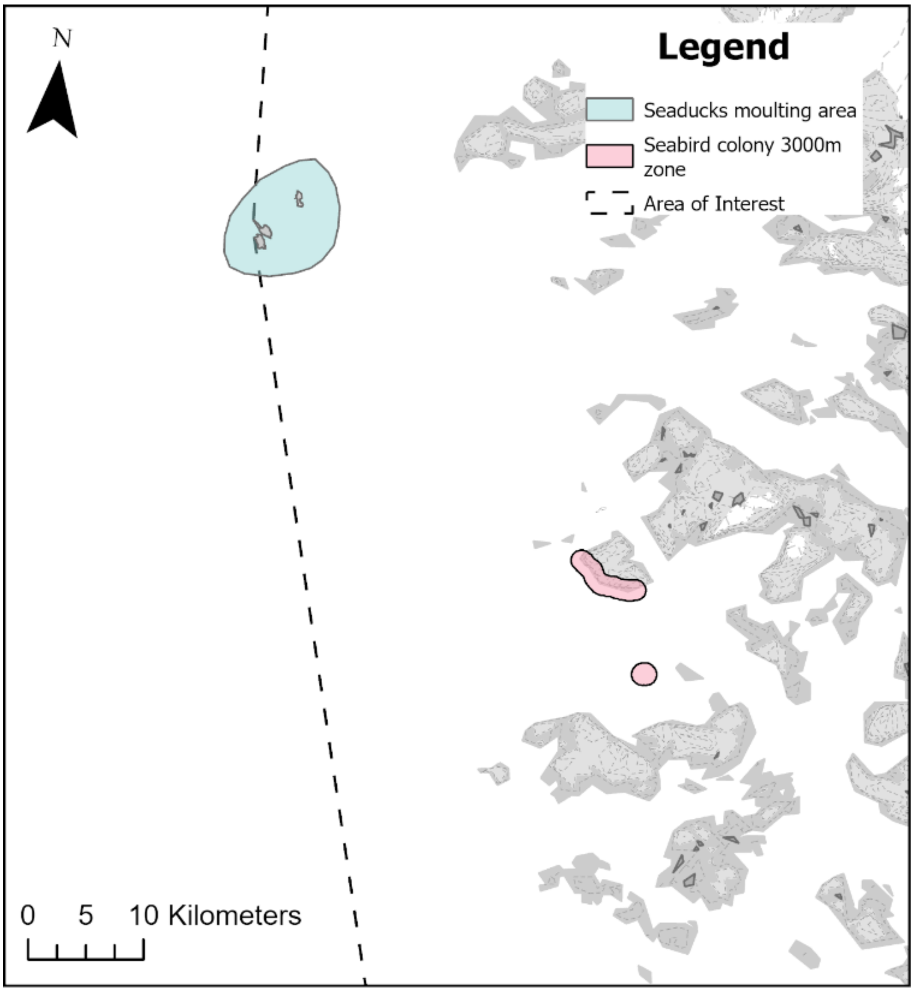
Figure 5.12. Thick-billed murre colonies (black dots) in the North Water region. The colour gradients in the marine areas indicate a theoretical, relative density (red-high, blue-low) of birds on the sea, calculated by distributing the number of breeding birds from the individual colonies within a foraging radius of 114 km (as identified by GPS tracking of breeding birds from the North Water) (source: Christensen et al., 2017).



Moulting and wintering seaducks are concentrated in areas with good feeding conditions where they can dive to the seafloor and forage on benthic fauna (Mosbech et al., 2006); see the example in Figure 5.13. Here, the seaduck populations will be sensitive to both disturbance and changes in food availability. King eider moulting and wintering areas at the shallow Store Hellefiskebanke are especially sensitive (Figure 5.14) (Mosbech et al., 2007).

The latest aerial surveys from 2017 show that up to one million king eiders now overwinter in areas of the bank with water depths less than 50 meters (Merkel et al., 2019). The birds congregate in openings between ice floes in the pack ice and dive for food, resting in large flocks on the ice floes as they drift over the seabed, making new feeding areas accessible. The birds conserve energy by resting on the ice and allowing themselves to be transported to new feeding areas.

Figure 5.13. Example of coastal seabird colonies and a seaduck moulting area in the vicinity to the area of interest in the Upernavik region. The large seabird colony is the Apparsuit colony of Thick-billed murres, which can forage more than 75 km to the west into the area of interest. (data from NatureMap).



The king eider is a very rare breeding bird in East Greenland and the northernmost part of Northwest Greenland, but it is widespread as a common breeding bird in the vast tundra areas of Arctic Canada. Satellite tracking of king eiders from moulting areas in Greenland and breeding areas in Canada also showed that many king eiders on Store Hellefiskebanke come from Canada (Mosbech et al., 2007). The males arrive as early as in July-August, having left the incubating females on the tundra. They arrive at remote coastal areas in northern West and Northwest Greenland to moult their flight feathers, while staying in a safe place for about three weeks during which they cannot fly until the new feathers have grown. Later, females and juveniles arrive from Canada, and from October the birds move south to their wintering grounds on Store Hellefiskebanke and other coastal and bank areas further south in Greenland (Mosbech et al., 2007).

In Southwest Greenland, light-induced bird strikes are known to occur when vessels navigate during darkness in icy waters using powerful searchlights (Figure 5.15). Merkel & Johansen (2011) collected reports of incidents of bird strikes over 2-3 winters (2006–2009) from navy vessels, cargo vessels, and trawlers (total n=19). Forty-one incidents were reported: mainly close to land (<4km, 78%), but one as far offshore as 205km. Up to 88 birds were reported killed in a single incident. All occurred between 5 p.m. and 6 a.m., and significantly more birds were involved when visibility was poor (snow) rather than moderate or good. Among five seabird species reported, the common eider (*Somateria mollissima*) accounted for 95% of the bird casualties. Based on spatial analyses of data on vessel traffic intensity and common eider density, Merkel & Johansen (2011) predicted areas with a high risk of bird strikes in Southwest Greenland (Figure 5.15).

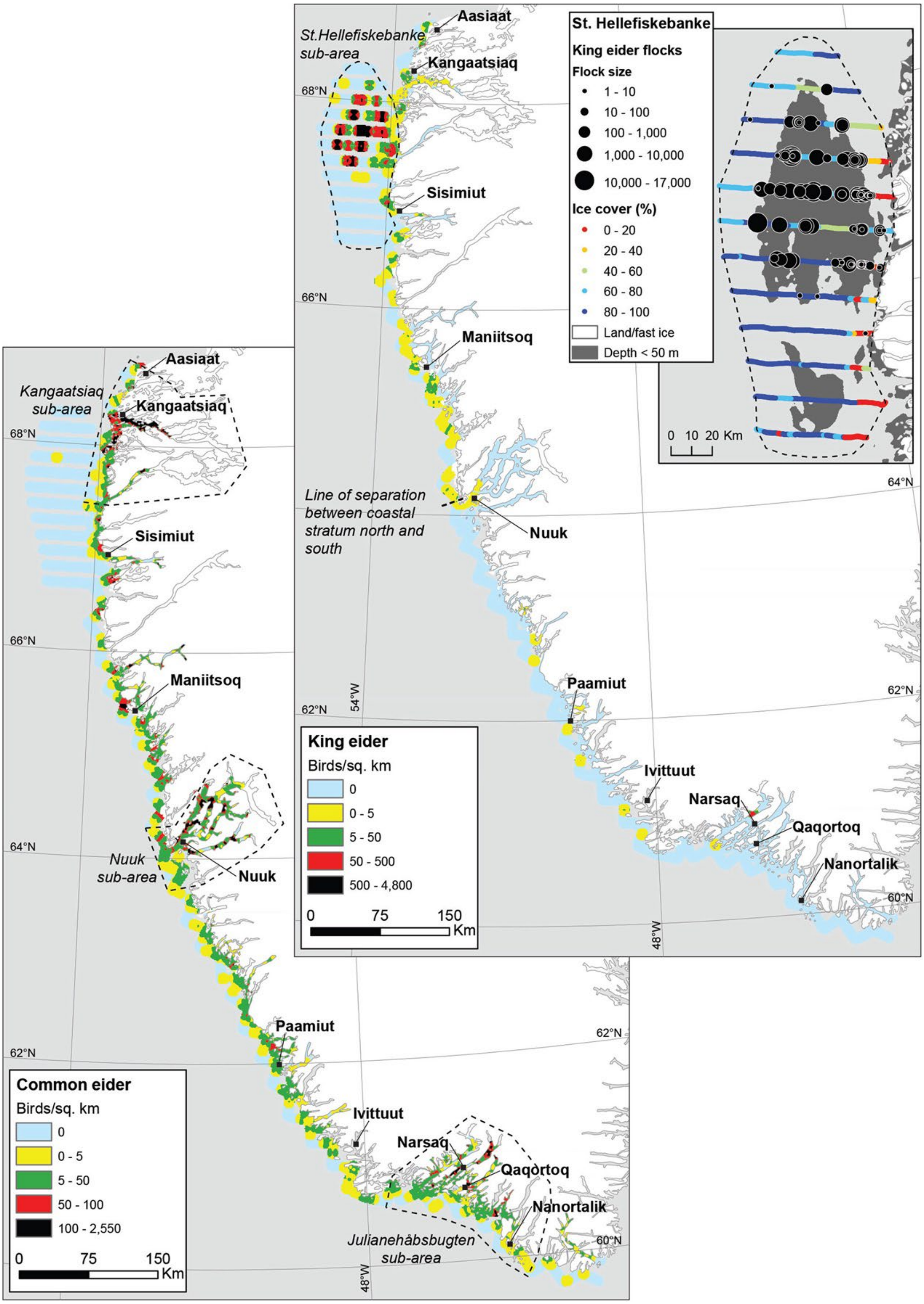


Figure 5.14. Distribution and interpolated densities (see Materials and methods) of wintering king eider (Somateria spectabilis) and common eider (Somateria molisima) in south-west Greenland, 2–17 March 2017 (figure from Merkel et al., 2019). Fjord areas covered with solid land-fast ice at the time of the survey are shown as white, as are terrestrial areas. A detailed map of Store Hellefiskebanke is shown in the top left corner, with king eider observations, observed ice cover (coloured lines), and shallow-water areas <50 m deep.

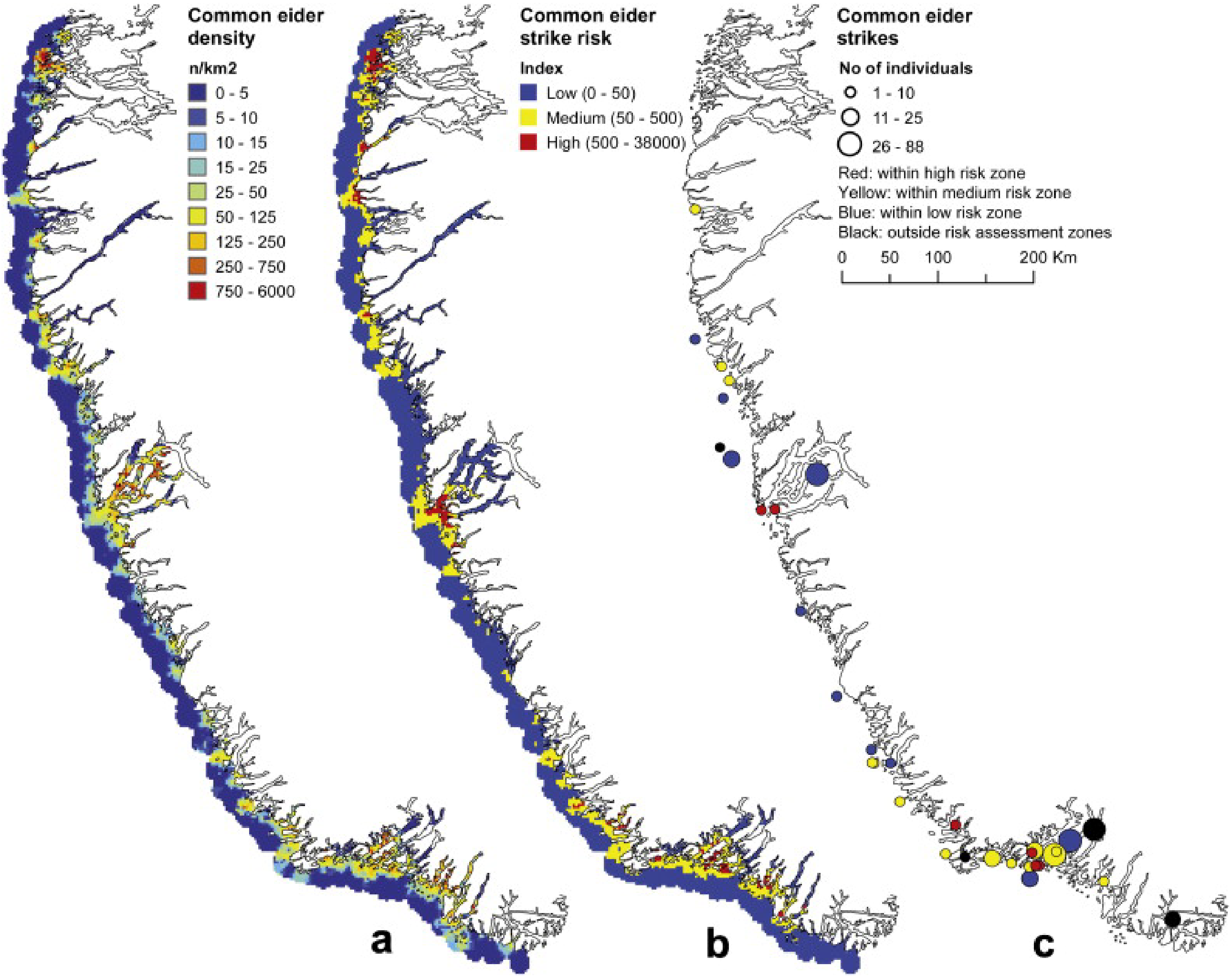


Figure 5.15. (a) The density of common eider in the winter of 1999 based on an aerial survey(b) Predicted common eider strike risk zones based on the classification of an index calculated from the density of common eiders and the traffic intensity of both fishing and cargo vessels (see Chapter 2). (c) The reported common eider strikes in Southwest Greenland graduated in size according to the number of birds involved and colour-coded according to the risk zone within which they occurred (figure a-c from Merkel & Johansen, 2011).

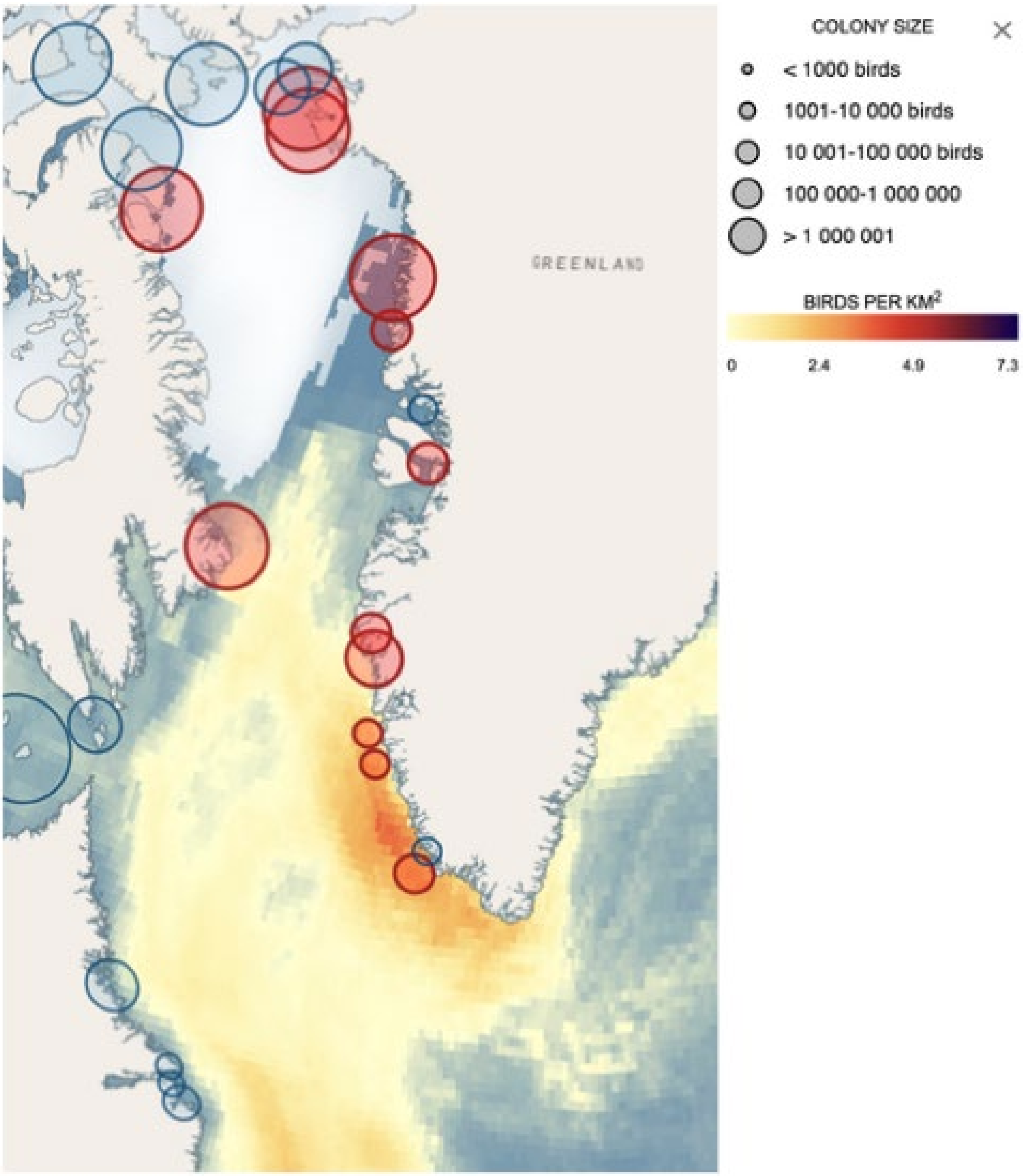


Figure 5.16. Thick-billed murre abundance in December indicating the importance of the Southwest Greenland offshore area as a wintering area for seabirds. Modeling based on SeaTrack data where murres have been tracked year-round with small leg-attached geolocators. (SEATRACK.NO). Birds have been tracked from the red Thick-billed Murre colonies as well as from colonies distributed in the North Atlantic outside the map.

The North Water Polynya region and the Store Hellefiskebanke region

Though an integrated spatial analysis of sensitivity towards marine mining in western Greenland has not been conducted yet and would be hampered by lack of data, the North Water Polynya region and The Store Hellefiskebanke region have previously been identified as marine areas of outstanding international value (see Hornby et al., 2021; Christensen et al., 2016; Speer et al., 2017).

The North Water Polynya

The North Water Polynya region is in focus in a joint Canadian, Greenlandic, and Danish effort to establish measures to manage and protect the ecosystem, including the well-being and lifestyle of the local inhabitants. Due to its ecological, socioeconomic, and cultural importance, the area has been evaluated as unique through several international processes (Hornby et al., 2021)

The North Water Polynya, also known as *Pikialasorsuaq* ("great upwelling") in Greenland, is a recurring area of anomalously thin sea ice and/or open water surrounded by thicker sea ice. Being redominantly a latent heat polynya, the North Water forms southward of a recurrent ice bridge (or arch) across the Nares Strait and is maintained by strong winds, currents, and upwelling of warm water carried from the Atlantic by the West Greenland Current. For millennia, the Inuit have regarded the North Water as a place of great cultural and spiritual significance and rely on the sea ice/ice edge environment as an important hunting ground and transportation corridor (Pikialasorsuaq Commission, 2017). The North Water is considered to be one of the largest (80,000 km^2) polynyas in the Arctic and is well known for its early and reliable productivity, and high biodiversity. The region is home to an estimated 60 million birds, including the endangered Ivory Gull and the largest aggregation of dovekies/little auks on Earth. The open water and productive coastal and ice edge environments provide critical habitat in all seasons for many marine mammal species, such as Atlantic Walrus, Beluga and Bowhead Whales, Narwhal, Ringed Seal, Bearded Seal, and Polar Bear. (from Hornby et al., 2021; see also Christensen et al., 2017 and the proceedings from the International North Water Conference 2017, https://conferences.au.dk/fileadmin/user_upload/NOW_Conference_book_White_paper.pdf)

The North Water Region includes large sensitive areas outside of the territorial baseline see example in Figure 5.17.

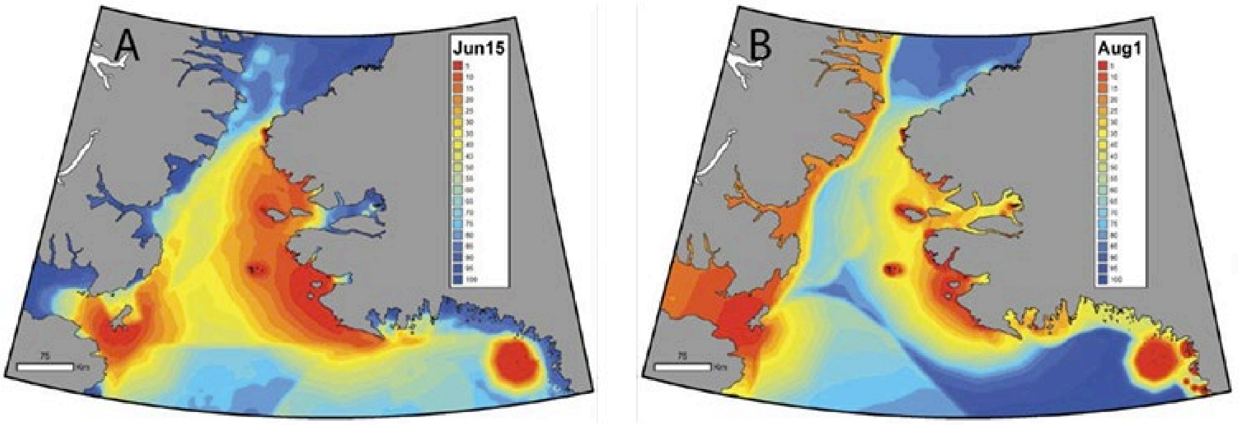


Figure 5.17. Map of biologically important areas in the North Water Region as indicated by a GIS overlay analysis of the distribution of important species (marine mammals and birds) and ecosystem components. The map is an example showing the summer season only (June 15/August 1). The map is colour-shaded in 5% percentiles on a scale from dark blue (lowest values), over yellow, to dark red (highest values). A) By mid-June, millions of seabirds are actively breeding in large colonies around the North Water, and the foraging ranges around these colonies, where many birds are concentrated, now dominate the relative distribution of important areas. The large red areas are primarily driven by thick-billed murre, dovekie/little auk, and common eider colonies. The large red dot in Melville Bay reflects a large and unique Sabine's gull (and Arctic tern) colony. B) In early August, the foraging habitats around large seabird colonies are still highlighted as the most important areas (in red), as are common and king eider moulting areas along Greenland's coasts. However, compared to map A, much of the relative weight/importance has shifted to the Canadian coast, where narwhal, walrus, and polar bear now concentrate (large orange area). Inglefield Bredning and Melville Bay also have higher relative importance due to narwhal, and narwhal and polar bear concentrations, respectively (source: Christensen et al., 2017).

Store Hellefiskebanke

Store Hellefiskebanke is unique in a Greenlandic context by being a relatively shallow marine area extending up to 120 km from the coast, out to a slope towards deeper waters. At the same time, Store Hellefiskebanke has high biological productivity because ocean currents and tides push nutrient-rich water from greater depths over the bank where sunlight can penetrate. Store Hellefiskebanke is also an important area for whales, seals, fish, and shrimp. Part of the biological production in the water column ends up being consumed by a rich fauna of benthic animals, which the king eiders feed on during winter.

In a GIS analysis by Christensen et al. (2015), 41 map layers describe the spatial distribution of important marine species and ecosystem components in the region (Fig. 5.18). These maps are combined to show the biologically most important areas according to a set of criteria that incorporate those used by the Convention of Biological Diversity (CBD) to identify Ecologically or Biologically Significant Marine Areas (EBSAs) and by the International Maritime Organization (IMO) to identify Particularly Sensitive Sea Areas (PSSAs) Each of the biological layers are further assessed and ranked according to their specific sensitivity to potential environmental effects caused by shipping. Environmental impacts from shipping in the area can potentially include oil spills, disturbances of wildlife through noise over and underwater, collisions between ships and marine mammals, and light-induced collisions between ships and seabirds. These impacts can potentially act together with impacts from other activities in the area, i.e. fishing, hunting, mineral exploration, and tourism, as cumulative impacts.

Christensen et al. demonstrate that several smaller areas around Disko Bay and Store Hellefiskebanke are sensitive or very sensitive to the environmental impacts that shipping may cause. Five sub-areas are identified where there may be a need for heightened awareness in relation to impacts of shipping (Figure 5.18). Christensen et al. recommend that ecosystem-based management (EBM or EA) should be applied in this area, inspired by current work in the Arctic Council and Norwegian integrated ecosystem-based management plans.

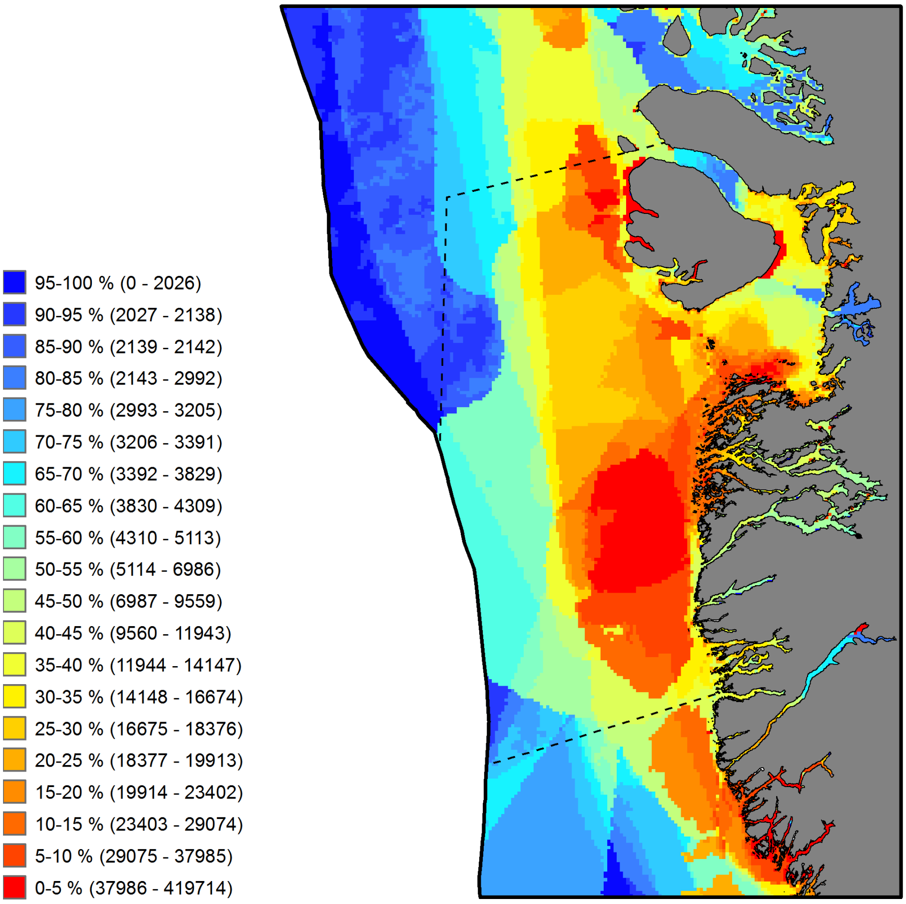


Figure 5.18. Map of the accumulated environmental sensitivity across the five environmental impacts related to maritime traffic, which are included in a spatial analysis of the 41 map-layers describing the spatial distribution of important marine species and ecosystem components in the Store Hellefiske region. The five environmental impacts related to maritime traffic are oil spills, disturbances of wildlife through noise over and underwater, collisions between ships and marine mammals, and light-induced collisions between ships and seabirds (Christensen et al., 2015).

Impact of climate change on the marine environment

The Arctic is warming at a much faster rate than other parts of the globe through a process known as arctic amplification, where the loss of sea ice increases the impacts of global climactic changes (Serreze & Barry, 2011; AMAP, 2021). These changes will likely have a profound impact on marine ecosystems (Walsh et al., 2011). The marine environment will experience increased sea temperatures and decreased sea ice cover. Greater coastal freshwater input from faster snow and ice melt as well as greater precipitation result in localized salinity decreases. There is also potential for more extreme weather events. Further, there is the potential for secondary effects related to changes in climate, including ocean acidification and the potential for invasion by new and exotic species, either through range expansion or accidental introduction.

Pelagic ecosystems are likely to be affected by climatic changes in several ways. Decreased or thinning ice cover can result in an increase in primary production and phytoplankton biomass (Qu et al., 2006; Arrigo et al., 2008). Warming sea temperatures and changes in circulation patterns can also result in changes in the composition and abundance of arctic plankton, including the introduction of new species, changes in the range of existing species, or changes in biomass (Pedersen & Rice, 2002; Reid et al., 2007). Benthic ecosystems will be similarly impacted by the same climatic drivers affecting the pelagic environment. In addition, changes in the pelagic communities can propagate through to the seafloor, especially where the majority of the primary production occurs in the water column. Nearshore shallow coastal benthic environments can also be impacted by changes in the freshwater input from faster glacial and snow melt, which can deliver increased sediment loads. This can increase or decrease the abundance of some species, change the distribution and composition of communities, or change life history such as growth rates (Overland et al., 2004; Grebmeier et al., 2006; Berge et al., 2009; Sejr et al., 2009).

These impacts as a result of global climactic change will likely result in habitats and organisms being less resilient to the effects of marine mining. Benthic species that are already experiencing changes in their habitat, life history, and community are likely to suffer greater mortality from physical disturbance and slower post-impact recovery. The modification of the structure of the seafloor as a direct result of mining coupled with changes in environmental conditions from climate change might make the establishment of new species and invasive species more likely at the expense of existing ones. The Arctic seabed is also a major sink for carbon, and disturbing benthic marine ecosystems through mining may in itself add to the impacts of climate (Souster et al., 2024).

6 Mitigation and regulation

Implementing effective mitigation strategies can be crucial to reducing the environmental impacts of marine mining. Mitigation strategies could include **technological** improvements or implementing the **mitigation hierarchy**. Current status, regulatory frameworks, and mitigation strategies from **Norway** and the **International Seabed Authority** can also provide valuable guidance in minimizing environmental impacts.

Technological mitigation aspects

Technological mitigation options aim to reduce the environmental impact of marine mining operations while maintaining the efficiency of resource extraction. These approaches focus on minimizing physical, chemical, and biological disturbances to marine ecosystems. These could include the use of Precision Mining Technologies (by using ROVs and AUVs). These vehicles enable precise and targeted mining as it focuses on removing only the necessary mineral deposits. Other technologies could include mining tools that minimize sediment disturbance and spread such as suction heads with sediment filtration systems, which can capture and control sediment dispersal (Haalboom et al., 2023; Weaver et al., 2022). These minimize plume generation by immediately collecting sediment as it is disturbed, preventing it from spreading through the water column.

Various technologies can be employed to reduce noise from mining machinery and vessels, which may disturb marine life. These include advanced sound-dampening systems, vibration isolation mechanisms, specially designed propellers, and the use of bubble walls to lower the acoustic impact of operations.

For the generation and discharge of wastewater and process water, which may contain heavy metals, toxins, or sediments, several technologies can be employed. These include water screening and treatment, such as filtration systems and chemical neutralization units, ensuring that the discharged water meets environmental standards. Additionally, improved recycling, closed-loop water systems, and waste-handling procedures could prevent harmful chemicals and sediments from entering the ocean (European Academies Science Advisory Council, 2023; Miller et al., 2018).

The mitigation hierarchy

The mitigation hierarchy is a framework used in environmental management and conservation to guide the process of minimizing negative impacts on biodiversity and ecosystems resulting from development projects or other human activities. It is structured as a sequential approach with four key steps *avoidance*, *minimization*, *restoration*, and *offsetting (compensation)*. It has been proposed to be an effective approach to ecosystems likely to be affected by deep-sea mining activities (Miller et al., 2018; Niner et al., 2018; Thompson et al., 2018; Tucker et al., 2020) and could be a potential approach for marine mining as well.

Building on an assessment of the potential environmental impacts of marine mining, it is crucial to develop and implement measures to *avoid* and subsequently *minimize* these impacts. In practice, this can be achieved through spatial planning strategies, such as identifying and designating protected marine areas, key fishery grounds, or areas of high biodiversity, while establishing buffer zones, where mining activities are *avoided and prohibited.* These measures help preserve ecologically sensitive habitats, species, and areas vital to key biological processes, including breeding, feeding, and spawning (Howard et al., 2020; Miller et al., 2018). Additionally, temporal planning, such as scheduling operations to avoid critical periods like seasonal whale migrations, can further reduce environmental disturbances (Howard et al., 2020). Additionally, *minimizing* overlap with other commercial and local community activity areas will ensure that relevant stakeholders are involved.

Although measures are taken to avoid and minimize the impacts as far as possible, some impacts may be unavoidable. To address these, strategies for *remediation* and *offsetting* can be applied.

Remediation strategies could be post-mining habitat restoration, which should be integrated into the initiation of marine mining projects (Miller et al., 2018). Strategies could include replanting disturbed seagrass beds or using coral transplants to restore benthic communities. The creation of artificial reefs can also improve ecosystem recovery as these structures provide new habitats for marine life. The speed of physical recovery after shallow-water mining is primarily influenced by substrate type and tidal currents, with the fastest restoration occurring in fine mud and sandy sediments (Howard et al., 2020). Over time, dynamic natural processes will allow the ecosystem to recover if conditions are favourable and the pressures from the mining operation have ceased.

Species conservation efforts near the mining operation are also crucial for minimizing the impacts on marine biodiversity. Strategies could include creating biological corridors where mining is prohibited, relocating species to undisturbed areas, and implementing measures to reduce machine noise and sediment plumes during operations to limit disturbance to marine organisms (Miller et al., 2018).

If biodiversity losses are inevitable, biodiversity *offsetting* or *compensating* could involve the restoration or protection of equivalent ecosystems elsewhere (Miller et al., 2018). This might include preserving habitats that support the same or similar species impacted by mining activities elsewhere. Building artificial reefs is an effective offset measure to compensate for habitat loss. These structures mimic natural reef systems and can enhance local biodiversity by providing habitats for fish, corals, and other marine organisms. Overall, this ensures that the ecological footprint of mining is balanced by broader conservation efforts. Another option could be to compensate for the environmental impacts that the mining activities can cause by funding dedicated ecological reserves or relevant research initiatives. This will ensure that mining activities contribute to broader conservation and sustainability efforts.

The Norwegian approach

There is no large-scale shallow-water mining industry in operation in Norway. However, Norway is moving forward with deep-sea mining of polymetallic sulphides and manganese crusts. In January 2024, the Norwegian Parliament passed legislation allowing companies to apply for mapping and exploration permits across 280,000 square kilometers in the northern Norwegian Sea of the extended Norwegian continental shelf inside the EEZ, which was formally opened by the King in Council in April 2024. According to the Norwegian Government, "*Before any potential extraction can be permitted, more knowledge is needed. Any plans for extraction must be approved by both the* *ministry and the Norwegian parliament. Plans will only be approved if extraction can be done in a sustainable and responsible manner."* (https://www.regjeringen.no/en/aktuelt/norway-gives-green-light-for-seabed-minerals/id3021433/). Additionally: *"Before any exploitation can begin, the licensees must have proven that there are resources in place, identified a technical solution that makes production profitable, and made an investment decision for the project. The licensees must then prepare an exploitation plan, which includes conducting an impact assessment process, which must be approved by the Ministry. In order for the Ministry to approve specific exploitation plans, the plan must show that the project can be implemented in a sustainable and responsible manner. The first plans must also be submitted to the Norwegian Parliament."* (https://www.regjeringen.no/en/aktuelt/public-consultation-of-the-first-licensing-round-for-seabed-minerals/id3047008/).

The passed legislation was based on prior research, which is ongoing, evaluating the environmental consequences of deep-sea mining activities in Norwegian waters. This has been published in the reports by Larsen et al. (2022) and Olje- og Energidepartementet (2022) and supporting reports referenced herein. See also Frigaard Rasmussen et al. (2024). Here, several mitigation strategies aiming to reduce the environmental impacts of deep-sea mining on the Norwegian continental shelf have been identified. These are outlined (and translated) in Table 6.1.

Activity	**Effort**
Seabed extraction	Mapping of vulnerable habitats/marine organisms before start-up of production, corresponding to baseline surveys and activity-specific seabed mapping in connection with petroleum activities, and use of the results in further planning to reduce environmental impact.
	The area use at each extraction site is kept as low as possible so that the directly affected bottom area is minimized.
	Any interim storage on the seabed of sulphide ore is established in areas where the cover has already been removed.
	Establish distance requirements between active production sites in the direction of the current, defined on the basis of the expected amount of particles and dispersion distance.
	The use of technology to minimize the amount of suspended particles when crushing metals in a closed system will reduce exposure to harmful substances and spread away from the extraction site. This will also reduce the spread of metals in the water mass.
	Establish environmental monitoring with pre- and post-surveys to assess the effect of the activity.
Discharge of return water	Transporting ore in containers or using combined gas lift or baskets and hydraulic lifting will reduce the amount of water and thus the amount of return water and emissions of particles.
	Purification of water after dewatering before discharge to the sea.
	Release the return water directly above the seabed, or below the photic zone, so that horizontal dispersion in the water column is reduced and that particles that settle will affect benthic communities that are already affected by the particle cloud from recovery vessels and/or removed and destroyed by the recovery units.
	Establishment of environmental monitoring for particle dispersion in order to gain knowledge about the dispersion and effect of the impact.

Table 6.1. Identified mitigation strategies aiming to reduce the environmental impacts of deep-sea mining on the Norwegian continental shelf (Larsen et al., 2022, Olje- og Energidepartementet, 2022).

Norway is still in the assessment phase, studying the environmental impacts of deep-sea mining and potential risks to marine ecosystems.

Like Greenland, Norway has a history of deposition of mine tailings in fjords (submarine tailings disposal in shallow waters (0-200 meters) and deep-sea tailings placement at depths below 1000 meters) from onshore metal extraction (Vare et al., 2018), which could serve as a reference to marine mining operations.

The environmental effects of mine tailings disposal in fjords have included sediment smothering of benthic habitats altering ecosystems (Trannum et al., 2018), release of toxic elements (e.g. heavy metals and processing chemicals) (Pedersen et al., 2017; Sternal et al., 2017), and long-term dispersion of tailings (Pedersen et al., 2017; Ramirez-Llodra et al., 2015).

To minimize the environmental risk from submarine tailings disposal, the Norwegian government requires an EIA depending on the size of the mining project (Skei et al., 2019), which is controlled by the local government where the mine is situated. The EIA shall describe the present environmental setting, consequences for natural resources, and the society in the area expected to be influenced by the mining project. A potential waste discharge permit issued by the Norwegian Environment Agency requires additional mandatory tests and investigations (not already included in the EIA), as well as a monitoring program.

The International Seabed Authority's approach

The deep sea outside the EEZ is regulated by the International Seabed Authority (ISA), which is an intergovernmental organization of 168 member states and the European Union founded under the 1982 UNCLOS and 1994 Agreement on Implementation. ISA's primary role is to regulate all mineral-related activities in the international seabed area which lies beyond the jurisdiction of any single nation. The purpose of ISA is to ensure that seabed mineral resources are developed in a way that benefits humanity, while also protecting the marine environment from harmful impacts. ISA is purposed to create legal frameworks, issue mining licenses, and create environmental regulations to protect sensitive marine ecosystems.

ISA is currently working on regulations for deep-sea mining *exploitation*. The finalization of these regulations has been delayed since over 32 countries, including the Kingdom of Denmark, and the European Parliament, among others, have called for a moratorium in 2024. They advocate postponing deep-sea mining activities until more comprehensive regulations are established and scientific understanding of the environmental impacts is improved (Amon et al., 2022a; Amon et al., 2022b). The regulations were discussed in the International Seabed Authority (2017) and later formulated in draft regulation ISBA/25/C/WP.1.

However, ISA has entered 15-year contracts for the *exploration* of polymetallic nodules, polymetallic sulphides, and cobalt-rich ferromanganese crusts in the deep seabed with 22 contractors (https://www.isa.org.jm/exploration-contracts/).

Exploration permits require the contractor to gather oceanographic and environmental baseline data to assess the possible effects of exploration activities (International Seabed Authority, 2015). Additionally, an environmental impact assessment and a program to monitor and report on such effects during and after the activities are required. The contractor must report annually on the results of its environmental monitoring programs. Detailed guidance is available in ISBA/25/LTC/6 that defines the activities requiring EIAs, the form and content of such EIAs when required, as well as guidance on baseline studies, monitoring, and reporting during prospecting and exploration.

The required monitoring plan is purposed to minimize direct and indirect damage of mining-related activities to marine organisms, habitats, and the ecology of the region. Avoiding impacts requires monitoring such that impacts are readily detectable and assessable before they cause serious harm (Jones et al., 2020). This is implemented in the establishment of Impact Reference Zones (IRZ) and Preservation Reference Zones (PRZ) as spatial management zones. An IRZ is the area affected by mining operations, while a PRZ is situated outside the impact area and serves as a control site but should be selected from areas with a similar environment to the IRZ. By monitoring both zones, contractors and the ISA can determine whether changes observed within an IRZ are due to mining activities or other factors (Jones et al., 2020; Pickens et al., 2024).

7 Conclusion and recommendations

Based on our review, we conclude that marine mining may potentially have a severe impact on biodiversity and the marine environment. However, the impact is highly dependent on location and timing as well as on the size of the operation and the technology used. Small operations outside sensitive areas may have only local impact.

In this report, we have summarized the available knowledge on sensitive and important marine areas in West Greenland EEZ as well as defined important data gaps. Detailed biodiversity information is lacking in many areas, especially on benthic biodiversity in offshore areas. Information is also sparse on population robustness towards the potential impacts of marine mining for marine mammals, seabirds, fish, and other pelagic and benthic fauna.

The information presented in this report may serve as a starting point for future discussions on the environmental planning and regulation of marine mining projects in West Greenland. These discussions could include considerations of topics such as:

1. Areas, which could be open for licensing but with specific requirements to conduct studies in the EIA process to fill relevant data gaps in the area concerned.
2. Areas, which should be closed for licensing due to documented ecological values at risk.

3. Areas, which should be temporarily closed for licensing due to lack of knowledge about potentially significant ecological values.

4. Areas, which could be open for licensing with the condition that relevant biodiversity knowledge is obtained early in the exploration phase and used for regulation (inspired by Norwegian practices).

5. Areas, where studies can be conducted to delineate the areas that could be opened for licenses.

Moreover, the introduction of enhanced monitoring programs in the regulation of marine mining may be considered with the aim to improve general knowledge about the impact of various activities.

Summary of areas of high concern

The overview below highlights areas identified as areas of high importance to multiple or specific species sensitive to marine mining processes. These areas were mainly identified by Christensen et al. (2016), the GINR benthic database, and Greenland Fisheries License Control-restricted areas for fishery, and are discussed in Chapters 4 and 5.

Table 7.1. Areas of high importance to species sensitive to marine mining processes. The ID refers to the areas in Fig. 7.1., BI no. refers to numbers in Christensen et al. (2016). See Chapters 4 and 5 for details.

ID	Area	BI no.	Characteristics
A	Northern Qaanaaq	1	Area of outstanding international importance. Most productive polynya in the Arctic. Important area for polar bears, narwhal, beluga, bowhead whales, and Atlantic walruses. Important breeding area for black-legged kittiwake (*Rissa tridactyla*), Arctic tern (*Sterna paradisaea*), thick-billed murre (*Uria lomvia*), little auk (*Alle alle*), Atlantic puffin (*Fratercula arctica*), and Sabine's gull (*Xema sabini*). Very few investigations of benthic communities.
B	North Water Polynya	2	
C	Southern Qaanaaq & Melville Bay	3	
D	Northern Upernavik	4	Area for polar bears, narwhal, beluga, bowhead whales, and Atlantic walruses. Important breeding area for red-breasted merganser (*Mergus serrator)*, black-legged kittiwake (*Rissa tridactyla*), Arctic tern (*Sterna paradisaea*), thick-billed murre (*Uria lomvia*), Atlantic puffin (*Fratercula arctica*), and Sabine's gull (*Xema sabini*). Some offshore investigations of benthic communities in Baffin Bay along banks and throughs.
E	Central Upernavik	5	
F	Sigguup Nunaa, off	6	
G	Qeqertarsuaq, off	7	Area of international importance Important areas for bowhead whale, beluga, narwhal, Atlantic walrus, and bearded seal (*Erignathus barbatus*). Important area for fin whales, and humpback whale Very important wintering area for king eider, and important wintering area for common eider and thick-billed murre. Breeding area for many seabirds near shore. Nursing grounds for the offshore West Greenland Atlantic cod stock. Benthos: Many investigations, rich fauna found in many regions dependent on habitat factors.
H	Store Hellefiskebanke	10	
I	Lille Hellefiskebanke	12	
J	Fyllas Banke	15	Important area for humpback whales, and offshore for sperm whales, fin whales, bottlenose dolphins, and seal species. Wintering area for eider and king eider. VME-appointed area for a soft coral garden along Toqqusaq Banke off Nuuk. Spawning ground for the offshore West Greenland Atlantic cod stock Benthos: Many investigations, rich fauna found in many regions dependent on habitat factors.
K	South of Paamiut	17	
L	Julianehåb Bay	18	Important area for hooded seal (*Cystophora cristata*), harbour seal, and eider. Breeding and wintering area for many seabirds and seaducks. Benthos: Some investigations, rich fauna found in many regions dependent on habitat factors.
M	Nunap Isua	19	
N O P	VME potential areas	-	General areas for potential VMEs informed by the abundance and diversity of species identified as having high sensitivity to disturbances to the seabed. Geomorphological features such as trenches are not considered and are purely based on taxa presence.
P N	Protected areas	-	Areas under existing or planned protection by the Government of Greenland from bottom trawling fishery, e.g. with observation of sea pens, or identified as a VME candidate.
	Important areas	-	Important areas identified in *Rules for fieldwork and reporting regarding mineral resources* ('Field Rules'): around seabird colonies with moulting seaducks for Atlantic walrus in winter and spring for beluga whale for bowhead whale for narwhal in winter and spring

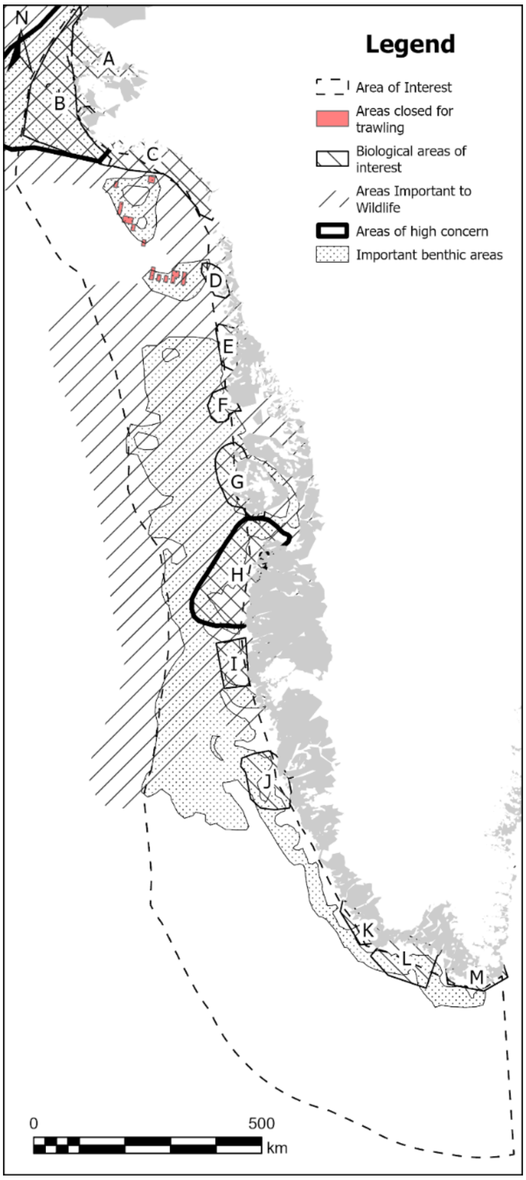


Figure 7.1. Areas of high concern and importance. See Table 7.1 for explanations. Information from Christensen et al. (2016), NatureMap Areas Important to Wildlife, and Greenland Fisheries License Control restricted areas for fishery.

Information needs and data gaps – impact studies and baseline

Establishing a baseline of the marine environment, including specific mapping of sensitive organisms and areas of high concern, is essential for managing the environmental impacts of marine mining operations. A comprehensive baseline aids in assessing the environmental changes over short and long terms and provides a foundation for developing a regulatory framework, including monitoring programs, to effectively manage the environmental impacts of a marine mining industry.

To some extent, information on the potential impacts of marine mining can be drawn from studies of other marine activities, such as shipping, trawling, and oil and gas exploration, which have provided environmental baseline data on marine ecosystems and their robustness. However, these studies may only represent some of the impacts of a marine mining project in the Arctic, and depending on the project (including site, mineral, size, and technology to be used) specific impact studies will be needed to assess the likely impact.

Several information needs and data gaps have been identified, which should be addressed to ensure responsible management of marine resources in the western Greenland marine environment. Table 7.2. provides a summary of information needs and data gaps, as highlighted in Chapters 4 and 5.

Table 7.2. Summary of information needs and data gaps on the West Greenland environment and species vulnerability to marine mining.

Species	Area	Description
Benthos and epifauna	West Greenland	Mapping of the benthic and epifaunal environment is poor, which limits our understanding of these communities, especially in deeper offshore areas and in the northern regions of the Greenland shelf. No VME areas are yet designated in Greenland waters. Data is missing on the short- and long-term impacts on benthic and epifaunal organisms and communities particularly regarding their sensitivity to sediment disturbance, habitat alteration, contaminant exposure, and other related pressures caused by marine mining activities.
Shrimps	Baffin Bay	It is unknown if the area also serves as a nursery area for shrimp.
Fish	West Greenland	Further research is needed into the long-term effects of behavioural changes in fish
Whales	West Greenland	The long-term consequences of short- and long-term noise exposure for whales, especially bowhead whales are still uncertain.
Seabirds	West Greenland	Mapping of key foraging areas from the large seabird colonies. Impacts of sediment plumes on foraging seabirds
Carbon sequestration	West Greenland	Lack of studies investigating the impact of marine mining particularly on seabed carbon sequestration. Seabed ecosystems, especially benthic communities and sediments, are crucial for carbon storage. Mining activities could disturb these systems, potentially releasing stored carbon and disrupting natural sequestration processes.

General recommendations for EIAs of marine mining projects

Based on the findings of this report, the following recommendations for EIAs of marine mining projects have been identified, addressing specific topics that could support effective environmental management.

Impacts on ecosystem function

- It is important to establish ecological baselines at the appropriate spatial and temporal scales.
- Multiple reference sites, both near and far from intended mining sites, should be established and monitored in advance of mining to capture the natural variability.
- In mining fields, the mining footprint should be constrained to the smallest possible area to limit sediment disturbance and compaction, both of which may inhibit ecosystem recovery.

Plumes in a dynamic environment

- Baseline studies will need to assess current and eddy regimes for modeling and evaluating the spread of plumes generated at the seabed and discharges to the surface water from ships.
- Models are vital tools for predicting and understanding the spread and impacts of plumes – particles as well as dissolved substances in the seawater.
- For species of concern thresholds for impacts should be estimated.

Ecotoxicology

- Knowledge of the ecotoxicological limits of Arctic species of concern helps to assess their tolerances and define the limits of ecotoxicological impact from a mining site, including limits/thresholds for the potential impacts of avoidance behaviour by fauna, both invertebrates, and vertebrates.

- The bulk toxicity of each prospective resource should be established in advance, and at different times during the biological and seasonal cycles, for a range of species of concern relevant to the region surrounding the area of immediate impact. Such an approach should also be adopted to assess the potential toxicity of discharge waters from any dewatering of ore and waste slurry.
- Spatial limits for the influence of the plumes produced and their metal content and other toxic substances.
- As larval stages are more susceptible to toxic effects, knowing the reproductive and spawning seasons of species, if relevant, may permit identification of the times of the year when mining should be suspended for a particular location/resource (i.e. it may be necessary to introduce 'mining seasons' to avoid key reproductive events. This may be included in adaptive management plans.
- Operations will need contingency plans if/when discharge waters exceed toxicity thresholds, as determined during EIAs.

Ecosystem resilience and recovery

- The resilience of a community or organisms (i.e. degrees of resistance and recovery) should be assessed relative to each type of ecological risk from extractive activities. The data can be used in an environmental impact assessment (EIA) of the extraction activities.
- Mitigation of mining effects should be designed to ensure that tipping points or points beyond which no ecosystem or community recovery is possible are avoided.
- These actions should include spatial and temporal management of mining operations as well as engineering and operational designs able to minimize, e.g. plume size on the sea floor, toxicity of the return plume, and sediment compression.

Disturbances from underwater noise

- The International Maritime Organization's Marine Environment Protection Committee's (IMO MEPC) guidelines on the reduction of underwater radiated noise could be considered, including the additional guideline from the Inuit Circumpolar Council adopted by the IMO MEPC.
- The Ocean Noise Budget, Passive Acoustic Monitoring (PAM) and Marine Mammal and Seabird Observation (MMSO) system, modeling of effects and propagation of noise, and plans of mitigation efforts could be considered to assist in minimizing underwater noise from marine operations, including transportation on the ocean surface, acoustic measurements, and communication, as well as operations on the seabed and in the water column.

Mitigation of light pollution

- Models of light pollution from planned marine operations, evaluate effects on seabirds and other species sensitive to light and collisions depending on seasonality, traffic density, and locations, and plan and conduct mitigation efforts.
- Possible mitigation efforts could include reduction of the radiance and direction of lights, reduction of vessel speeds, and avoidance or reduction of the use of areas during sensitive periods.

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9 Appendix: Underwater noise and vibration

Introduction

The oceans and waters around Greenland involve natural ambient sounds from sources such as iceberg calving, movements of icebergs and sea ice, wind and waves, and vocalization, movements, and activities from marine mammals and fish and more rarely, geological events such as earthquakes or landslides (Hildebrand, 2009).

According to Hildebrand (2009), anthropogenic activities produce noise, predominantly and generally from vessels transits and operations (boats, pelagic and bottom trawling, shipment of goods, cruise ships and ferries etc.), during construction phases (blasting, drilling, dumping materials etc.) and through acoustic sources (navigational echosounders, underwater positioning, exploratory sonars and related instruments, seismic exploration equipment etc.).

Depending on the depth and the activities, the sound distribution can be different. The noise can be measured with hydrophones attached to moorings distributed around the site (Ladegaard et al., 2021). Choice of sound frequency bands set on the hydrophones depends on an assessment of which marine species to address in terms of their abundance and sensitivity to sound emissions.

In Arctic waters, certain conditions must be considered (Boertmann et al, 2021). The water column is often stratified which causes refraction of sound waves (Ladegaard et al., 2021). Therefore, a simple relationship between sound pressure levels and distance to source cannot be assumed. This makes it difficult to base impact assessments on simple transmission loss models (spherical or cylindrical spreading) or to apply results from assessments performed at southern latitudes to Arctic waters (Urick, 2013). The sound pressure, for instance, might be significantly higher than expected in convergence zones far (> 50 km) from the sound source. This has been documented by means of acoustic tags attached to sperm whales, which recorded high sound pressure levels (160 dB re µPa, peak-peak) more than 10 km from a seismic array (Madsen et al., 2006).

Noise from surface vessels

Vessels of the ocean surface emit sounds from the propeller. The size of the propeller directs the sound frequency of the underwater noise produced, and vessels with fixed pitch propellers produce low frequency noises with long propagation range. Noise from propellers is divided into cavitating and non-cavitating sounds. Moreover, trailing edge and leading-edge noise is produced by the propeller. Cavitation is a major source of underwater noise, particularly at higher speeds – even as low as 8 knots – and design of the propeller is important, although the physics of cavitation and emission of noise is complex (Smith & Rigby, 2022).

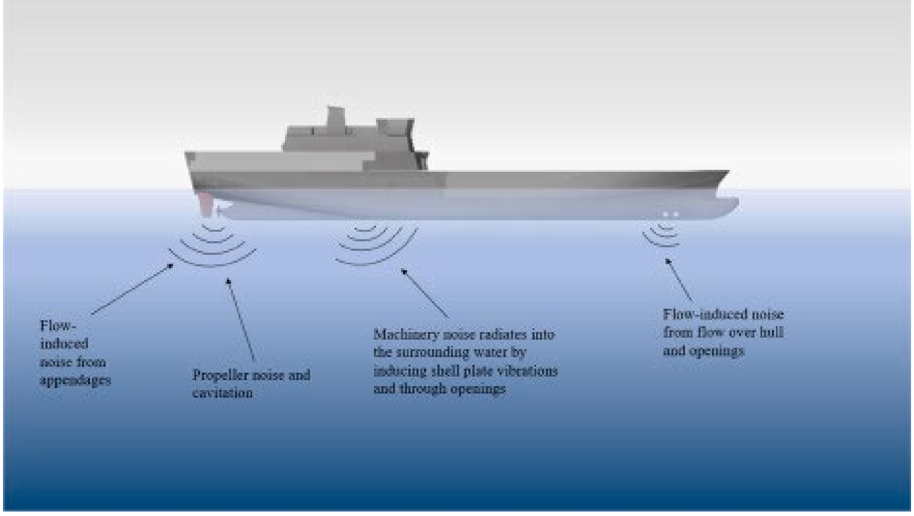
The power of the noise depends on the speed of the ship, and there is a direct link between the speed of the ship and the underwater radiated noise, and slower speed will reduce noise emissions (Smith & Rigby, 2022; Vakili et al., 2023).

The design of the ship and its propulsion system also has an effect, and through international classification societies (i.e. DNV), a vessel can obtain a Quiet Ship Notation for operations in general or for certain operational or propulsion modes.

The shipping world is slowly moving towards other energy sources than diesel and oil; however, vessels with fully electric propulsion systems still radiate underwater noise, although the airborne noise is reduced (Andersson et al., 2024). The issue with radiation of noise underwater is not related to the energy source but to the propeller, thruster or jet propulsion system producing cavitation bubbles or other noise from movement in the water.

Noise is also produced when water is passing along the hull as well as over openings (i.e. thrusters and pumps) or equipment attached to or a part of the vessel (rudder, fins) and creating turbulence and mixed movements of water (Smith & Rigby, 2022).

Figure A.1.1. Sources of radiated noise from propulsion systems or through the hull (Smith & Rigby, 2022).



When crew on a surface vessel is remotely manoeuvring equipment in the water column or on the seabed, it is often required to maintain its coordinate position with high precision using a Direct Positioning System, DPS, which controls and runs the vessels thrusters (often bow, stern, and azimuth) and main propeller simultaneously (Mehrzadi et al., 2020). The spinning pitch and power of the thrusters and main propeller depend on the sea state, ocean environment and operational requirements, and likewise the emission of sound from the machinery into the water column.

Internal sounds and vibrations from operations onboard the vessel from using cranes, winches, or other machinery or equipment are radiated through air and through the hull of the vessel into the water column, however not well studied. General regulations on health and safety onboard considering noise on the deck should be met, and a Quiet Ship Notation class with focus on vibrations from equipment and propulsion systems could be applicable to reduce radiation of noise from operations onboard.

Noise from acoustic instruments and equipment

During marine mining operations, a great variability of instruments and equipment are used with their main task of actively producing sound. All surface vessels will have a navigational echo sounder, exploration of the seabed surface geology and morphology including top layers require sonars, profilers or seismic instruments, positioning of and communication with deployed equipment is done through acoustic instruments, and the currents are measured acoustically. Below is an overview of acoustic instruments and equipment actively emitting sounds during operations.

For initial surveying of the seabed, an array of different acoustic instruments is needed, depending on the scope of the project (Figure A.1.2).

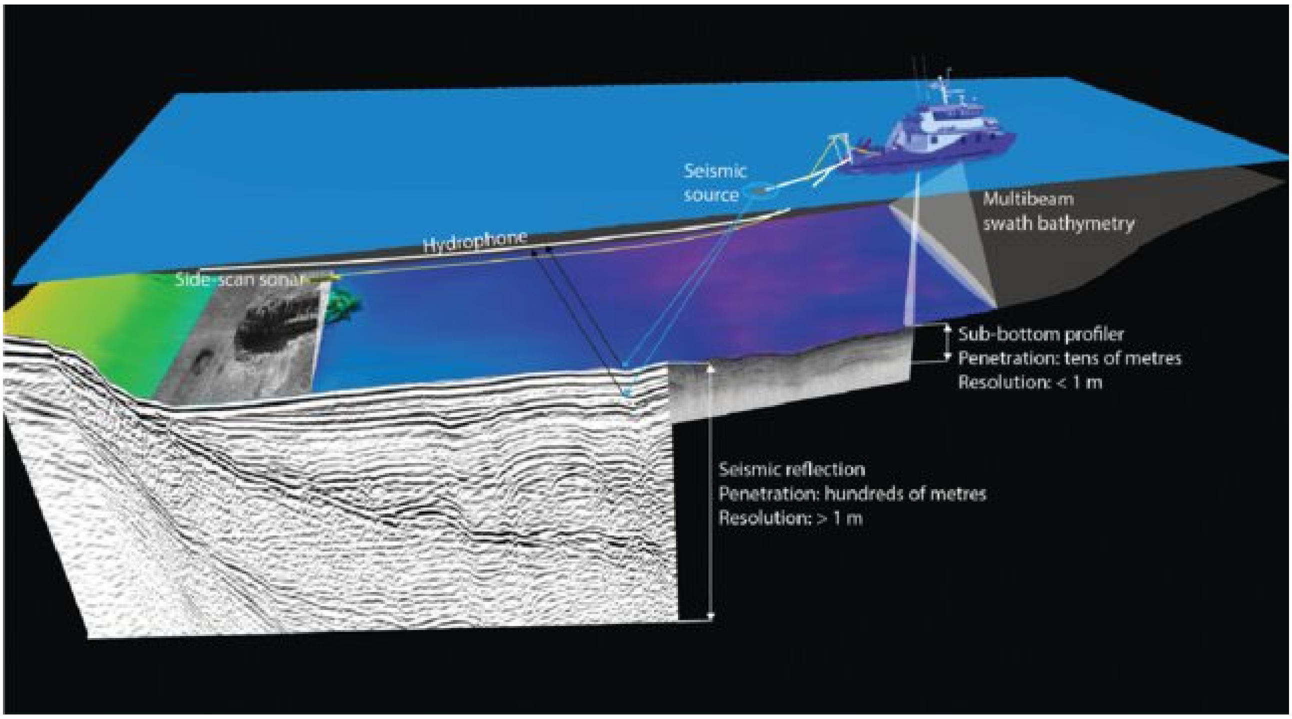


Figure A.1.1. Multi-beam bathymetry, side-scan sonar, sub-bottom and seismic-reflection profiling information brought together in a 3D environment for geological interpretation (Jakobsson et al, 2016).

Single-beam echo sounders

Single-beam echo sounders are used continuously through exploration and exploitation phases during general navigation at sea, operating of marine surveys, deployment of underwater gear, support during operations, transportation of equipment, materials and people.

Navigational echo sounders vary in frequencies and sound pressure level. Larger vessels are obliged to carry echo sounders for navigation in coastal waters, often with relatively high frequencies to obtain precise and quickly updated measurements of the water depth in shallow waters where obstructions and hazards to navigation can occur. For deeper water, the echo sounder needs to be of lower frequency to reach the seabed.

A single-beam echo sound transducer sends a cone of sound towards the seabed, which reflects the sound to be received by the transducer to measure depth by time of flight. The beam must be as narrow as possible to accurately detect the seafloor but depends on the frequency of the sound and design of the transducer. In deeper waters, lower frequencies must be used and the distance between the transducer and seabed is larger and consequently, the conical spreading of the beam will be larger.

Multi-beam sonars

Multi-beam sonars are used for hydrographic surveys and mapping of the seabed morphology primarily. They are often constructed with a separate sound transmitting unit (projector) and a separate sound receiving unit (hydrophone), unlike navigational echo sounders of usually one unit. The transmitter has an array of built-in units of piezoelectric ceramics translating electrical signals into acoustic waves. Multiple acoustic pulses are transmitted in a swath of acoustic waves perpendicular to the vessel as the unit (Jakobsson, 2016).

Through beam forming methods, the pulses are designed to have narrow footprints along-track on the seabed, however with sidelobes around the pulses in the upper water column. Across-track, the combined footprint of the beams are large, up to some kilometres, depending on the combination of depth range, angles (often 130°-150°), frequency and power.

The sound waves are reflected from the seafloor and refracted (bended) through the water column and surface geology, and the reflected sound is received by the hydrophone array, which further narrows the beam for as exact definition of every beam as possible considering frequency, distances, as well as the content and properties of the water column (density, temperature, salinity, biological or geological elements).

Like navigational echo sounders, multi-beam sonars vary in frequencies and sound pressure level depending on their use. For investigations with a relatively short distance between the sound source (transmitter) and the object (sea floor) high frequencies are used, usually shallow waters or if the instrument is attached to a submerged vessel (ROV, AUV, etc.) measuring the sea floor.

Side-scan sonars

Side-scan sonar can be mounted to the hull of a surface vessel or more usually towed from a ship and positioned close to the seabed. The sonar type is effective in identifying objects on the seabed, as the side-scan sonar ensonify the seabed with two transducers pointing to either side along-track from a low incidence angle (usually below 1 degree) with short pulses. Objects or other irregularities on the seabed will cast a shadow in the returning acoustic backscatter.

Side-scan sonars are often of very high frequency (>1000 kHz) but also exist for very low frequencies (<10 kHz) (Jakobsson et al., 2016).

Sub-bottom profiler

Sub-bottom profilers (SBP) are usually hull mounted and designed to penetrate layers in the upper sediment below the seabed. They are designed with one transducer like single-beam echo sounders but with higher output of energy. The choice of frequency depends on the distance to the target. In shallow waters and thin sediment layers (less than 100 m water depth) frequencies above 20 kHz can be applied, while deeper waters and thick sediment layers require lower frequencies (Jakobsson et al., 2016).

Parametric SBP's (or other echo sounders) transmit sounds with high intensity at two frequencies simultaneously from the transducer. The interference of the two frequencies generates secondary frequencies, one with a high frequency and one with a high energy, narrow and low frequency beam propagating far to reach the targeted sediment layers. The sidelobes produced a very small and sound emission outside the beam is limited (Jakobsson et al., 2016).

Seismic-reflection profiling

To penetrate deeper into the marine deposits or geology acoustic pulses of higher energy than for a sonar or SBP are required. In seismic-reflection profiling, the sound transmitter and receiver are always separated, and commonly towed behind a surface vessel. The transmitters are located near the vessel, and receivers (hydrophones) further behind. The transmitters can be of the types of boomers, air guns and sleeve guns, and sparkers (Jakobsson et al., 2016). For larger air guns and sleeve guns, please refer to environmental guidelines concerning seismic surveys.

Boomers consist of plates flexing in the water and producing a pressure pulse, generally in the frequency range of 0.5-1.5 kHz or eventually up to 20 kHz and like air guns and sleeve guns producing a positive pressure pulse (Jakobsson et al., 2016).

A Sparker releases a high-voltage electrical charge, which results in a water bubble implosion of high pressure and a sound frequency range of 0.020-0.200 kHz, depending on the design (Jakobsson et al., 2016).

Seismic-reflection instruments are thus emitting sounds of low frequencies, which are less directed in beams, involve sound wave pulses of high energy, and have an expanded propagation of sound into the water column and geological layers below.

Choice and deployment of a seismic-profiling instrument depends on the targeted geological resources of the individual marine mining project. It is likely that Sparkers and Boomers will be used to investigate the upper geological layers at a high detail when towed closer to surface. This has been the case for investigations near Maniitsoq. It is less likely that air guns will be used to penetrate deep geological layers, as the target deposits often are located closer to the surface below water.

Underwater acoustic positioning system

Deployment of equipment in the water column or on the seabed requires that the operator at the surface vessel(s) knows where the equipment is located. A method to achieve this is attachment of instruments for underwater acoustic positioning. Different categories of instruments exist (Vickery, 1998):

A Long Baseline System, LBL, includes a network of acoustic transponders deployed on the seabed as reference points in a local coordinate system supporting a high level of positioning accuracy for the equipment in triangulations relative to and between the transponders. The transponders operate on frequencies and with operating ranges relevant to their use: high frequency (i.e. 120-180 kHz) providing a high communication bandwidth but low operating range (i.e. 300 m), or low frequency (i.e. 5-20 kHz) with long operating range (i.e. 5000-8000 m) but little bandwidth. Depending on the design, the transponders can communicate in horizontal, vertical or slant directions, and some instruments can have a wide-angle, conical or omnidirectional directivity (Vickery, 1998).

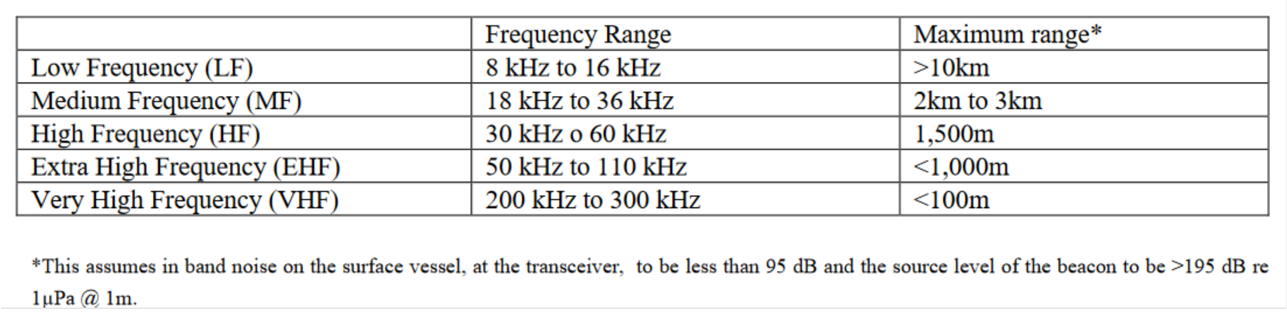
An Ultra Short Baseline System, USBL, involves a transducer mounted to the hull of the surface vessel. The transducer has multiple hydrophone receivers with extremely short individual distances. The hydrophones receive pings from an acoustic beacon attached to the equipment in the water column or on the seabed transmitting signals, and with knowledge of the internal distances in the transducer, a triangulation with range (time of flight) and bearings from the transducer at the hull to the pinging beacon is calculated (Vickery, 1998).

Short Baseline systems are likewise mounted at a surface vessel; however, with multiple transducers around on the vessel and not all included in one transducer unit (Vickery, 1998). The different positioning systems may be combined depending on the operational requirements.

Vessels, e.g. drill or dredging ships, operating from the ocean surface can use dynamic positioning systems to stay steady over a geographical coordinate. Some systems have acoustic transponders mounted on the seabed as fixed base stations. The transponders on the seabed communicate acoustically with sensors on the vessel. Often, the acoustic transponders on the seabed are not retrieved after operation (Kyhn et al., 2011).

For acoustic positioning systems in the context of emission of noise into the water column, it is relevant to know the frequency range, ping rate, transmitting power, and direction (wide-band, omni-directional, or conical) to determine the propagation of sound into the water column in and around the operational area, particularly for low frequency systems communicating over long distances (Figure A.1.3).

Table A.1.1. Frequency bands and maximum range (Vickery, 1998).



	Frequency Range	Maximum range*
Low Frequency (LF)	8 kHz to 16 kHz	>10km
Medium Frequency (MF)	18 kHz to 36 kHz	2km to 3km
High Frequency (HF)	30 kHz o 60 kHz	1,500m
Extra High Frequency (EHF)	50 kHz to 110 kHz	<1,000m
Very High Frequency (VHF)	200 kHz to 300 kHz	<100m

*This assumes in band noise on the surface vessel, at the transceiver, to be less than 95 dB and the source level of the beacon to be >195 dB re 1µPa @ 1m.

Underwater acoustic communications

Underwater Acoustic Communications (UAC) is used for transmitting and receiving messages in water from point to point and the recent decades also in underwater communication networks. To obtain a relatively broad bandwidth, high frequencies are required at the cost of transmission time. Multiple issues occur in underwater communication including multi-paths of signals, absorption of signals in the water column, variations in flight of time, and fading of signals (Chitre et al., 2008).

As with other acoustic equipment the signals are propagated into the water column depending on frequency and signal strength. The duration of the communication naturally depends on the operational needs: is the acoustic communication utilized during pre-production surveys or during the production phase? Further, it is relevant to know how many units are communicating at the same time, i.e. in a network.

Noise from equipment on the seabed

Operations on the seabed produce sounds, and today, bottom trawling with gear dragged on the seabed in Greenland waters produce sounds, and so do occasionally construction work, and during dredging for sand resources through sucking and pumping of sand. The sound occurs suddenly or develops or extends gradually over time.

Sounds from bottom trawling gear (i.e. heavy trawl doors and chains) during activities on the seabed have been measured to be a strong underwater noise pollutant considerably louder than the ambient background noise and underway vessels, and with longer propagation due to low transmission loss compared to noise from the water surface (Daly & White, 2020).

Similarly, other heavy equipment dragged on the seabed may produce strong noises when scraping the deposits or hitting stones.

During the exploration phase of a marine mining project, different types of physical equipment are likely to be utilized such as draglines, box corers, grabs, coning, probing, and drilling.

For exploitation of the resource, the methods of mechanical dredging, hydraulic dredging, or other means of dredging could be used depending on depth and geology, please refer to Chapter 2.

Table of acoustic geophysical survey instruments and emission

Adapted from: Hildebrand, 2009. Typical sources of anthropogenic noise. CW: continuous wave; V: vertical; H: horizontal

	Source level (dB re 1 µPa @ 1m)	Power (W)	Total energy per pulse (J)	Bandwidth Δ = 10 dB (Hz)	Source direction	Pulse duration (s)
MBES deep water (Example: EM122)	approx. 245	0.077x10^6	760	11500-12500	1.0˚×120˚V	0.01
Multi-beam sonar shallow (Example: EM 710)	c. 232	2.2 × 10^3	4.5	70 000 -100 000	0.5 × 140° V	0.002
Sub-bottom profiler (Example: SBP 120)	c. 230	2.1 × 10^3	210	3000 - 7000	3 × 35° V	0.1
Deep sea mining	c. 180-200					CW
Cargo vessel (Example: 173 m length, 16 knots)	c. 192	66	-	40 - 100	80 × 180°	CW
Acoustic telemetry (example: SIMRAD HTL 300	c. 190	42	-	25 000 - 26 500	90 × 360°	CW
Dredging	160-180					CW
Small boat outboard engine (20 knots)	160	42 × 10^{-3}	-	1000 - 5000	80 × 180°	CW

Attenuation of sound intensity and propagation of sounds

The effect of sound is measured as Sound Pressure Level (SPL). SPL is a physical parameter measured by hydrophones recording the radiated noise. It is defined as the root mean square sound pressure in decibels and is a logarithmic measure of the effective pressure of a sound relative to a reference value, typically 20 micropascals (µPa) in air and 1 µPa in water. SPL is expressed in decibels (dB) and quantifies the intensity of sound waves.

Sound behaves as a radiating wave in a circle and is **transmitted** through a medium: water, air, steel, etc.

Sound sources are characterized as:

Considering pulses:

- Impulsive, with brief and high peak pressure sounds in a single event or repetitive. Examples: Seismic airguns, boomer, sparker, pile driving, explosives)
- Non-impulsive, with no high peak sound pressure, can be continuous or intermittent.

Considering duration:

- Intermittent, with bursts of sound interchanging with silence, often with regular intervals. Examples: Multi-beam and single-beam sonar, sub-bottom profiler, impact pile driving/ramming.
- Continuous, with remaining emission over the observation period. Examples: Drilling or vibratory pile driving.

Depending on the properties of the sound and of the medium, sound can through the travel of sound after emission be:

- **reflected** by surfaces or other mediums withstanding the wave, sending it in backward directions,
- **refracted** changing angle and course inside the medium,
- **diffracted** through the medium changing angle and course into multiple paths inside the medium,
- **absorbed** and kept in the medium with no further travel,
- **scattered** on the medium into multiple paths.

The energy of sound is reduced mainly by following 3 factors:

a. Geometric spreading

b. Absorption

c. Transmission loss

during its travel through different mediums.

Geometric spreading depends on the beamforming of the transmitted sound wave front, if it is spherical, cylindrical etc. If we take spherical as an example, the sound intensity I in a given distance r can be described as:

$$I(r) = \frac{I_0}{r^2}$$

Where I_0 is the transmitted sound intensity. That means the sound intensity decays with the distance squared, only by looking at the geometric spreading.

Absorption is the energy loss when sound propagates through a medium. The medium transforms some of the energy of the sound waves into heat, due to molecular vibrations and viscosity in the medium. A higher frequency means more rapid vibrations, thus the higher frequency sound waves decay faster.

When sound waves propagate to another medium, some of the energy is reflected, refracted, diffracted and scattered at the transmission between the two mediums. And if you are aiming to survey e.g. sediments below the seabed, enough energy is needed to transmission into the sediments and reflect the energy back to the surface.

Water is a different medium than air, and sound travels about five times faster in water than in air, c. 1500 m/s in water and c. 340 m/s in air. The properties of water apply to sources of reflection, refraction, absorption, etc.

The speed is not constant but varies according to the water properties: temperature, salinity, and pressure. Changes in temperature have the greatest effect on sound speed. In the upper part of the water column, the surface layer and the seasonal thermocline layers, provides the greatest changes to sound speed until the temperature change settles at the Sound Speed Minimum level, and pressure provides the greatest changes below that with often an increasing speed of sound.

Certain water properties and layering can provide additional variations in speed and direction of sound. Examples related to Greenland waters are:

1. Currents of heavier and warmer water, as along the West Greenland Shelf, will contribute to changes related to temperature at a deeper level.

2. Changes in salinity have usually only a little contribution to changes in speed of sound, except where a flow of freshwater is applied, in Greenland often from melting of sea ice and icebergs, or from rivers.

3. Ice keels from multi-year ice or large icebergs can scatter or block sounds of frequencies above 30 Hz (Worcester, 2020).

4. Sound travels differently in shallow water than in deeper water due to reflections from seabed, waves, changes in temperature, freshwater content, and mixed layering in the upper water column. In Greenland, there is often a cool layer near the surface in the coastal region from meltwater, precipitation, and outlet from rivers.

Management of underwater noise

Several national and international organizations and governments are managing emissions of underwater noise through reports, guidelines, impact assessments and legislation.

Management and mitigation of underwater noise

Sources and distribution of underwater noise should be managed, and this can be done by providing an overview of the existing soundscape, the planned activities producing underwater noise, and setting up an Ocean Noise Budget to provide an overview of the level and effect (Miller et al., 2008). The result can be held against the current knowledge of marine biology sensitive to noise in the region of interest and the surrounding area determined by sound propagation modelling.

The Ocean Noise Budget can point towards activities, operations, areas and equipment that should be of focus for mitigating and minimizing the effects of noise to the marine environment.

Mitigation strategies to reduce underwater noise in the Arctic and North Atlantic regions are essential to protect marine life. Several approaches have been proposed and implemented, focusing on regulation, technological innovations, spatial and temporal management, monitoring and research, and international collaboration.

Regulation and Policy

Implementing stricter regulations on noise levels from shipping and industrial activities is a critical step. This includes setting noise thresholds and enforcing compliance through monitoring and penalties. The International Maritime Organization (IMO) has recently issued revised guidelines for the reduction of underwater radiated noise from shipping to address adverse impacts on marine life (IMO, 2023). These guidelines recommend measures such as optimizing ship design, maintenance, and operational procedures to minimize noise emissions. The revised guidelines were published on August 22, 2023, with effect from October 1, 2023. They provide updated technical knowledge, including reference to international measurement standards and recommendations for ship owners to develop underwater radiated noise management plans.

Technological Innovations

Developing and deploying quieter ship technologies is another effective strategy. Innovations such as improved hull designs and propeller modifications can significantly reduce noise at the source. For instance, using air bubble curtains around noisy equipment during industrial activities, such as pile driving and seismic surveys, can help dampen the sound and reduce its impact on marine life (Würsig & Jefferson, 2000). Additionally, the adoption of quieter machinery and the use of noise-reducing coatings on ship hulls can further mitigate noise pollution.

Spatial and Temporal Management

Designating marine protected areas (MPAs) where noise-generating activities are restricted or prohibited is an effective spatial management strategy, also in relation to marine mining activities. MPAs can provide safe havens for marine species, allowing them to carry out critical behaviors such as breeding and feeding without the disturbance of anthropogenic noise. Implementing seasonal restrictions on noisy activities during critical periods for marine life, such as breeding and migration seasons, can also be effective. For example, certain areas can be designated as quiet zones during the breeding season of specific marine mammals to minimize disturbances (PAME, 2019).

Monitoring and Research

Enhancing monitoring programs to track noise levels and their impacts on marine life is crucial. This includes deploying underwater acoustic monitoring systems to continuously measure noise levels and identify sources of noise pollution. Continued research is needed to better understand the effects of noise on different species and to develop more effective mitigation strategies. For instance, studies on the behavioral and physiological responses of marine mammals to noise can inform the development of noise exposure criteria and guidelines (Southall et al., 2007).

International Collaboration

International cooperation to address underwater noise pollution is essential, given the transboundary nature of marine environments. International organizations such as the PAME Working Group of Arctic Council and the North Atlantic Marine Mammal Commission (NAMMCO) play a key role in facilitating collaboration and developing joint strategies to mitigate underwater noise (PAME, 2019). Additionally, regional agreements, such as the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic, facilitate coordination of efforts to manage noise pollution at a regional level (OSPAR Commission, 2009).

10 Appendix: Resources of information on the Benthic and pelagic environment

Strategic environmental impact assessments

Danish Center for Environment and Energy at Aarhus University and Greenland Institute of Natural Resources in Nuuk have over the years produced Strategic Environmental Impact Assessments, SEIAs. The assessments have covered potential impacts from activities related to exploration and extraction of hydrocarbons in certain areas and waters around Greenland. The SEIAs provide comprehensive baseline data on marine ecosystems, including information on biodiversity (seabirds, marine mammals, fish, benthic and intertidal samplings, coastal sensitivity to oil spills, etc.) and habitat conditions or environmental variabilities (primary production, ocean currents, sea ice). This data can be directly applied to assess the potential impacts of marine mining activities on similar environmental parameters.

The methodologies used in the SEIAs for evaluating the environmental impacts of hydrocarbon exploration and exploitation can be adapted for marine mining. This includes approaches to assessing underwater noise, chemical discharges, and physical disturbances. Moreover, the SEIAs generally include recommended mitigation measures to minimize environmental impacts. Some of these strategies can be adapted to address the specific challenges posed by marine mining, such as sediment plumes and habitat disruption.

The report titled “Davis Strait: An Updated Strategic Environmental Impact Assessment of Oil and Gas Activities in the Eastern Davis Strait” provides a comprehensive evaluation of the environmental implications of petroleum activities in the region. This updated assessment, prepared by DCE and GINR, aims to inform decision-making processes regarding future oil and gas exploration and exploitation. The assessment area spans from 62° N to 67° N and extends to the EEZ boundary. The report highlights the physical and biological environment, conservation efforts, and the status of threatened species. It also assesses potential environmental impacts, including oil spills, and identifies research needs to enhance data for environmental impact assessments and regulatory measures.

The assessments are published as reports at the DCE AU website and data packages for GIS and statistics can be requested from DCE AU. The process of providing direct spatial display of the GIS data from the different SEIA projects on NatureMap is currently ongoing, online access via https://naturemap-nature.hub.arcgis.com

Examples of recent or updated SEIAs are:

Report	Link
Davis Strait – an updated strategic environmental impact assessment of oil and gas activities in the eastern Davis Strait. Merkel, F., Boertmann, D. & Mosbech, A. 2020. Scientific Report from DCE – Danish Centre for Environment and Energy No. 439, 332 pp.	https://dce2.au.dk/pub/SR439.pdf
Disko West – an updated strategic environmental impact assessment of oil and gas activities. Boertmann, D. & Mosbech, A. 2020. Scientific Report from DCE – Danish Centre for Environment and Energy No. 438, 384 pp.	https://dce2.au.dk/pub/SR438.pdf
Baffin Bay. An updated strategic Environmental Impact Assessment of petroleum activities in the Greenland part of Baffin Bay. Boertmann, D. & Mosbech, A. (eds.) 2017. Aarhus University, DCE – Danish Centre for Environment and Energy, 320 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 218.	https://dce2.au.dk/pub/SR218.pdf
South Greenland. A Strategic Environmental Impact Assessment of hydrocarbon activities in the Greenland sector of the Labrador Sea and the southeast Davis Strait. Frederiksen, M., Boertmann, D., Ugarte, F. & Mosbech, A. (eds) 2012. Aarhus University, DCE – Danish Centre for Environment and Energy, 220 pp. Scientific Report from DCE – Danish Centre for Environment and Energy Nr. 23.	http://www2.dmu.dk/Pub/SR23.pdf
Biologiske interesseområder i Vest- og Sydøstgrønland. Kortlægning af vigtige biologiske områder. Christensen, T., Aastrup, P., Boye, T., Boertmann, D., Hedeholm, R., Johansen, K.L., Merkel, F., Rosing-Asvid, A., Bay, C., Blicher, M., Clausen, D.S., Ugarte, F., Arendt, K., Burmeister, A., Topp-Jørgensen, E., Retzel, A., Hammeken, N., Falk, K., Frederiksen, M., Bjerrum, M., & Mosbech, A. (2016). Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 210 s. - Teknisk rapport fra DCE - Nationalt Center for Miljø og Energi nr. 89.	https://dce2.au.dk/pub/TR89.pdf

ICES

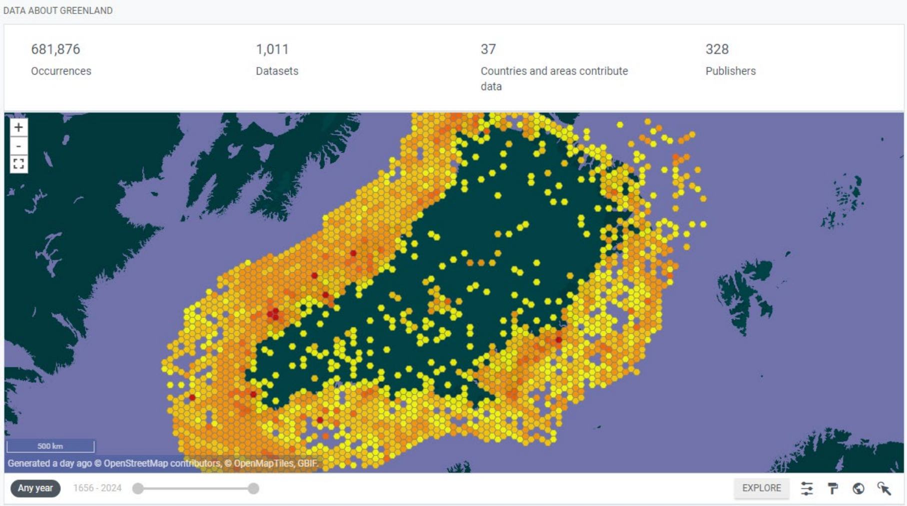
The International Council for the Exploration of the Sea (ICES, https://ices.dk) is an intergovernmental marine science organization encompassing a network of over 20 member states. The ICES Data Centre holds data sets related to the marine environment with data themes on biological communities, catch statistics, contaminants, trawl surveys, oceanography and more. The data centre covers only the eastern part of the waters of Greenland dividing at Cape Farewell; however, not all data layers cover Greenland waters, but have their focus in the North Sea or the Baltic, including the layer of *biological communities* displaying phytobenthos and -plankton and zoobenthos and -plankton only for these regions.

GBIP

The Global Biodiversity Information Facility (GBIF) is an international network and data infrastructure (https://www.gbif.org/) aimed at providing open access to data about all types of life on Earth. The platform aggregates data from numerous sources, including natural history collections, research institutions, and citizen science initiatives.

The user can search, download, and analyse data on species occurrences, distributions, and ecological interactions. Researchers can use GBIF data to study species distributions, community structures, and ecological dynamics. The repositories mainly hold data on terrestrial species, but also marine.

GBIF is the main international open portal for data on occurrences. Many of the data repositories below directly feed into or have been transferred to GBIF.



DATA ABOUT GREENLAND

681,876 Occurrences

1,011 Datasets

37 Countries and areas contribute data

328 Publishers

Data from GBIF can be retrieved through the *Occurrences* search platform, in scripting languages of R and Python, and through QGIS using a plugin.

OBIS and EUROBIS

The Ocean Biodiversity Information System (OBIS), and the European Ocean Biodiversity Information System (EurOBIS,) are online marine biology spatial database that compiles data on all living marine organisms. EurOBIS is the European node of the international Ocean Biodiversity Information System (OBIS), OBIS and EurOBIS focuses on publishing distribution data on marine species collected within European marine waters or by European researchers outside these waters. The taxons are matched with the World Register of Marine Species (WoRMS). The data is available through OBIS as an export in CSV format of the entire dataset, but also through other portals, particularly GBIF, and also through spatial web services. GBIF can be consulted for data stored or managed through OBIS and EurOBIS.

PANGAEA

PANGAEA - Data Publisher for Earth & Environmental Science is a digital data library and a data publisher for earth system science. Scientific data are Open Access and archived with related metadata through an editorial system. It is hosted by the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) and the MARUM – Center for Marine Environmental Sciences both in Germany.

The data repository holds data from scientific cruises, particularly from German vessels. A few include stations in Greenland waters. Data from PANGAEA is distributed online to GBIF.

A search in the data repository revealed the following records with samples located in Greenland waters.

Relevant data sets found in query:
Bergsten, Helene (1994): Benthic foraminifera of surface sediments in the Arctic Ocean [dataset publication series]. PANGAEA, https://doi.org/10.1594/PANGAEA.728640, Supplement to:
Bergsten, H (1994): Recent benthic foraminifera of a transect from the North Pole to the Yermak Plateau, eastern central Arctic Ocean. Marine Geology, 119(3-4), 251-267, https://doi.org/10.1016/0025-3227(94)90184-8
Zehnich, Marc (2020): Benthic and planktic foraminiferal records of sediment core PS93/025 [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.923845
Zehnich, Marc (2021): Benthic and planktic foraminiferal data of sediment core PS93/016 [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.939632
Seidenkrantz, Marit-Solveig**:** Benthic foraminifera measurements from sediment core HUD91/039-007BC and HUD91/039-008P. *PANGAEA*, https://doi.pangaea.de/10.1594/PANGAEA.785781

Critterbase (AWI)

Critterbase, developed by the Alfred Wegener Institute (AWI) and the Helmholtz Institute for Functional Marine Biodiversity (HIFMB), is an advanced ecological information system designed to manage and analyze sample-based biodiversity data. This open-source platform provides access data on marine biota. Data types include counts, abundances, and presence/absence records. Critterbase enables the study of species distribution, community composition, and ecological interactions on a global scale (Teschke et al., 2022). The data can be used to monitor changes in benthic ecosystems, assess the impacts of human activities, and develop conservation strategies. The content relays to published papers, and for North West and North East Atlantic, two papers are currently found building on sources from published and unpublished scientific cruise data sets. For the paper by Piepenburg et. al. (2011, unpublished data) was transferred to the Arctic Ocean Diversity (ArcOd) database and available through OBIS and GBIF, and the published often through PANGAEA. GBIF can thus be consulted for data mentioned in Critterbase.

Relevant data sets found in spatial query:
Roy, V., Iken, K., Archambault, P. (2014) Environmental Drivers of the Canadian Arctic Megabenthic Communities. PLOS ONE 9(7): e100900. https://doi.org/10.1371/journal.pone.0100900
Piepenburg, D., Archambault, P., Ambrose, W.G. *et al.* Towards a pan-Arctic inventory of the species diversity of the macro- and megabenthic fauna of the Arctic shelf seas. *Mar Biodiv* **41**, 51–70 (2011). https://doi.org/10.1007/s12526-010-0059-7

EMODnet

The European Marine Observation and Data Network (EMODnet) is a data platform initiated by the European Commission assembling data on the marine environment including metadata from sources within the European Union. Data is available without restriction, and the portal holds sub-portals with different themes, including the Biology Data Portal and Seabed Habitats Portal as of particular interest to environmental assessment of marine mining. The Biology Data Portal hold information on benthos, macroalgae, phytoplankton, zooplankton as well as marine mammals, birds and fish.

The coverage is mentioned to include the Arctic Ocean and North Atlantic Ocean. However, according to the EMODnet Map Viewer, this is only true for some datasets. The *EurOBIS database observations* coverage of occurrence data is displayed, and the full dataset can be downloaded in the open-source Apache Parquet file format used in Apache Hadoop, otherwise at EurOBIS. The data layers displayed under *Benthic invertebrate abundance and distribution* don't cover Greenland waters, and neither do other data layers within EMODnet Biology or EMODnet Seabed Habitats.

EMODnet Biology also draws from the World Register of Marine Species (WoRMS) and is supported by the EurOBIS data infrastructure. Data and metadata follow the EU INSPIRE directive on interoperability compliance including OGC webservices for use of data in GIS, and the FAIR principles.

EMODnet is currently of no use for information on the benthic or pelagic environment in Greenland waters, and GBIF should be consulted instead.

Arctic Ocean Diversity (ArcOD)

Arctic Ocean Biodiversity (http://www.arcodiv.org/) was a census of marine life in the Arctic Ocean and adjacent oceans performed in the 2000-2010's in relation to the International Polar Year. Existing and unpublished datasets were consolidated, often rescued or extracted with the majority of data points within the Russian and Alaskan waters, however also some around the North East Greenland Shelf. Data was transferred to OBIS, the Ocean Biodiversity Information System. The website of ArcOD is no longer updated, and the external data content referred to on the website is invalid. It is thus unnecessary to investigate ArcOD for further data.

MARINE MINING IN GREENLAND

A strategic assessment of potential impacts

Aarhus University, DCE - Danish Centre for Environment and Energy, and Greenland Institute of Natural Resources (GINR) have prepared a report on the potential impacts related to marine mining in Greenland with a special focus on West Greenland. The report provides a basis for environmental assessments and regulation for authorities. It summarizes existing knowledge and highlights knowledge gaps, especially for sensitive areas and species in West Greenland. The report concludes that marine mining could potentially have significant impacts on biodiversity and the marine environment, with effects depending on location, timing, operation size, and technology.

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