Little Giants: Utilisation of Calanus and krill

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Title	**Little Giants: Utilisation of Calanus and krill** Litlir risar: Nýting rauð- og ljósátu		
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Executive Summary:	This report explores potential utilisation of *Calanus finmarchicus* and krill in Nordic waters. Both are key zooplankton species that play vital ecological and economic roles in the marine ecosystems. The report therefore highlights their importance in supporting marine food webs, contributing to carbon sequestration, and offering potential applications in food production, pharmaceuticals, and aquaculture. The report identifies key challenges to sustainable harvesting, including ecological risks, technological constraints, and the need for regulatory oversight. It also highlights opportunities for innovation through technological advancements, market expansion, and regional collaboration among Nordic countries. Recommendations focus on fostering research and development, harmonising regulatory frameworks, and engaging stakeholders to ensure long-term sustainability. By addressing these aspects, the report aims to support informed decision-making and promote the development of Calanus and krill fisheries as part of a broader strategy for sustainable ocean resource management in the Nordic region. The report is an outcome of an AG fisk supported networking project aiming to facilitate networking and sharing of knowledge among different Nordic stakeholders on utilisation of Calanus and Krill. Much of the information presented in the report originates from a workshop held by the project, in Copenhagen on May 15th 2024. Further information is available on the project's webpage https://little-giants.net/		
English keywords:	*Zooplankton, Calanus finmarchicus, Krill*		

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1 Introduction

The sustainable management of marine resources is a cornerstone of economic and environmental policy in the Nordic region. This report investigates the untapped potential of *Calanus finmarchicus* and krill, two abundant yet underutilized zooplankton species with immense ecological and economic significance.

Calanus finmarchicus and krill are critical components of Nordic marine ecosystems, serving as essential food sources for key fish species, including herring, mackerel, and blue whiting. These zooplankton also play a pivotal role in the biological carbon pump, a natural mechanism that sequesters carbon dioxide from the atmosphere and stores it in the deep ocean. This dual role in supporting biodiversity and mitigating climate change highlights the importance of managing their utilization sustainably. Beyond their ecological value, these species present opportunities for innovation in fields such as food production, pharmaceuticals, and aquaculture. Their successful exploitation could diversify Nordic economies and solidify the region's position as a global leader in sustainable marine resource management.

However, harnessing the full potential of Calanus and krill requires addressing complex challenges related to ecology, technology, and regulation. The unique biological characteristics of these zooplankton demand specialized harvesting techniques and processing technologies to ensure their quality and minimize environmental impacts. For example, Calanus has high enzymatic activity that necessitates immediate processing after harvesting, posing logistical challenges. Moreover, the ecological role of these species as foundational elements of the marine food web underscores the need for precautionary management to avoid disrupting predator populations and overall ecosystem stability.

The Nordic countries, with their shared waters and strong commitment to sustainability, are uniquely equipped to pioneer the responsible development of Calanus and krill fisheries. The objectives of this report are to:

- Analyse the current understanding of the ecological and economic roles of Calanus and krill.
- Identify key challenges in sustainable harvesting, including technological limitations, ecological risks, and regulatory hurdles.
- Explore opportunities for innovation in harvesting technologies, processing methods, and market expansion.
- Recommend policies and research priorities that align with the Nordic Council's sustainability goals.

Additionally, the report emphasizes the importance of regional collaboration to harmonize regulatory frameworks and share best practices. Coordinated efforts between countries can leverage scientific advancements to establish effective quotas, reduce bycatch, and support adaptive management in response to climate change. As ocean temperatures rise and ecosystem dynamics shift, ensuring the resilience of Calanus and krill populations becomes increasingly critical.

Through regional collaboration and scientific advancement, the Nordic countries can establish a model for sustainable marine resource management. Such efforts would not only unlock the potential of Calanus and krill but also ensure the long-term preservation of marine ecosystems. By integrating environmental stewardship with economic innovation, this approach provides a path forward those benefits both the region and the global community.

2 The workshop

The workshop held on May 15, 2024, at the Best Western Plus, Kastrup Airport in Copenhagen, was a cornerstone event in advancing sustainable practices and collaboration on the utilization of *Calanus finmarchicus* and krill in the Nordic region. The event brought together an interdisciplinary group of stakeholders, including scientists, policymakers, industry representatives, and environmental advocates. The workshop's central purpose was to create a forum for open dialogue and knowledge exchange. Discussions focused on assessing the current state of Calanus and krill utilization, identifying challenges and opportunities, and laying the groundwork for future joint projects and policy initiatives. The workshop also served as a networking platform, fostering stronger relationships among Nordic countries and stakeholders with vested interests in the sustainable management of these marine resources.

Participants included representatives from prominent research institutions, such as Matís in Iceland and the Institute of Marine Research in Norway, as well as industry leaders like Calanus AS. These participants shared valuable insights into ongoing trials, technological innovations, and regulatory frameworks already in place or under development. The multidisciplinary composition of the attendees ensured that ecological, technological, economic, and policy perspectives were thoroughly explored.

Key themes of the workshop included the ecological importance of Calanus and krill, their role in the marine food web, and their contributions to carbon sequestration through the biological pump. The participants also addressed the challenges associated with harvesting these species sustainably, such as bycatch issues, technological constraints, and the impacts of climate change on population dynamics. Presentations and discussions highlighted advancements in selective fishing gear and onboard processing technologies, which are essential for minimizing environmental impacts while optimizing efficiency.

The outcomes of the workshop were significant. It provided a clearer understanding of the priorities for research and development, including the need for more precise biomass assessments, enhanced monitoring programs, and in-depth studies of ecosystem impacts. Moreover, the event underscored the importance of harmonizing regulatory approaches across the Nordic region to ensure consistency and sustainability in Calanus and krill fisheries. Participants expressed a collective commitment to pursuing collaborative projects under frameworks such as Horizon Europe and Nordic Innovation's Sustainable Ocean Economy initiatives.

This workshop marked a vital step forward in building a unified strategy for the sustainable exploitation of Calanus and krill. The discussions and partnerships forged during this event will undoubtedly shape the future of these fisheries, fostering innovation and ecological stewardship across the Nordic region.

The consortium around the project itself was made up of two groups i.e. core partners that were responsible for the project's implementation, and associated partners that were invited to the conference and will present/represent on behalf of their country/company/institution.

Partners:
1. Matís ohf. – Stefán Þór Eysteinsson (Iceland)
2. University of Iceland – María Guðjónsdóttir (Iceland)
3. Calanus AS / Zooka – Siv-Katrin Ramskjell (Norway)
4. IMR – Ole Tomas Albert (Norway)
5. DTU – Sigrún Jónasdóttir (Denmark)

Associated partners:
1. SVN – Sindri Sigurðsson (Iceland)
2. Rauðátan ehf – Hörður Baldvinsson (Iceland)
3. MFRI - Hildur Pétursdóttir (Iceland)
4. Nofima – Inger Beate Standal (Norway)
5. Aker Biomarine - Shauna Cecilia McNeill (Norway)
6. Havstovan - Eilif Gaard (Faroe Islands)
7. Sjokovin – Unn Laksá (Faroe Islands)
8. Naturinstituttet - Klaus Nygaard (Greenlandi)

Zooka – Calanus AS and Aker Biomarine are companies that are already at various stages of commercial utilisation of Calanus & Krill. The former opened last year a Calanus processing plant in Norway and has been operating three large freezer-trawlers for the fishery. They have also been developing the fishing gear and on-board handling.

The Faroese have been trying out commercial fisheries for Calanus and trials have started as well in Iceland. Trial fishery around Westmann Islands were conducted in May 2024, using a vessel from the Icelandic Marine and Freshwater Research Institute (MFRI), Bjarni Sæmundsson, and fishing gear from Zooka – Calanus AS. Similar story is to tell about krill fisheries, where Aker BioMarin have paved the way with over a decade of R&I. However mostly in Antarctica. Trials with Krill fisheries in Nordic waters have been taking place, with variable success.

It is worth noting that AG fisk supported a project in 2016/17 that has successfully contributed to Nordic collaboration on R&I in utilisation of *Calanus finmarchicus*. There are currently ongoing national and international projects that were created through the networks established in the AG fisk project. This project followed a similar approach, where the future impact is highlighted.

The workshop programme can bee seen below and all presentations are available the project website https://little-giants.net/.

Programme

The Utilization of Calanus and Krill

09:00	**Welcoming address**	**AG-Fisk**
09:20	Catch efficiency and technology	Ole Petter Pedersen, Zooka
09:40	Harvesting zooplankton – Experiences from Iceland	Ástþór Gíslason, Marine and Freshwater Research Institute
10:00	Ecological importance of Calanus in Faroese waters and potential for sustainable harvesting	Eilif Gaard, Faroese Marine Research Institute
10:20	Calanus finmarchicus vertical distribution: hotspots detection and model representation	Eva Chamorro Garrido, Arctic University of Norway
10:40	**Coffee break**	
11:10	Ecology and Importance of west Greenland Calanus populations	Torkel Gissel Nielsen, National Institute of Aquatic Resources
11:30	Fishing down the food web	Andre Visser, National Institute of Aquatic Resources
11:50	Alternative methods for utilizing zooplankton	Stefán Þór Eysteinsson, Matís Food and Biotech R&D
12:10	Legislation and catching regulations	Jón Þrándur Stefánsson, Icelandic Food ministry
12:30	**Lunch**	
	Group and panel discussion	
13:20	Introduction before discussion	Stefán Þór Eysteinsson, Matís Food and Biotech R&D
13:40	Group discussions	
16:10	Presentation of group work and wrap up	Representative from each group
17:00	**End of workshop**	

3 Current knowledge and practices

Calanus finmarchicus and krill occupy a central role in Nordic marine ecosystems, serving as foundational species in the food web. These zooplankton are primary prey for a variety of fish species, including herring, mackerel, and blue whiting, which are themselves critical to commercial fisheries. The abundance and health of Calanus and krill populations directly influence the survival rates and recruitment success of these fish, highlighting their ecological importance.

3.1 The role of and significance of Calanus in the ecosystem

Beyond their role in marine food webs, Calanus and krill contribute to the biological carbon pump. By migrating vertically and producing fast-sinking detritus, they facilitate the transfer of carbon from surface waters to the ocean's depths. This process plays a significant role in carbon sequestration, underscoring their relevance in global efforts to mitigate climate change. As such, any considerations of their exploitation must account for their contribution to maintaining ecological balance and climate regulation.

The biggest deployment challenges in utilising *Calanus finmarchicus* is if the commercial harvesting can be sustainable, profitable and with social acceptance. In addressing these challenges, several key points emerged from during the workshop discussions, such as:

- **Impact on Existing Fish Populations**: Many fish populations are currently either fully exploited or over-exploited. Introducing a new fishing target further down the food web, such as *Calanus finmarchicus*, could have significant repercussions. Harvesting this copepod, which serves as a crucial food source for various marine species, might exacerbate the pressure on already vulnerable fish populations. It's essential to thoroughly assess how removing Calanus could ripple through the ecosystem, potentially affecting the survival and reproduction of species that rely on it for nutrition.
- **Understanding Natural Processes:** A comprehensive understanding of the natural processes governing Calanus populations is vital. This includes studying their life cycles, reproductive rates, and population dynamics. Without this knowledge, it is challenging to set sustainable harvest limits. Detailed ecological models and long-term monitoring programs are necessary to predict how Calanus stocks might respond to fishing pressure and to ensure that harvesting practices do not lead to their decline.

By considering these factors, the feasibility and sustainability of harvesting *Calanus finmarchicus* can be better evaluated. It requires a multidisciplinary approach, combining ecological research, climate science, and fisheries management to create a balanced and informed strategy.

Expanding on the discussion surrounding the sustainability and feasibility of harvesting *Calanus finmarchicus*, the following items need to be considered such economic viability and market demand, social acceptance and stakeholder engagement, regulatory and legal frameworks as well as climate change impacts.

By addressing these additional considerations, policymakers, scientists, and stakeholders can work towards a more comprehensive understanding of the sustainability and feasibility of harvesting *Calanus finmarchicus*. This holistic approach encompasses ecological, climatological, and fisheries management perspectives to ensure the responsible utilization of this marine resource. A key issue in the development of sustainable fisheries of Calanus is the knowledge and predictability of the ocean ecosystem dynamics. An assessment of biomass through modelling and interconnectedness within the marine ecosystem – impact of fisheries and other environmental factors. Figure 1 shows some of the natural processes that Calanus serves and the effect it has on other marine species.

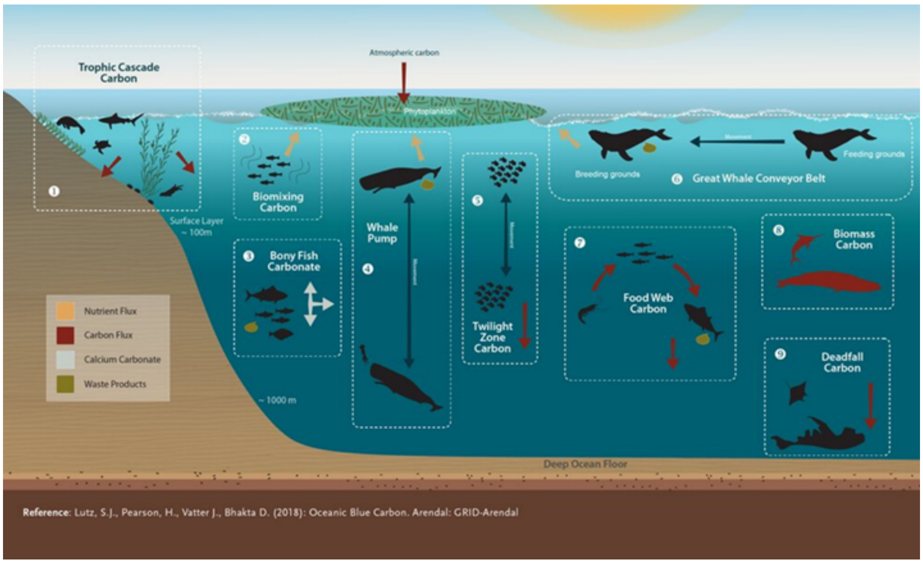

Figure 1: The natural process of Calanus and the effect on other species

The questions that need to be asked are if knowledge is sufficient to estimate the biomass of Calanus and if the joint surveys are accurate enough? and, what effect will considerable fishing of Calanus have on fish populations further down the food web, which many are already fully or over-exploited? It is necessary to understand the natural processes and their effect on other fish stocks. Also, effects of changes due to climate change, such as change in ice coverage, nutrition composition and how that effects the blooms (e.g., timing and intensity).

There is a need to consider seasonal migration and a period coming up where there is a shifting in production patterns and different type of blooms, or more protracted blooms. Data collected by ICES in the Norwegian Sea during at least two surveys (many ships) were essential to estimate the predation of the Calanus. Climate change poses additional uncertainties. Changes in ice coverage, water temperature, and nutrient availability can significantly impact Calanus populations and their primary food source, phytoplankton. For instance, alterations in ice coverage could shift the timing and extent of phytoplankton blooms, which are crucial for Calanus nutrition. Understanding these climate-driven changes is crucial for predicting future stock levels and implementing adaptive management strategies to ensure sustainability.

There is anticipation of a period characterized by shifting production patterns in marine ecosystems. This shift may entail changes in the types and durations of phytoplankton blooms, potentially impacting the availability of food resources for *Calanus finmarchicus*. Understanding these shifts is crucial for predicting how Calanus populations may respond and for devising adaptive management strategies.

Accurately estimating the biomass of *Calanus finmarchicus* requires a thorough understanding of its predation dynamics. Predation rates by various marine organisms directly influence Calanus population levels. Utilizing existing data and establishing comprehensive monitoring programs are essential steps in developing representative models for Calanus biomass. However, careful consideration must be given to the accuracy of these estimates, as uncertainties in predation rates and other ecological parameters can impact the reliability of biomass assessments.

Monitoring and Impact Assessment with continuous monitoring of Calanus harvesting activities is imperative for evaluating their impact on standing stocks. Monitoring programs should track changes in Calanus abundance, population structure, and ecosystem dynamics over time. This data is crucial for assessing the sustainability of harvesting practices and making informed management decisions to ensure the long-term health of marine ecosystems. There is a need for ecosystem knowledge and predictability of ocean ecosystem dynamics using assessment of biomass through modelling. Using interconnectedness within the marine ecosystem and impact of fisheries and other environmental factors. The question remains; do we know enough?

Blue carbon is considered as all carbon sequestered in ocean reservoirs (coastal, pelagic ocean, benthic communities, and marine sediments) that derives from biological production. That included particulate and dissolved organic carbon (living and dead), respired carbon and mineral carbonates. Sequestered carbon is considered as captured carbon from the atmospheric carbon dioxide (CO2) that is stored in a stable, long-term reservoir in the earth system. Zooplankton play an important role in this carbon pump, as shown in Figure 2

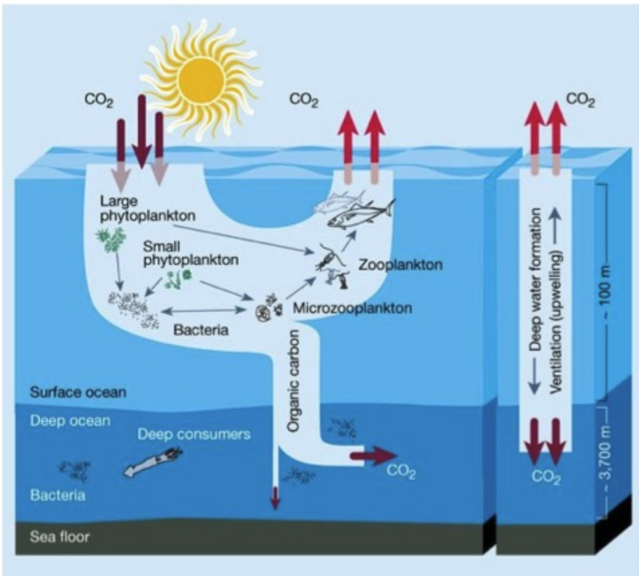

Figure 2: Biological Carbon Pump

Sequestration contribution is around 3 to 5 Pg C each (population & areal extent) with a time scale around 550 years each.

The value of krill faecal pellets is not as an offset to carbon emissions, but rather in maintaining legacy carbon reservoirs in the oceans. A 10% loss in krill biomass due to exploitation would result in net emissions 2MtC/year which would incur a cost of 400 to 4.000 million $USD per year.

Vertically migrating species (squid, mesopelagic, Calanus) or those that generate fast sinking detritus (krill) play a disproportionately large role in sequestering carbon through the Biological Carbon Pump, as shown in Figure 3. Harvesting these species will invariably incur a cost through the emission of legacy carbon back to the atmosphere. Sustainability of the industry must account for these costs.

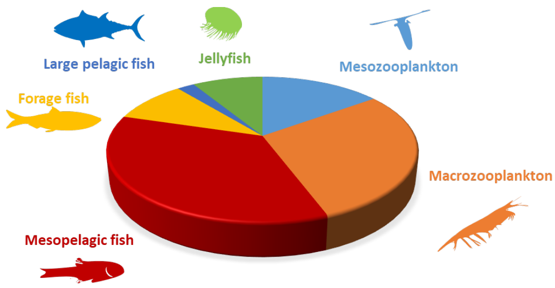

Figure 3: Vertically migrating species.

The ecological importance of west Greenland of the Sea Ice Cover and Primary Production for the Calanus populations is substantial. The loss of ice cover in certain regions raises questions about its potential impact on primary production. Ice cover influences nutrient availability and light penetration, both of which are critical for phytoplankton growth. Therefore, changes in ice cover could disrupt the timing and extent of phytoplankton blooms, ultimately affecting the food availability for Calanus. Examining the relationship between ice cover loss and primary production is essential for assessing the sustainability of harvesting Calanus. Disko bay is the southern border of Sea Ice, around 30 % of the Greenlandic population lives in the Bay area and it is a very important fishing and hunting area. Figure 4 show important marine species in Greenlandic waters, where Calanus plays a vital role.

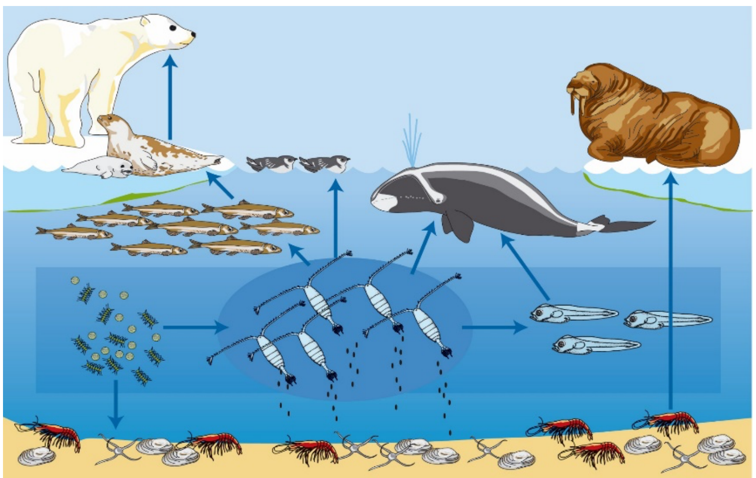

Figure 4: Important species in Greenland waters

In a warmer future, the primary production of the spring bloom will be initiated by the light rather than the ice-break up and the productive season will be longer with total primary production increased. The fate of the primary production will depend on the timing of the *Calanus* migration from the overwintering depths top to surface layers where they exploit spring bloom.

3.2 Harvesting of Calanus and Krill

Harvesting of *Calanus finmarchicus* and krill remains in its early stages, with ongoing efforts to develop efficient and sustainable methods. Norway has been at the forefront, implementing a quota system informed by stock assessments. Fisheries in Iceland and the Faroe Islands are in experimental phases, conducting trials to refine harvesting technologies and assess the feasibility of commercial operations.

Current harvesting methods for Calanus include the use of specialized trawls designed to operate within the upper layers of the water column. These systems incorporate continuous pumping mechanisms to reduce handling time and maintain product quality. Similarly, krill fisheries utilize advanced trawl nets and onboard processing to minimize degradation of the catch, which is essential given the high enzymatic activity of these zooplankton.

Despite these advancements, challenges remain. Issues such as bycatch, processing logistics, and the need for immediate freezing or stabilization of the catch require further technological innovation. The development of selective fishing gear and optimized onboard processing systems is a priority to ensure both efficiency and sustainability.

The sustainability and feasibility of utilizing Calanus will be the main challenge in the future, using current state of knowledge and future research. The major challenges and key issues facing Calanus fisheries currently is lack of ecosystem knowledge and predictability of ocean ecosystem dynamics.

There is a need for assessment of biomass through modelling and interconnectedness within the marine ecosystem, and what impact of fisheries other environmental factors will be. More knowledge is needed.

The question whether Calanus fisheries will be feasible remains unanswered. The government's role and responsibilities to ensure sustainable utilization will be of outmost importance, and to determine the role of regulatory authorities in establishing new fisheries. Stakeholder engagement from all those effected will be necessary, and it will as well be pivotal to ensure public acceptance if such fishery is to prevail.

In exploring the feasibility of *Calanus* fisheries, the following key points have been identified:

- **Efficiency in Harvesting Operations:** Implementing continuous pumping systems on trawling vessels can significantly enhance the efficiency of Calanus harvesting. This method allows for the seamless transfer of catch from trawls to the ship, minimizing handling time and preserving the quality of the harvested copepods. Improving harvesting techniques is essential for optimizing yield while minimizing environmental impact.

- **Leveraging Experience and Knowledge:** The lack of experience in Calanus harvesting poses challenges to achieving efficiency in operations. It is crucial to leverage the expertise gained from successful harvesting endeavours in Norway and apply this knowledge to build and strengthen the industry in regions such as the Faroes and Iceland. Collaboration and knowledge-sharing between stakeholders can expedite the development of sustainable harvesting practices.
- **Reforming Licensing Systems:** The current licensing system for Calanus harvesting in Norway may require re-evaluation and reform. Adjustments may be necessary to ensure equitable access to fishing grounds and to address emerging challenges in the industry. Streamlining the licensing process and implementing effective management measures can promote the long-term viability of Calanus fisheries.
- **Processing Challenges and Product Diversification:** The perishability of raw Calanus material underscores the importance of developing efficient processing methods. Diversifying final products, whether for human consumption or feed purposes, necessitates careful consideration of processing techniques. Tailoring processing methods to the intended end use of Calanus products can maximize value and market potential.

By addressing these considerations, stakeholders can work towards establishing sustainable and economically viable Calanus fisheries. Emphasizing innovation, collaboration, and adaptive management practices is essential for realizing the full potential of this valuable marine resource.

There are controversary surrounding the catching of Calanus and a need for a cautionary approach which is guided by scientific advice. This is a slow approach and by-catching of fish larvae could be a major concern. The economic feasibility is also a concern with low price for the raw material and an ethical component with a need for DHA and EPA in developing countries.

Calanus is an important feed for herring, mackerel, blue whiting, and many other species. Feeding activity is higher in areas with higher abundance of food and it is difficult to say how much dies unused. More research and knowledge are therefore needed.

An industrial value-chain has been developed and established based on Calanus. The value chain embodies harvesting, production, certifications, marketing, and sales: B2C and B2B. Calanus AS has in the last 10 years developed fishing gear and pre-production lines on board the fishing vessels. Calanus has high enzymatic activity resulting in a rapid degradation of the raw material and must be frozen within few hours after catching. The company uses a twin trawl technology within surface depth of 0-15 meters, with overlapping, non-load-absorbing plankton nets on the inside, as shown in Figure 5. The trawling speed is approx. one knot and normally a trawls haul lasts for 5-12 hours. This is based on experience and acoustic integration.

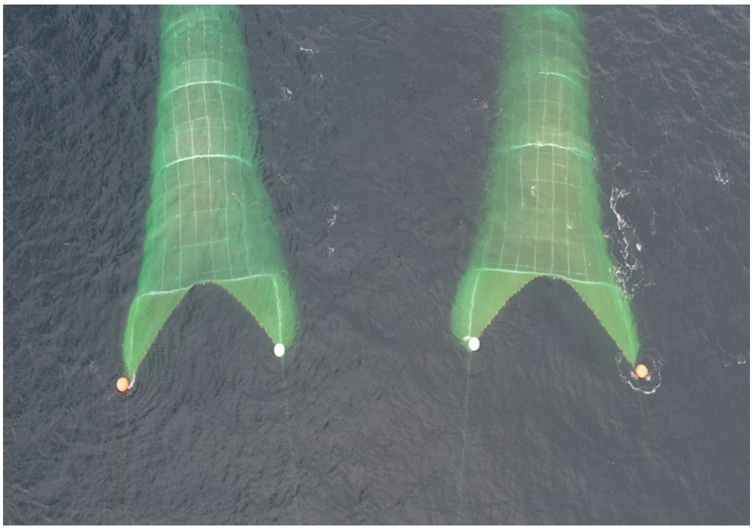

Figure 5: Twin trawl fishing gear for Calanus.

The maximum catch is around 15 tons per haul and total catch is maximum around 1.400 tons per year. In 2023 the catch was only 60 tons and zero in 2024. The catch rate has increased during the years and is now around 640 – 890 kg/hour. The rate is however highly dependent on several independent factors. The Calanus fishery in Norway started in 2006 and has progressed since then as shown in Figure 6.

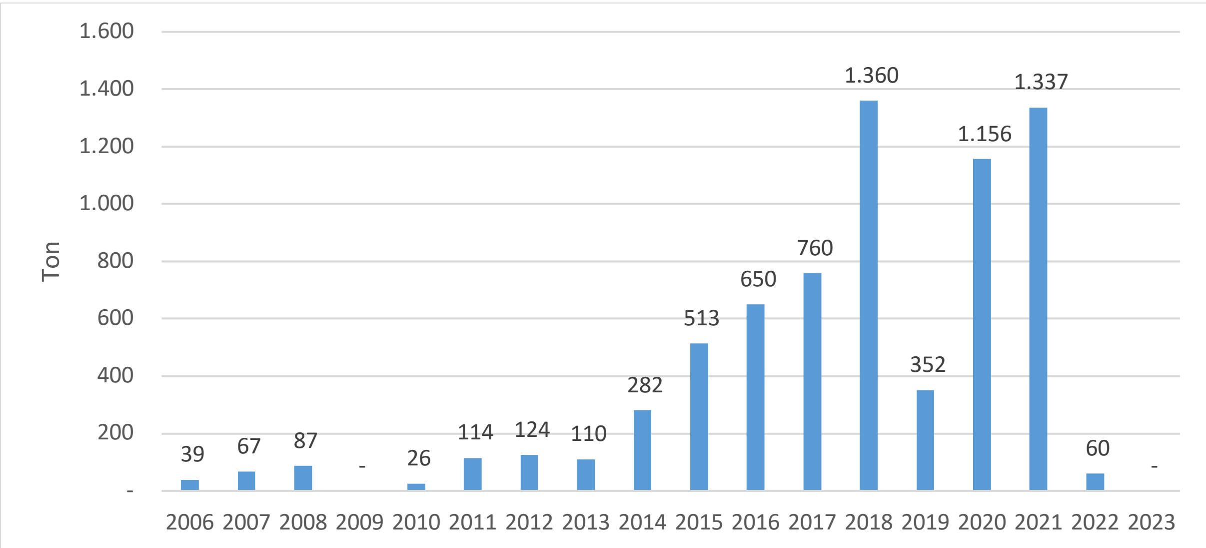

Figure 6: Development of catch volumes by year in Norway

Another important question to answer is how much *Calanus* is there in reality in the surface layer of 0-15 meters, independent of towing time and size of trawl opening? The assumption is that towing speed of one knot, the vessel is moving 0.51 meters forward (SpeedThroughWater), with a trawl opening at 2 x 8 x 16 m^2, equal to 256 m^2. Therefore, in one second 256 x 0.51 m^3 = 130.56 m^3 is filtered. (In T seconds: T x 130.56 m^3 is filtered). The weight of one *Calanus* is around 1 mg (1000 organisms per gram raw feed). Example from a random trawl haul from one of the vessels harvesting: In 8h15min of towing, 29.700 seconds the water filtration is 3,877,632 $m^{3\ \text{with}}$ catch of 8.900 kg = 8900 x1000 x 1000 = 8,900,000,000 *Calanus.* Number pr m^3 = 8,900,000,000 / 3,877,632 = **2,295 *Calanus* / m^3 = 2,295 g /**

m³. It needs to be noted that this is a calculation example, and that this number will differ between trawl hauls. The advantage with this norm-number is that it can be used directly in comparison to scientific investigations and model-runs, meaning that for the first time we are able to take numbers from scientific investigations and relate them to a commercial harvesting context.

When *Calanus* is harvested, 16% of the raw material is produced into a liquid protein concentrate that is used as animal nutrition, e.g. as a functional ingredient in aquaculture feed. If the entire recommended quota of 3 million tons (In the Norwegian Management Plan for *Calanus finmarchicus*), it would give approximately 480,000 tonnes of liquid concentrate which again contains 33% protein. The fishery could therefore give 160,000 tonnes of pure marine protein. If this entire amount of protein is used for aquafeed with 2% inclusion of protein, the Calanus could be used to produce 8 million tonnes of feed. With 8% inclusion of protein, it would amount to 2 million tonnes of feed. If 50% of the salmon feed would consists of protein from *Calanus*, it would amount to approximately 320,000 tonnes of salmon feed, i.e. approx. 1/3 of the projected Norwegian aquaculture feed gap in 2030.

The technology of the future will call for detection and harvesting based *apriority* and external information sources (models, on-board UAVs, AUVs, Satellites, USVs, AI forecasting +). The purpose is to reduce search time and increase the effective harvesting time. The process onboard starts with vacuum pumping of the catch from the cod end of the trawl, passing through a foreign-object grader. Water is then separated from the catch. More water is then separated, until the catch looks like clay and then frozen in a plate-freezer. The production ashore is carried out where oil is separated, and then the rest, the protein, is processed into hydrolysate or a dry powder.

Calanus AS believes that future challenges include detection technology for avoiding bycatch. Onboard handling with new technology and increase knowhow for higher quality, based on different physical principles and R&D companies, and use of compressed air to create local upwelling zones. Figure 7 shows a new trawl design patented by Calanus AS that uses compressed air to “guide” Calanus into the trawl.

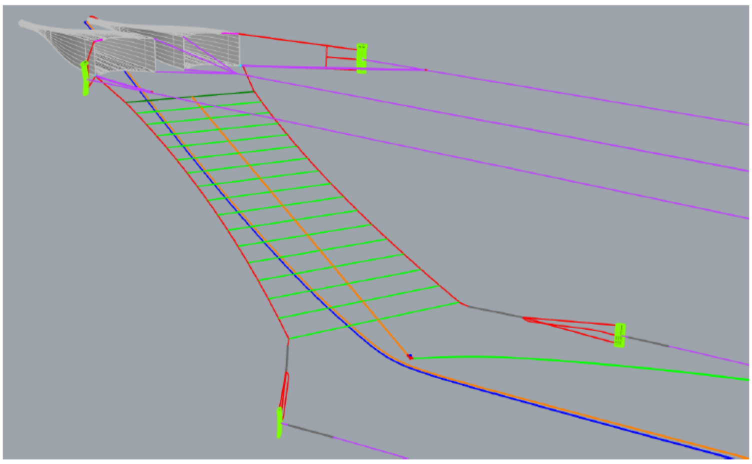

Figure 7: New idea of trawling gear for the future harvesting of Calanus

This is a fishery still in development stages, which requires researchers, private companies, authorities and other stakeholders to combine efforts to make meaningful advances.

Icelanders have been experimenting with harvesting and processing zooplankton for some years now. Widespread and detailed *Calanus* exploratory survey was carried out around Iceland in 2012, which concluded that "*Results indicate that during the first half of June the densities of C. finmarchicus are sufficiently high for commercial harvesting in several areas south of Iceland, especially near the shelf breaks. There are indications that the latter half of June and early July may be more favourable time for harvesting, as C. finmarchicus may have accumulated more fat and astaxanthin. The westernmost regions were characterized by a massive phytoplankton bloom that had wide coverage and that hampered harvesting Calanus*" (Gíslason, Karlsson, Tande, & Jóakimsson, 2021). Earlier research had shown that the abundance of Calanus is greatest along the south coasts, reaching up to 100,000-140,000 per m^3 during the summer months, as shown in Figure 8 (Gíslason, 2000).

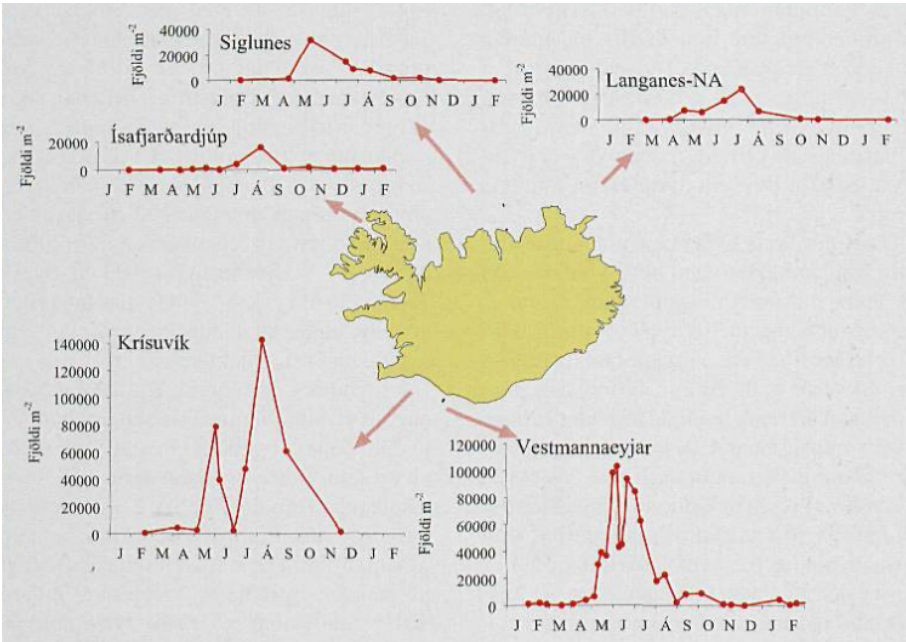

Figure 8: Research have shown that the abundance of Calanus around Iceland is by far the greatest along the southern coast

The abundance and utilisation opportunities of Krill have as well been explored around Iceland. A trial was done in Ísafjarðardjúp 2011 and 2012 focusing on harvesting of krill, with five cruises from August 2011 to August 2012. Fishing gear, fishing areas and depth was tested as well as biology and chemical composition of krill was measured. The highest densities were in the middle trough, under 100 meters. Average annual krill biomass of ~40 thousand tones was estimated and ~60 thousand tons of production. August and September were the best moths for the fisheries, considering lipid and protein content, and with bycatch at a minimum. Best time for fishing were at daytime when the krill aggregates in dense layers relatively deep.

The gear used was krill trawl, Tor-Net of 8 mm mesh size in whole trawl opening of 16 m^2. The total catch was from, 104 kg/hour up to 348 kg/hour. There were some experiments of processing the catch by drying.

Exploratory fishery of Krill in Ísafjarðardjúp using a pumping system, attracting the Krill with lights, was conducted in 2018. Permission was granted for a limited time, first for three weeks, and later extended to two months. Observer was requested to be onboard for the whole time. Two experiments were conducted in July and September/October 2018. The catch was processed onboard into meal and oil with the total catch around 17 tonnes. Krill surveys were as well conducted in Steingrímsfjörður in 2021 and 2022, with six cruises, with similar methodology and results as in Ísafjarðardjúp.

Average annual biomass of Zooplankton within Icelandic 200-mile Exclusive Economic Zone is believed to account for more than half of the total biomass of all groups in the ecosystem, and production of zooplankton far exceeds that of other groups (>80%) (Astthorsson, Gislason, & Jonsson, 2007). The main groups that have the potential of being harvested in Icelandic waters are *Calanus* species and Krill. Astthorsson et al. (2007) estimated the available biomass and annual production, as shown in Table 1.

Table 1: Estimated biomass and annual production of Calanus and Krill

	Biomass WW (10^6 tonnes)	Production WW (10^6 tonnes)
Cfin	7	28
Chyp	2	3
Krill	5	7,5

Exploratory survey for *Calanus finmarchicus* (June 2012) designed to explore if Zooca-*Calanus* methodology could be used to catch *Calanus* in Icelandic waters. The main results include:

- *Calanus* is harvestable by the methods used by Zooca
- June and July most suitable for harvesting
- Biomass greatest on the shelves
- Most of the stock (>80%) in the upper 50 m
- Older stages (C4-6) generally dominate – spawning still on-going.
- By-catch (fish larvae) mainly nearest to the coast
- Importance of monitoring by-catch is emphasized.

Another company followed on Harðfrystihúsð Gunnvör attempts in 2022. This is the company Rauðátan ehf (e. Calanus ltd.), which among major shareholders include two big seafood companies located in Westman islands. The company has been granted a five-year research quota of 1,000 ton per year, and trial fisheries were conducted in the summer of 2024 using borrowed fishing gear from Calanus AS. The results were promising, as average catch rate was around 800 kg/hour and bycatch rates were very low. Following on these trials, which were largely overseen by MFRI, and other available data, the institute has now estimated the abundance of Calanus at 2.9 million tonnes and recommended a quota of 59 thousand tonnes.

Figure 9: Pictures from experimental fishing trials of Rauðátan ehf. in cooperation with MFRI by the south coast of Iceland in 2024. The fishing gear was borrowed from Calanus AS in Norway.

The MRI has monitored the distribution and abundance of krill annually in May for several years. Results indicate that krill is generally most abundant in the fjords, and over edges and clefts/valleys of the continental shelf. There are four main species:

- *M. norvegica* shelf edges
- *T. inermis*, shelf
- *T. longicaudata*, oceanic
- *T. raschi*, fjords

New harvesting technology is emerging, and other marine stocks are fully utilized leading to increased interest in harvesting zooplankton. Adoption of an Icelandic management plan for harvesting zooplankton is needed with precautionary approach. There is a need for better data on stock sizes, production, and trophic role. Also, how the zooplankton stocks would respond to fishery as well as how predators respond to fishery. Further, the issue how the by-catch will affect other stocks should be investigated. The question also is if fishing at lower trophic levels is bad, like fishing down the food web or should we aim at a "balanced" fishery? But balanced harvesting over a broad range of species, stocks and size groups would be more ecological correct than a focusing on a few large single fish stocks.

The Faroese Marine research institute and private companies have as well researched zooplankton and potential utilisation. Ecological importance of *Calanus finmarchicus* in Faroese waters is vital, but there are potentials for sustainable harvesting in the future. The main feeding area for large straddling stocks of blue whiting, mackerel and Norwegian spring spawning herring/Atlantic-Scandic herring is mainly north of the Faroe Islands and also in larger areas in the Norwegian Sea. Zooplankton (Calanus) biomass in the area north of the Faroe Islands in spring is variable and is influenced by variable strength of the East Icelandic current. Large quantities of Calanus spp. are advected southwards with this current and Faroese monitoring has shown that the zooplankton biomass co-fluctuates with the strength of this current. From start of the zooplankton monitoring and until 2003 the East Icelandic Current was strong and the biomasses of *C. finmarchicus* and *C. hyperboreus* were high. From 2003 to 2017 the current was weak causing reduced transport of Calanus from the north into the area north of the Faroe Islands. Since 2018 the East Icelandic current has been increasing causing increased transport of Calanus spp. from the north. Figure 10 shows the currents effecting Calanus distribution and abundance in the NE-Atlantic.

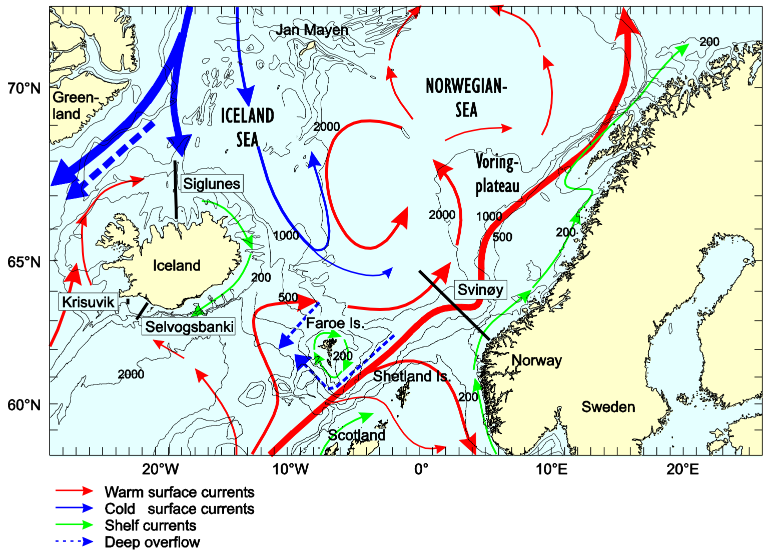

Figure 10: Currents affecting Zooplankton distribution and abundance in the NE-Atlantic

East of the Faroe Shelf, a persistent overflow of cold deep Norwegian Sea Water is entering the Faroe Shetland Channel, is transported southwards at depths > ~500 m through the Faroe-Shetland Channel and northwards through the deep part of the narrow Faroe Bank Channel. Calanus finmarchicus which during winter are hibernating in these depths in the southern Norwegian Sea, are caught by this current and are transported with the deep overflow through the channels. The Faroe Marine Research Institute is monitoring the deep overflow through the Faroe deep part of the Faroe Bank Channel. The volume transport is in average about 2.2 Sverdrup (106 m3/sec.). At the narrowest passage between the Faroe Bank and Faroe Shelf, the current speed increases to about 1 m/sec, as shown in Figure 11.

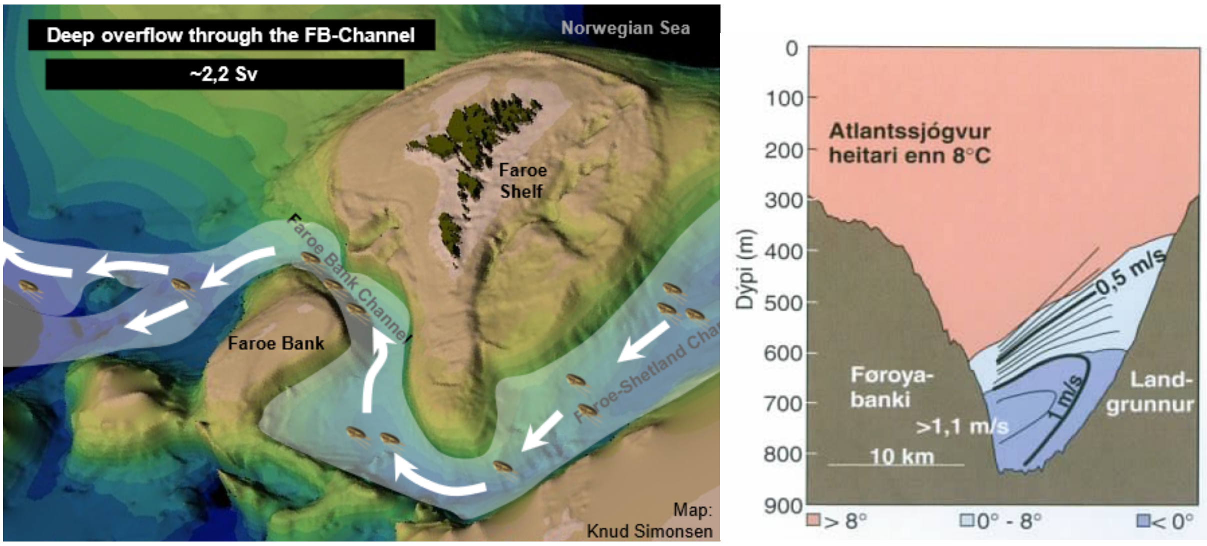

Figure 11: Deep overflow through the Faroe Bank Channel

The Faroe Marine Research has studied the potential for sustainable harvesting of the *Calanus*, that is advected the deep overflow through the Faroe Bank Channel during winter. The main results of that work are:

Estimated transport of overwintering *C. finmarchicus* through the Faroe Bank Channel:

- Abundance estimates (preliminary): ~ 130-280 indi/m^3
- Biomass (WW): ~ 130-280 mg/m^3
- Flow: ~ 2.2 mill. m^3/sek
- Estimated transport of *Calanus*:
  - Between ~25 000 and ~53 000 tonnes WW/day
  - Between ~ 3.7 mill. and ~8 mill tonnes WW/winter.

Potential harvesting of over-wintering *C. finmarchicus* in the Faroe Bank Channel overflow

- Horizontal flow of *Calanus*: ~ 0.5-1 kg/m^2 transect/hour.
- Test trawling's have confirmed this.
- Apparently too high costs of commercial trawling
- Next step: "Passive" gear, using the strong horizontal flow.

Future Research

- Further advection, dispersion, and mortality/survival of *C. finmarchicus* after leaving the Faroe Bank Channel during winter.

- Importance for potential predators during winter.
- Preliminary results indicate that after leaving the FBC.
  - most individuals are advected along the southern slope of the Faroe-Iceland Ridge.
  - An apparently smaller amount seems to be transported close to the seabed in southwestern direction.

There are currently five exploratory licenses valid in Faroe Islands, but activities have been little in the last few years.

4 Challenges and risks

Calanus finmarchicus and krill offer tremendous potentials as sustainable marine resources, but their exploitation is not without challenges. These challenges span ecological, technological, and regulatory domains, requiring a balanced and collaborative approach to address them effectively.

The ecological risks associated with harvesting zooplankton like Calanus and krill are significant due to their foundational role in marine food webs. As a primary food source for fish species such as herring, mackerel, and blue whiting, their removal could have cascading effects throughout the ecosystem. Predators dependent on these species, including fish, birds, and marine mammals, may experience reduced survival and reproductive success. Additionally, the role of Calanus and krill in the biological carbon pump highlights another critical risk. Overharvesting could disrupt carbon sequestration processes, resulting in increased carbon emissions and further exacerbating climate change.

Climate change adds another layer of complexity to these ecological risks. Warming ocean temperatures, changes in ice cover, and shifts in phytoplankton blooms—key food sources for Calanus and krill—could alter their population dynamics and distribution. Such changes may complicate stock assessments and the establishment of sustainable harvest quotas.

From a technological perspective, existing methods of harvesting Calanus and krill are still developing. Continuous pumping systems and selective trawls represent significant advancements, but bycatch remains a persistent issue. Fish larvae and other non-target species are often captured unintentionally, raising ecological and ethical concerns. Further innovation in fishing gear and processing systems is necessary to improve selectivity and efficiency.

Economic viability is another critical hurdle. The market for Calanus- and krill-derived products, such as omega-3 oils and aquaculture feed, is relatively small and underdeveloped. High operational costs, including the need for onboard freezing facilities, further challenge the profitability of these fisheries. Establishing a reliable market while maintaining ecological safeguards is essential for long-term success.

Public acceptance of Calanus and krill fisheries is still limited, partly due to concerns about ecological impacts and the ethical considerations of exploiting lower trophic levels. Transparent communication and educational campaigns will be necessary to build trust and understanding among stakeholders.

Regulatory frameworks also require significant attention. While Norway has established a quota system informed by stock assessments, other Nordic countries are still in the exploratory phase. Harmonizing regulations across the region will be critical for ensuring consistent and sustainable practices. This includes establishing quotas, monitoring bycatch, and enforcing compliance through robust oversight mechanisms.

Addressing these challenges requires a coordinated approach that integrates ecological research, technological innovation, economic analysis, and regulatory oversight. The Nordic region has the expertise and resources to develop a model for sustainable exploitation of Calanus and krill, but success will depend on collaboration and a commitment to balancing economic growth with environmental stewardship.

5 Future utilization of Calanus

The future of *Calanus finmarchicus* and krill fisheries presents significant opportunities for innovation, economic growth, and sustainability. These opportunities are grounded in advancements in technology, expanding markets, and collaborative regional efforts.

The development of advanced harvesting and processing technologies is key to realizing the potential of these zooplankton. Technological innovations, such as selective fishing gear, continuous pumping systems, and onboard processing methods, are already enhancing the efficiency and sustainability of operations. Emerging technologies, including artificial intelligence (AI) for resource detection, satellite-based monitoring, and autonomous underwater vehicles (AUVs), could further optimize harvesting practices while reducing environmental impacts.

The main challenge in future utilization of Calanus is limited knowledge, and lack of experience. The Norwegians are ahead of other nations in research and development in this fishing, and possibly that knowhow could be transferred to other countries, like Iceland and Faroe Islands.

Fishing and processing of Calanus is complicated, the catch must be pumped from the cod end of the trawl, which has enormous, small mesh. The product must be frozen within few hours, because of high enzyme content, so processing and freezing onboard is the only option.

This is an early-stage operation and will need government support in the beginning, financially and more input to research funds. Technological development is mostly funded by government grants and need to support companies in the development of new value chains.

Market development is another critical area of opportunity. Calanus and krill-derived products, such as omega-3 oils, protein concentrates, and functional ingredients for pharmaceuticals and cosmetics, have growing potential in global markets. Expanding consumer awareness of the nutritional and health benefits of these products can drive demand, especially as sustainability becomes a priority for consumers. Additionally, diversification into aquaculture feed and biotechnological applications can broaden the economic base of these fisheries.

Collaboration among Nordic countries provides a unique advantage in developing these fisheries sustainably. Joint efforts in research and development can accelerate technological advancements and foster best practices. Programs like Horizon Europe and Nordic Innovation's Sustainable Ocean Economy initiative offer platforms for coordinated action, funding, and knowledge exchange. Harmonizing regulatory frameworks across the region can ensure consistency in practices, promoting both ecological conservation and economic viability.

There is a need for research to collect more data for reliable future modelling etc, and the impact on the marine. This is crucial to get stakeholder acceptance as well as to control bycatch which has been decreasing but made up of 1,6% of the total catch. One problem with this is that fishermen do not want bycatch as it does not add value, with the risk of discharge.

Public engagement will play a crucial role in supporting the growth of this industry. Educational campaigns that emphasize the ecological and economic benefits of Calanus and krill harvesting can help build trust and acceptance among stakeholders. Transparency in operations, coupled with demonstrable sustainability practices, can strengthen public confidence.

In the long run for utilizing Calanus, social acceptance is needed and enlightenment to the public of the operation. People need to be educated, and the regulators and the stakeholders to make it a sustainable marine value chain. It must be licensing based fisheries and exploitation for the benefit of food production. There is a lack of competitive elements in this business. The basic premise is flawed because it is an unused resource. It is also a valuable component of the climate system and not yet industrialised. Also, the licenses were used as leverage to finance boats/companies and need for activity requirement to be included. Improving selective catching is important, to prevent by-catch, and looking into the utilization of side-streams.

6 Policy- and research recommendations

The successful development of Calanus and krill fisheries in the Nordic region depends on well-crafted policies and a robust research framework. These measures must balance ecological preservation with economic viability, ensuring long-term sustainability for the industry and the environment. A harmonized regulatory framework across the Nordic region is essential to establish consistent practices and standards. This framework should include:

- **Comprehensive Licensing Systems**: Regulations should specify the conditions for obtaining harvesting licenses, including quotas, seasonal restrictions, and observer requirements. Licensing systems must promote equitable access while ensuring strict compliance with sustainability guidelines.
- **Quota Management**: Quotas should be informed by accurate and up-to-date stock assessments. These assessments must account for the ecological role of Calanus and krill and

include precautionary buffers to mitigate uncertainties related to climate change and ecosystem dynamics.

- **Monitoring and Enforcement**: Effective monitoring systems are needed to track bycatch rates, compliance with regulations, and ecosystem impacts. Enforcement mechanisms, including penalties for violations, should be in place to maintain industry accountability.
- **Incentives for Innovation**: Governments should offer financial incentives to companies that adopt sustainable practices or invest in research and development. This could include grants for developing selective fishing gear or subsidies for eco-friendly processing methods.

Scientific research must underpin the development of policies and practices. Priority areas include:

- **Ecological Research**: Understanding the role of Calanus and krill in marine ecosystems is critical for assessing the potential impacts of harvesting. Studies should explore their trophic interactions, contributions to carbon sequestration, and resilience to environmental changes.
- **Stock Assessment and Monitoring**: Accurate methods for estimating biomass are essential to set sustainable quotas. This includes long-term monitoring programs to detect population trends and the effects of environmental factors, such as ocean warming and acidification.
- **Technological Innovation**: Research into advanced harvesting technologies, such as AI-driven resource detection and selective fishing gear, can minimize environmental impacts while improving efficiency. Onboard processing systems should also be optimized to preserve product quality and reduce waste.
- **Economic Feasibility Studies**: Research on market trends, consumer preferences, and cost-benefit analyses will help determine the economic viability of Calanus and krill fisheries. Exploring new applications for these species in pharmaceuticals, cosmetics, and functional foods can expand market opportunities.
- **Climate Change Adaptation**: Predictive models that assess the effects of changing ocean conditions on Calanus and krill populations are essential for adaptive management. These models should guide future policies and industry practices.

Regional collaboration is a cornerstone of effective policy and research initiatives. The Nordic countries should continue to leverage platforms such as Horizon Europe and Nordic Innovation to pool resources and expertise. Joint research projects can address common challenges, such as bycatch reduction and ecosystem modelling, while fostering innovation in sustainable practices.

Building public trust and support is vital for the long-term success of Calanus and krill fisheries. Transparent communication about the ecological and economic benefits of these resources can enhance public acceptance. Educational campaigns should highlight their role in addressing global challenges, such as food security and climate change.

7 Conclusions

The sustainable exploitation of Calanus finmarchicus and krill offers a transformative opportunity for the Nordic region to address pressing ecological, economic, and social challenges. These species, central to marine food webs and critical for carbon sequestration, have the potential to drive innovation in aquaculture, pharmaceuticals, and other industries while contributing to global climate solutions.

This report has highlighted the significant role that Calanus and krill play in marine ecosystems and outlined the challenges that must be addressed to ensure their sustainable utilization. From advancing harvesting technologies and mitigating ecological risks to expanding markets and harmonizing regulatory frameworks, the path forward requires a coordinated and multidisciplinary effort. The Nordic region, with its rich marine resources and commitment to sustainability, is uniquely positioned to lead by example.

Key recommendations include fostering regional collaboration to standardize practices and regulations, investing in research and development to fill critical knowledge gaps, and engaging the public to build trust and acceptance. By integrating science, policy, and industry expertise, stakeholders can unlock the full potential of these resources while safeguarding marine ecosystems for future generations.

The successful development of Calanus and krill fisheries will require a shared commitment to innovation and ecological stewardship. As the Nordic countries continue to prioritize sustainability and cooperation, they can set a global standard for responsible marine resource management, demonstrating how economic growth and environmental preservation can go hand in hand.

8 Acknowledgements

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