SUSTAINABLE AQUACULTURE 2030

BELLONA

POSITION STATEMENT

Measures for the aquaculture industry towards 2030

The environmental foundation Bellona's vision is a carbon-negative society with restorative growth. The foundation aims to work towards increased ecological understanding and protection of nature, the environment, and health by initiating measures that promote this purpose. Bellona's approach is technology- and solution orientated and based on systems thinking. We collaborate with businesses, academia, and other public and private institutions on public benefit measures with a significant, positive impact on the climate and environment. Founded in 1986, Bellona now employs more than 70 engineers, biologists, physicists, chemists, economists, political scientists, and journalists with offices in Oslo, Brussels, Berlin, and Vilnius. Guaranteed independence of the organization's work at all times is of vital importance to Bellona, and we, therefore, do not enter agreements based on exclusivity or market individual stakeholders.

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Content

Bellona’s motivation for working with aquaculture

To prevent global warming of more than 1.5°C, the world will have to achieve net zero emissions of greenhouse gases by 2050. Cutting emissions must happen simultaneously, with the development of our food production systems, which will need to supply food to around 9.7 billion people. Estimates of increased food production vary, ranging between 25 and 70% [1]which will put heavy pressure on the world’s already depleting bioresources. Today's food production accounts for 80% deforestation, 70% freshwater use, and is the single largest cause of biodiversity loss on land [2]. Furthermore, the world ‘s current food production system accounts for one-third of total global man-made greenhouse gas emissions [3].

In 2021, the European Commission Knowledge Center for Bioeconomy and DG Research & Innovation published four scenarios for Europe's bioeconomy towards 2050 [4]. One of these scenarios,” Scenario 2- Do it Together”, meets the goals of the Paris Agreement, in large part, due to the statement that agricultural emissions must be reduced by 80%. Agricultural land area has not expanded significantly, compared to 2020, while at the same time, we have achieved a massive increase in protected natural areas. The demand for biomass to make bio-based products is predicted to increase significantly in the coming years. In Scenario 2, it is proposed that production from aquaculture should increase by 15% before 2030 and 25% before 2050, compared to 2020 production levels. In a report on the availability and need for future bioresources[5], the Energy Transitions Commission (ETC) concludes that: “*Potential needs far exceed sustainable supply. If left unchecked, these trends will increase the risk of unsustainable management of bioresources, including deforestation, biodiversity loss, and soil depletion”*.

One of the greatest challenges the world will face will be meeting the rising demand for food, while simultaneously halting further ecosystem destruction, making substantial cuts in greenhouse gas emissions, and securing sufficient sustainable biomass, as we transition from a fossil-based to a bio-based economy.

Since 1961, the annual global growth in fish consumption has been twice as high (3.2%) as the human population growth (1.6%) [6]. The United Nations Food and Agriculture Organization assumes no significant potential for further expansion of the wild catch fishing industry. Sea-based aquaculture - sea farming - is often referred to as an industry capable of being developed, scaled, intensified, and diversified, meeting the principles of modern agricultural practices. In principle, large areas in the sea are available for aquaculture, and sea-based production saves land area and spares freshwater resources. Additionally, many marine species can be farmed with high efficiency. Sustainable food and biomass from the sea, must therefore be a significant part of the solution in how we shape future food production and further develop a circular and resource-efficient Norwegian bioeconomy. The aquaculture industry should have a central role in the green transition that Norway is going through, and many systems are already in place for increased, efficient, and climate-smart production in the sea. But even with a solid base to build upon, there are still significant challenges to overcome for Norwegian aquaculture to be able to realize these opportunities.

In Norway, aquaculture mainly consists of salmon production, which accounts for 94.6% of total production [7]. Norwegian farmed salmon cannot solve the world's need for food, but the Norwegian aquaculture industry can play an important role, globally. It can do so by developing knowledge, production methods, and technological solutions that lead the way in reducing the carbon footprint and counteracting negative impacts on the ecosystem. At the same time, the Norwegian aquaculture industry has a unique opportunity to drive sustainable growth by scaling up low-trophic aquaculture—the farming of species lower on the food chain. For several decades, Bellona has been a central driving force of the Norwegian aquaculture industry toward a more sustainable direction. Going toward 2030, the Bellona Environmental Foundation will secure its position as a leading force in the sustainable advancement of the aquaculture industry, focusing on 3 key challenges and opportunities:

- Reducing the carbon footprint from salmon farming
- Reducing the environmental impact from salmon farming
- Up-scaling of low-trophic aquaculture

1. Reducing the carbon footprint from salmon farming

In the Norwegian media, headlines can range from "*Eat salmon - be climate-friendly*" to "*Norwegian salmon farming is a climate bomb*". The truth is that the carbon footprint of farmed salmon can be highly variable. Served on a Norwegian dinner table, farmed salmon can have a CO_2 footprint of 4.8 kg CO_2 per kg [8]. In this case, it has a carbon footprint that is slightly higher than chicken. If the same amount of salmon is instead flown to and served on a dinner table in South Korea, the carbon footprint is over 27 kg of CO_2 per kg, which makes it far less climate friendly.

For farmed salmon not transported via airfreight, an average of 75% of the carbon footprint is attributed to the production and transport of salmon feed [8]. Therefore, it is essential to develop new, more sustainable sources of raw materials for salmon feed in order to reduce the carbon footprint and future-proof Norwegian farmed salmon.

If we are to reach the goal of limiting global warming to 1.5 °C, total greenhouse gas emissions must be cut by 50-55% by 2030 and be close to zero by 2050 [9]. All industries that want to play an important role in tomorrow's marketplace must therefore cut their greenhouse gas emissions significantly towards 2030. A Norwegian aquaculture industry with big ambitions for production growth must subsequently be equally ambitious when cutting greenhouse gas emissions towards 2030. It is a prerequisite, for further development, that the industry takes total responsibility for the carbon footprint of its products, from feed components to production and transport to market.

2030 Vision:

A 55 % reduction of the carbon footprint from Norwegian aquaculture compared to 2020.

Key measures:

- 55 % reduction of the carbon footprint will require the implementation of a comprehensive set of measures, as described in this sub-chapter. In addition, it will be of great importance to:
- Establish national targets and an industry wide strategy for zero emissions in the aquaculture industry.
  A standard for all stakeholders will be to introduce comprehensive climate budgeting and reporting across the entire value chain.

Bellona will:

- Be the industry’s most important dialogue partner on climate, both in terms of challenges and opportunities.
- Have particular focus on implementing and scaling up already established solutions.
- Clarify the connection between reduced greenhouse gas emissions and growth opportunities in existing and new markets, and upstream activities such as new large-scale raw material production for feed.

1.1. Transport

Salmon transport is a significant source of CO_2 emissions in the production and export of salmon. Most fish products are exported to the European market by truck, yet transportation by airplane is the single largest contributor to the total carbon footprint of salmon. When flown to Asia or the USA, air transport of salmon accounts for 68-82% of the total carbon footprint. By comparison, emissions from transport by road or at sea account for less than 10% of the total carbon footprint [8]. By shifting transport from airplanes and trucks to trains and ships, CO_2 emissions can be considerably reduced. For example, the airfreight of salmon to Shanghai will have approximately fifteen times higher emissions than transportation by boat to the same destination[10].

Norwegian salmon has mainly been internationally marketed as a fresh product, which entails it has been transported by airplane to distant markets. Efforts should, therefore, focus on developing products with a longer shelf life, along with new technology that keeps products fresh for longer. This would, for example, enable the transport of salmon by ship or train to the Asian market, which is now primarily using airplanes, and from Northern Norway to Europe. At the same time, efforts should be made to establish frozen salmon as a full-fledged alternative to fresh.

Norwegian-produced salmon has an extra transport step in the production process, as parts of production are conducted abroad. Increasing the share of processing in Norway, as opposed to other locations, will reduce unnecessary transportation steps while enabling the effective use of by-products. Both of which will contribute to reducing the salmon's carbon footprint. Increased processing in Norway will also provide important resources for the Norwegian bioeconomy and contribute to sustainable feed.

2030 Vision:

A reduction of greenhouse gas emissions of 55% connected to the transportation of salmon by 2030.

Key measures:

- Phasing out salmon transport by airplane, through measures such as:
- Increase the quantity of salmon transported by ship and train.
- Stimulate investment in cooling and storage technologies that prolong the shelf life of fresh salmon products during transport.
- Increased marketing of frozen salmon – especially in markets with long transport distances.
- Increase salmon processing in Norway by leveraging political measures to enhance market access and supporting investments in advanced robotics technology.

Bellona will:

- Establish an overview of new shipping methods and technologies to pinpoint the most climate-friendly transport choices for transporting salmon.
- Influence the transport sector to ensure that trains and ships become the preferred choice when transporting salmon.
- Collaborate with key-stakeholders in the technology and transport sector to reduce the carbon footprint of this sector.
- Influence international marking efforts to promote frozen and fresh products with a longer shelf life as a climate-friendly alternative.
- Work to promote further processing of salmon in Norway, as an important measure to achieve a lower carbon footprint for exported fish fillets and ensure control over by-products as an important bioresource for feed.

1.2. Feed

For salmon not transported to market by airplane, the feed accounts for 75% of the total greenhouse gas emissions [8]. To ensure farmed fish have lower greenhouse gas emissions, it is crucial to focus on minimizing the emissions associated with fish feed.

Predatory fish high up in the food chain, such as salmon, rainbow trout, and halibut, currently account for 99% of the biomass produced in Norwegian aquaculture. In 2020, 1.47 million tons of salmon were produced, raised on approximately 2 million tons of feed ingredients [11]. Feed is the most expensive input in production and is today comprised of both marine and terrestrial sources. Since 1990, the industry has gone from mainly using marine ingredients (approximately 90% fishmeal and oil) to predominantly plant-based ingredients (73%) in 2020. Using plant-based ingredients reduces the use of limited marine sources - simultaneously moving some of the environmental and climate effects elsewhere in the value chain. In 2020, Norwegian raw materials accounted for only 8% of the ingredients in fish feed (fishmeal and oil), opposed to 92% of imported ingredients.

The aquaculture industry is facing a transformation that will incorporate long-term sustainable feed resources. The challenge until 2030 is to produce enough feed, while ensuring sustainability and meeting the nutritional needs of farmed fish.

The initiative “Råvareløftet” and a national focus on new sustainable raw materials for feed
Since 2020, Bellona has through the collaborative platform "Råvareløftet" to partnered with key stakeholders in the aquaculture feed industry, identifying barriers and opportunities for incorporating new sustainable raw materials into feed. In 2020, only 0.4% of the feed came from so-called, “new raw materials”. "Råvareløftet” assessed the potential and barriers for scaling-up 15 new raw material sources, which were grouped into three categories:

Cultivated raw material for feed		Harvesting new marine raw material for feed	Increased utilization of by-products
Blue mussels	Phototrophic microalgae	Antarctic krill	The fishery industry
Tunicates	Heterotrophic microalgae	Mesopelagic fish	Aquaculture
Macroalgae			
Insects	Mushrooms	*Calanus finmarchicus*	Agriculture
Grass	Bacteria		

The “ Råvareløftet” report: «Hva skal laksen spise- barrierestudier og veikart 2022) contains a road map that presents recommendations for 21 measures and models, regarding the quantities of new Norwegian raw materials for feed, that can be realized in 2030 and 2040. In addition, it contains 11 barrier studies that provide a detailed analysis of what currently prevents scaling up production of the 15 raw materials in the table above. The report also introduces over 130 actionable measures designed to facilitate the adoption of sustainable raw materials in feed, paving the way for a more environmentally friendly industry. [12].

The "Hurdalsplattformen," the policy platform of the current administration established in 2021, outlines ambitious goals for Norway's feed industry. It proposes launching a dedicated program to promote sustainable feed production using Norwegian resources, driving increased sustainability in the sector. The goal is that all feed for the aquaculture industry must come from sustainable sources by 2030.

In 2022, the Norwegian government launched a social mission[1] for sustainable feed [13]. The targets of the mission were announced in March 2024 and include, among other things, the goal of increasing the share of Norwegian feed ingredients for aquaculture to 25% by 2034[14]. Bellona believes that realizing sufficient funding and implementing this social mission will be crucial in achieving national investment in sustainable feed. Bellona will continue its strong commitment on this topic and its central role in restructuring the Norwegian aquaculture feed system.

2030 Vision:

The more than 130 proposed measures from "Råvareløftet" are implemented to ensure that 42% of feed raw materials in Norwegian aquaculture originate from new sustainable sources with low environmental and carbon footprints by 2030.

Key measures:

- All levels of government must be strengthened to ensure increased use of circular bioresources for new feed raw materials. It will be of particular importance that the Norwegian Food Safety Authority (Mattilsynet) prioritizes active guidance for producers and businesses working with new raw materials for feed and issues related to food safety. Furthermore, a dedicated program should be established at Bionova, or another suitable government body, to address knowledge gaps related to food safety that currently prevent the use of unutilized bioresources in feed production.
- Conduct Life Cycle Assessments (LCAs) for new raw materials for feed produced in Norway, and documenting their impact on fish health.
- A "two-step strategy" for low-trophic aquaculture commitment, which on a short time scale requires area allocation. On a longer time scale, a national strategy will need to be developed for low-trophic aquaculture, emphasizing local municipalities' need for support in area planning.
- Regulatory changes to ensure the use of bioresources, such as fish sludge, as a substrate for insects.
- Political prioritization of the feed sector to secure new sustainable raw materials for food-producing animals and farmed fish.
- The government must establish a clear goal that all by-products from the fishing fleet are brought ashore by 2030.
- A robotization boost to lift further processing of Norwegian seafood in Norway should be a priority area in the social mission for sustainable feed.

Bellona will:

- As an essential part of a future-oriented food system, build on the work in "Råvareløftet" and collaborate with the blue and green sectors, to further raise awareness for the need for sustainable raw materials in feed.
- Actively participate in designing and implementing the social mission for sustainable feed.

[1] European Mission: A societal challenge identified by the European Commission for which it wants concrete and ambitious solutions by 2030. The societal missions aim to achieve that research and innovation policy is more focused on solving global societal challenges. By linking research and innovation more closely to political strategies, regulations, and data services, solutions should be established faster than before.

- Play a leading role in the debate about which biomass should be used and where - regarding new feed raw materials and the use of bioresources.
- Work to gain political acceptance for a value hierarchy for bioresources that assures the optimal use of resources.
- Challenge the industry to show leadership responsibility for the global feed system.
- Work actively to put regulatory changes in place that could lead to a larger proportion of bioresources being used. For example, advocating for the use of sludge as a substrate for producing insects, which will in turn be incorporated into feed.

1.3. Aquaculture production

In 2021, Bellona and ABB published the report «Helelektrisk havbruk – Hvordan oppnå nullutslipp innen 2030?" ("Fully Electric aquaculture production - How to achieve zero emissions by 2030?"). In the report, it became clear that there are still 375,000 tons of CO_2 emissions linked to the production phase at sea that can be cut with existing or imminent technology. This amount corresponds to emissions from more than 200,000 fossil fuel-powered passenger cars. In 2020, the combined electrification rate on feed transportation fleets, associated work, and boats located at fish farms, was only 38% [15].

The electrification of the aquaculture industry in Norway is progressing slowly. While more sea-based fish farms are gradually connecting to shore power, significant efforts are still needed to transition workboats to zero-emission solutions. Compared to emissions from other parts of the salmon production chain, such as feed and transport, emission cuts in the production phase at sea can be rapidly established. More ambitious political goals for emission cuts, stricter requirements for the industry, and goal-oriented financial support systems must be in place to ensure the fastest possible implementation of a fully electric operation in the marine stage of salmon production.

Speeding up the pace of electrification in the aquaculture production industry requires more energy. This industry is, however, already experiencing restrictions on electricity access as it competes with other projects that require electricity. At the same time, other parts of the sector, which demand conversion to other production technologies, such as land-based farming, closed/semi-closed solutions, or offshore aquaculture, require significantly more energy to operate. Therefore, development and the utilization of more differentiated production technology depend on increased energy access. The use of more energy is also crucial to enable new types of aquaculture facilities using zero-emissions technology, from the start. The last statement is considered a prerequisite by Bellona to further develop this industry towards 2030.

The report "Klimakur 2030", which investigates measures for cutting non-quota emissions by 50% by 2030, states that aquaculture has the largest reduction potential in the maritime sector. This part of the sector can cut over 2 million tons of CO_2 between 2021 and2030 [16]. These figures also include aquaculture associated activities such as transport of products via boats transporting live fish (well-boats) and boats transporting feed (feed-boats).

2030 Vision:

The marine phase of aquaculture production will be fully electric by 2030. And by 2040, it will be a requirement to phase in zero-emission solutions for this sector's associated activities, such as transport via well-boats. and feed-boats.

Key measures:

- Establish practical, easy to roll-out, tools in Enova [2] to ensure that emission-free technology is chosen over fossil alternatives.
- Establish comprehensive incentive schemes, where Enova has a key role as an accelerator and developer of support programs that take the industry to zero emissions. Enova has support schemes that ensure that zero-emission technology is adopted more quickly, especially for workboats and new modes of operation. It also supports the roll-out of existing/ mature technology to speed up the implementation of it.
- Adopt political guidelines and requirements for zero emissions in the marine production phase by 2030, including:
  - Zero emissions from new locations by 2025,
  - Conversion to zero emissions from existing location by 2028, and
  - Zero emissions from new boats by 2028
- Establish and develop infrastructure along the coast that allows for decarbonization of all maritime activities related to the marine phase of the production of salmon.
- Upgrading the electricity network capacity to ensure sufficient access where there is currently insufficient power supply. At the same time, arrange for charging and storage facilities in ports, especially for larger vessels like feed-boats and well-boats.

Bellona will:

- Work with Enova to realize programs that ensure comprehensive solutions for zero emissions in the marine production phase.
- Submit proposals to the Ministry of Trade, Industry, and Fisheries for regulations and requirements that set clear expectations for - and create predictability in the development of zero emissions, in the sea phase of aquaculture production.
- Collaborate with electricity producers and authorities to ensure access to enough energy for restructuring industry and businesses.

[2] Enova is a state enterprise that provides financial support to promote measures that contribute towards low-emission society by 2050.

2. Reducing the environmental impact of salmon farming

Within industry and at the political level, there is a stated goal of increasing salmon production in Norway. However, traditional operations in open-net pens face significant challenges with fish health and environmental impacts, including escapes and sea lice infestations. The latter also limits the potential for growth and increased production. This has led to the development of various aquaculture technologies aimed at reducing the industry's environmental footprint, including closed/semi-closed sea-based systems, shielded and submersible net-pens, offshore facilities and land-based facilities for producing large salmon.

The production of Norwegian salmon causes significant ecological challenges. More than 56,000 salmon escaped from Norwegian farm sites in 2022[17]. Escaped salmon from farming poses a genetic threat to wild salmon. Experiments where researchers studied offspring from farmed salmon and offspring from farmed and wild salmon, showed that these groups have a lower survival rate in nature than offspring from wild salmon. In addition, the transfer of lice from farmed salmon to wild salmon, on their way from the rivers to the sea, is one of the causes of mortality amongst wild salmon. Salmon lice also represent a fish health problem in the net-pens, causing a loss estimated at NOK 5.2 billion in 2018[18].

Fish mortality during production is a major challenge for industry. In 2023, the industry lost 70 million individuals, due to mortality, discards, escaping fish, and other causes [19]. This loss represents both environmental and climate problems, as well as an economic challenge for the salmon industry. Farmed fish, produced at sea, can be an energy- and resource-efficient form of food production. On the other hand, the current traditional open net-pen technology leads to significant amounts of nutrients being released into the environment. Sedimentation of organic waste (sludge) from fish farming can negatively impact the seabed below aquaculture facilities and the surrounding ecosystem. However, this sludge represents an untapped resource that can potentially be used in energy production, soil enhancer, and circular feed production.

Marine industries are a significant source of plastic pollution along the Norwegian coast. The aquaculture industry is a large plastic consumer in the marine production phase. Estimates suggest that Norwegian aquaculture facilities use up to 200,000 tons of plastic annually, producing up to 30,000 tons of plastic waste [20]. Unfortunately, some of this plastic is dislodged or lost into the environment, where it pollutes beaches, affects wildlife, and/or breaks down into microplastic particles. The amount of plastic that becomes dislodged or lost from these facilities is not currently known. Increased awareness of the reuse and recycling of plastic equipment is essential to ensure the sustainable use of plastic in the aquaculture industry.

The analysis of "big data" offers significant opportunities to enhance operational efficiency and reduce the environmental impact of aquaculture. Fish farmers and suppliers to the industry have increased their investments in developing new technology, in response to challenges with lice, escaping fish, fish welfare, and environmental impact. By using big data sets, there is considerable potential for increasing knowledge that can contribute to reducing the industry's environmental impact. Machine learning can provide a better overview in the marine phase of production. And blockchain technology can enhance processes throughout the entire value chain, from enabling more secure data sharing between stakeholders to highlighting helpful trends during customer experience. By adopting new standards and collecting data put into context, we will be able to understand even more of the interaction between the environment and fish in fish farms. This will give the aquaculture industry great opportunities to gain control over fish health, operate more efficiently, and decrease impact on the environment.

2030 Vision:

Using plastic waste and organic waste from fish farms (sludge) provides new income streams for the Norwegian aquaculture industry. Lice infections and escaping fish represent a significantly reduced threat to Norwegian wild salmon. Additionally, losses within industry and mortality rates amongst farmed salmon have been reduced to a minimum.

Key measures:

- Increase the knowledge-base and identify “best practices" to deal with the challenges of sea lice and escaping fish.
- Prioritize preventive lice treatments, and stricter requirements for what is considered an acceptable loss in production.
- Implement coordinated R&D investment from the authorities and industry to develop strategy and value chains for the sludge from the aquaculture industry.
- Implement several sustainability indicators for regulating the farming industry.
- Implement a comprehensive and circular plastic waste strategy for the aquaculture industry.
- Introduce new standards for data collection and monitoring, where the environmental perspective is central.

Bellona will:

- Put focus on reducing losses during production as a climate and environmental measure.
- Work with the entire value chain to better utilize aquaculture sludge as a resource.
- Work on a political level to ensure there are more sustainability indicators for regulating the aquaculture industry.
- Collaborate with the industry and authorities to reduce challenges related to plastic waste and increase resource utilization of plastics from the industry.
- Influence the authorities to actively implement new technology in administrating the aquaculture industry, both for monitoring the environmental impact on marine ecosystems and fish health.
- Work to include environmental impact and fish health as central elements in a new common standard for data collection.

2.1 Different salmon farming technologies

The foundation for sustainable aquaculture in 2030 and beyond, regardless of production methods (e.g., open net pens), must prioritize biology as the basis for technological advancements. A sustainable approach ensures low mortality rates, promotes fish welfare, reduces the carbon footprint and environmental impact of production, and supports circular resource utilization. Different production technologies have different strengths and weaknesses, and it is important to recognize that not one technology alone can solve all the challenges the industry faces today.

Open net pens

In the marine phase of production, open net pens are by far the dominant method in use. This form of production has significant negative environmental impacts, such as impacts from escaped farmed salmon and lice infestations amongst wild salmon. Additionally, challenges related to poor fish health and welfare persist, with recent years highlighting issues such as injuries and increased mortality rates associated with lice removal procedures. Also, there are no incentives today to collect sludge in the open net pens. If realized, collecting this sludge could present a significant recourse to the industry.

Open net-pen solutions offer several advantages, including excellent water flow through the pens, low energy requirements, and minimal material consumption compared to other aquaculture technologies.

Semi-enclosed and submerged net pens

One example of a semi-enclosed technique used in several places is “shielding.” This technique uses for example tarpaulin that is installed down to a depth of 20 meters, outside the nets, to protect the salmon from lice and their larvae, in the upper parts of the water column. Water from deeper parts of the water column is then pumped into the net pens to ensure a good water quality and minimize lice infestation. There are also techniques using submersible net-pens, where the salmon are produced at 30-meter depths, to avoid them swimming in upper parts of the water column, which have higher lice densities. These examples, as well as similar technologies, will minimize lice infestations and in turn, the need for “de-licing” treatments.

Shielding technologies will consume more energy than traditional open net pens, as water needs to be pumped into the net-pens with shielding. And both technologies have a somewhat higher material usage, depending on the type of construction.

Closed net pens

Several examples of closed-net-pen technology are currently in use, but these are in the pilot stage and must be further developed into large-scale solutions. Today, these set-ups are mainly used for large, post-smolt production [3], but also slaughter-size salmon can be produced using this technology. This type of production consumes significantly more material and energy compared to open-net-pen technology.

The advantage of this type of technology is the physical barrier between the fish and the environment, which prevents lice infection, reduces the risk of escaping fish, and allows for sludge collection. Reduced presence of

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[3] Post-smolt stage is the first period after smoltification, where the salmon have gone from being adapted to fresh water to being adapted to salt water. The size of the fish during the “large” post-smolt phase is not clearly defined but often concerns fish weighing between 250 grams and 1 kilogram.

lice will also be positive for salmon welfare and survival, as there will be no need for de-licing. Research has also shown that with future global warming and further ocean acidification, closed cage solutions, in the sea, will have the least impact, compared to other current solutions. [21]

Open ocean/offshore aquaculture

Farming in offshore facilities, in the open ocean, does not yet occur in practice, as it requires a new permit regime. Though the permit regime is currently under development, some offshore technologies have already been tested in coastal areas. Offshore production is planned after permits and risk assessments are in place.

There is great uncertainty regarding the actual environmental impact of offshore farming, as well as the impact on fish health and welfare in these facilities. Depending on the choice of technology, it is assumed that the impact of lice and escaping fish will be lower than near-shore facilities, but sludge collection will be more complicated. Additionally, material and energy use will be much higher than in open net pens close to the coast. Material and energy usage can be drastically reduced by co-locating fish farming with offshore wind, low-trophic aquaculture and/or utilizing phased-out infrastructure from the oil and gas industry.

Fish farming on land

Fish farming on land, when producing large post-smolt or slaughter-size salmon, is both land use- and energy-intensive. Establishing new land-based facilities requires large, irreversible interferences in nature. This type of technology has the highest energy requirements compared to sea-based solutions[4], in addition to high investment costs, despite the operating license being free of charge.

Land-based facilities avoid problems with salmon lice and provide the possibility for sludge collection, while decreasing the likelihood of fish escaping. However, with the encroachment on nature, material consumption, and the energy required for operation, land-based farming should only be seen as an alternative at already established industrial sites with access to enough renewable energy. They should not be the solution to a sustainable conversion or the desire for expansion in the industry.

Transition

Further development of various fish farming technologies is necessary to reduce the climate and environmental impact of the industry. Clear sustainability indicators must be in place for the industry to ensure that future operations, regardless of technology, are in harmony with nature and focus on the best possible fish health. New technological solutions must meet specific requirements that ensure significant climate and environmental benefits, efficient use of resources, scalability, and efficient availability. This calls for a holistic approach and strategic restructuring, where new farming technologies are deployed where they can have the least impact—for example, adopting high-shielding systems or closed solutions in regions with high farming densities and severe lice infestations.

	Open net pens	Shielded net pens	Closed Net pens	Land-based, commercial fish	Offshore facility
Fish escaping	significant problem	minor problem	effective solution	effective solution	minor problem
Lice	significant problem	effective solution	effective solution	effective solution	effective solution
Sludge collection	significant problem	significant problem	effective solution	effective solution	significant problem
Fish health	significant problem	minor problem	?	minor problem	minor problem
Carbon footprint	minor problem	minor problem	minor problem	significant problem	minor problem
Resource usage	effective solution	minor problem	significant problem	significant problem	significant problem
Energy consumption	effective solution	minor problem	minor problem	significant problem	significant problem
Irreversible interferences on nature	effective solution	effective solution	effective solution	significant problem	minor problem

= significant problem

= minor problem

= effective solution

? = unknown effect

Predictions open net pens:	*Difficult to collect sludge/sludge is not collected*
Predictions shielded net pens:	*Difficult to collect sludge/sludge is not collected*
Predictions closed net pens:	*Enables sludge collection*
Predictions land-based facilities:	*Requires land which puts nature under further pressure*
Predictions offshore:	*Requires renewable energy for transport and operation, difficult to collect sludge*

Figure 1. A comparison of the environmental impact of different technologies used during the marine phase of salmon farming. As several technologies have not yet been tested at scale, future developments, new knowledge, and more experience could influence the assessment of environmental impacts.

2030 Vision:

The aquaculture industry has implemented technology that has led to an average mortality of less than 5% in the marine phase of production. Furthermore, the industry has maintained a green light in the traffic light system without increasing the climate and environmental footprint linked to material- and land-use.

Key measures:

- Introduce a comprehensive and simplified permit system that includes:
  - A targeted conversion to sheltered or closed farming technology' during the marine production phase, in areas where the lice infection pressure is persistently high.
  - Areas or farms with persistently high mortality rates during the marine production phase must be required to convert to operating technology that reduces fish mortality.
  - All semi-closed and closed marine facilities must be required to collect sludge.
  - Requirements to implement zero greenhouse gas emission technology during the marine production phase, regardless of the currently used farming technology.
  - Investigations and permit systems should be designed to stimulate the development of technological concepts where infrastructure for offshore aquaculture is combined with other infrastructure such as e.g. offshore wind and low-trophic aquaculture, as well as utilization of phased-out oil and gas infrastructure.
  - Introduce requirements for climate and nature budgeting in the aquaculture permit system. That information should weigh in during auctions and other licensing criteria for new locations.

Bellona will:

- Work for a more comprehensive management system for Norwegian aquaculture that clearly specifies what environmentally sustainable aquaculture is, and that priorities fish health and welfare.
- Work to ensure the establishment of a system to collect information related to production methods and technology, for identification and comparison of methods to assess good climate and nature solutions.

2.2. Farmed fish escapes

Farmed salmon escaping from pens poses a significant threat to local wild salmon populations. These escapes can result in the transmission of diseases and parasites. Escaped farmed salmon can also pose genetic risks by interbreeding with wild salmon in rivers, potentially compromising the genetic integrity of wild populations. For the aquaculture industry, escapes are costly, leading to lost production and expenses related to recapture efforts. Despite a "zero escapes" vision shared by the industry[22] and regulatory authorities, escape incidents remain a persistent challenge**.** A total of 573,128 escaped farmed salmon were reported between 2017-2021. While the number of escaped fish varies annually, major escape incidents still occur. Current open-net pen technology makes it likely that such events will continue to occur. Therefore, the Institute of Marine Research believes that in large parts of the country, there is a moderate to high risk of escaped farmed salmon interbreeding with wild salmon populations in the years to come[17].

From 2010 to 2016, 76% of escape cases were caused by holes in nets[23]. Numerous factors can lead to fish escaping, many of which are unforeseen, but most escapes are due to human error. Transitioning to closed net pens or using shielding technology will probably reduce the risk of escapes, although escape incidents can never be fully prevented.

2030 Vision:

Norwegian aquaculture has, through an increase in competence and phasing in of new technology, considerably reduced the extent of escapes.

Key Measures:

- Industry-wide use of certified risk management systems.
- Usage of the best available escape-proofing technology and other escape prevention tools.
- Obligatory requirements to provide adequate training for new employees and usage of internal control systems.

Bellona will:

- Follow the developments around escaping farmed salmon carefully and be in continuous dialogue with the industry.
- Arrange platforms/forums for industry that map and keep track of the industry’s technological status and identify innovation needs.

2.3. Salmon lice control

One of the best-documented negative environmental impacts of Norwegian salmon farming is the transmission of salmon lice to wild salmonids. Excessive sea lice infection pressure from farmed salmon can harm wild salmon to the extent that it leads to increased mortality and, in the worst cases, threatens salmon populations. To reduce lice infection pressure, salmon farmers are required to maintain low sea lice levels in their farms. With open-net pen technology, strict sea lice limits are essential to protect wild salmonids [24]. However, in many cases, these limits are insufficient, as lice transmission to wild salmon remains high even when farmers comply with the limits. Additionally, these regulations pose significant challenges related to welfare, resource utilization, and resistance to treatment in farmed salmon.

Salmon lice have developed resistance to many of the existing chemical treatments. As a result, non-medicinal methods now dominate in lice controlling. These methods include brushing, flushing, freshwater and warm-water treatments, or combinations of these approaches. Physical handling and stress from these treatments are known to cause fish health and welfare problems, making non-medicinal treatments a leading cause of mortality during the sea phase of production. Despite the development of resistance, chemical treatments are still in use in industry. However, there is insufficient knowledge about the actual environmental effects of these medications and their impacts on other species. Current regulations regarding the discharge of chemical lice treatments into the environment are inadequate and fail to uphold the precautionary principle based on environmental considerations.

Cleaner fish, like wild-caught wrasse and farmed lumpsuckers eat lice from salmon and are part of the control strategy to control sea lice. In 2022, approximately 33.4 million cleaner fish were introduced to farm sites along the coast [25], with farmed lumpsuckers accounting for over 50%. The remaining amount consisted of wild-caught wrasse species. Mortality rates among cleaner fish in net-pens remain alarmingly high (registered mortality over 50% in 2022), despite measures such as vaccines, customized shelters, and specialized feed. This illustrates a significant animal welfare issue, suggesting that cleaner fish are not suited to life in salmon farming net-pens. Additionally, the effectiveness of cleaner fish as a lice control method remains uncertain. Over the past four years the use of cleaner fish has decreased by 44.5% since its peak in 2019 [20]. Wild-caught wrasse has been subject to quota regulations since 2018, but there is still insufficient knowledge about the impact of this fishery on populations and the potential spread of diseases.

The traffic light system is intended to ensure that growth in the aquaculture industry occurs in an environmentally sustainable manner. Despite political goals to expand the system with additional environmental parameters, sea lice remain the sole factor regulating growth or reduction in production. Production adjustments are made across 13 defined production areas (POs), where production is currently regulated based on sea lice-induced mortality in wild fish as the guiding indicator. If the burden is low (acceptable), moderate, or unacceptable, production in the area is set to increase (green), remain unchanged (yellow), or decrease (red), respectively. The current system allows for up to 30% probability of mortality in wild salmon due to lice before the "red light" is triggered. In red areas, production capacity can be reduced by 6%. In PO3 and PO4 (Vestland), which have had red status since the traffic light system implementation in 2018, analyses suggest it could take 20 years for the areas to achieve green status if production reductions are the sole mitigating measure [26].

The current regulations for sea lice management fail to adequately protect wild salmon, farmed salmon, or cleaner fish. Bellona argues that all future sea lice control must focus on preventing sea lice larvae from locating or attaching to farmed salmon. Only by using preventive measures can salmon farms avoid the many "consequential problems" of current sea lice treatments while protecting wild salmon from infection. Transitioning to new technologies, such as closed or shielded systems, will be necessary in many areas to protect both wild and farmed salmon. The industry itself must develop the solutions it requires, but stronger incentives are needed to accelerate the development and adoption of new technologies.

2030 Vision:

All forms of sea lice control are based on preventive methods that prevent sea lice larvae from finding or attaching to farmed salmon. Lice infection and the negative effects of lice treatment in Norwegian aquaculture has been significantly reduced.

Key Measures:

- Prioritize preventive methods for lice control and ensure their adoption through gradually stricter requirements for the industry towards 2030, ensuring significantly reduced lice infections.
- Strategic transition to closed or shielded technology in areas with persistent high lice levels.
- From 2025, all new facilities must be required to implement preventive methods as the primary measure against sea lice.
- Revise the traffic light system by 2025, to incorporate additional environmental parameters.
- Introduce stricter requirements for the welfare of cleaner fish, focusing on their entire lifecycle and requiring documentation of mortality rates and causes.
- Establish a scientific committee to assess and document suitable living conditions for cleaner fish in net-pens and the effectiveness of their use. If adequate documentation cannot be provided, the use of cleaner fish should be phased out.
- Ensure the responsible handling of cleaner fish as a resource after their use in sea lice control.
- Prohibit the discharge of chemical lice treatments that can be harmful to the environment by enforcing proper handling of treatment water after medicinal treatments.

Bellona will:

- Closely monitor the developments in salmon lice regulations and stay updated on new knowledge regarding lice infestation pressure and various control methods and technologies.
- Advocate for a strategic shift to closed or shielded technology in areas with consistently high lice infestation levels.
- Work for political mandate to achieve zero discharge of chemical lice treatments (bath treatments) into the environment.
- Work for stricter, better-regulated cleaner fish harvesting based on improved knowledge of impacts on wild stocks and potential spread of diseases.
- Work to establish better documentation on the effectiveness of cleaner fish, scientifically qualified assessments of their living conditions, and stricter regulations reducing mortality rates among cleaner fish in net-pens.

2.4. Mortality and losses during production

In recent years, 15-20% of the total weight of salmon in sea-based aquaculture has been lost. Losses are categorized as mortality, escapes, or “other losses.”[27]. In 2023, the total loss of fish during the sea phase was 70 million individuals, with mortality making up 89.7% of the losses. A total of 62.8 million salmon (16.7%,) died during the sea phase of production, marking the highest mortality rate recorded, in both number and percentage, to this date. Mortality rates vary significantly between production areas, ranging from regions with under 10% mortality to those with over 20%. An additional 37.7 million salmon died in the freshwater phase of production [20]. Improving survival rates is one of the most effective measures to enhance fish welfare while simultaneously reducing the overall carbon footprint of salmon production.

Sea lice treatments have become one of the greatest challenges of health of farmed fish in Norway. Due to significantly reduced sensitivity to most chemical delousing treatments, non-medicinal treatment methods are primarily used. Thermal, mechanical, and freshwater delousing methods are stressful and can have serious health and welfare consequences, potentially resulting in death. In 2023, a total of 2609 non-medicinal treatments were reported. The Norwegian Food Safety Authority received 1,419 welfare incidents reports from fish farms in the same year, 34% of which were related to non-medicinal delousing. Over the past three years, there has also been an increase in downgraded fish at slaughter, primarily due to "wounds and injuries», indicating reduced welfare even before slaughter [20].

Beyond sea lice treatments, diseases are a significant cause of production losses, with gill diseases and viral diseases as the dominating diseases in farmed salmon. Diseases are costly for industry, lead to poor animal welfare, and can be harmful to the environment. Implementing good biosecurity practices – with measures to prevent the introduction and limit the spread of infection – is essential to addressing the diseases the industry currently faces. Additionally, ensuring high smolt quality for robust fish and breeding for disease resistance are critical factors for maintaining good health and welfare.

High mortality rates during the sea phase of production have been a persistent problem for over a decade. During this period, the average weight of dead fish has also increased, meaning that larger fish are dying in the net-pens. This trend is primarily linked to frequent delousing using non-medicinal methods. The biological costs associated with disease and treatment have doubled from 2012 to 2022 and are now comparable to feed costs, which have historically been the largest cost driver in salmon production [28].

Fish mortality and production losses represent both a welfare and a resource problem, as well as a climate challenge. Increased mortality and reduced growth, due to sea lice infections and diseases, lead to lower resource efficiency of inputs such as feed, which in turn raises the carbon footprint of the fish. The larger the fish at the time of death, the greater the climate impact of mortality in salmon farming. This underscores the importance of improved fish welfare and health also for environmental and climate reasons, necessitating the urgent implementation of measures to significantly reduce mortality.

2030 Vision:

Coordinated efforts by industry and authorities have reduced losses and fish-mortality during the sea phase of production to below 5%.

Key-measures:

- Establish a national goal of less than 5% mortality during the sea phase of production, with specific actions to achieve this goal. This includes establishing a unified mortality calculation that is scientifically and professionally grounded.
- Conversion to closed or shielded technology to minimize mortality related to delousing, especially in areas with a high lice pressure requiring frequent delousing.
- Develop delousing methods that ensure and document gentle handling of fish without causing negative environmental impacts.
- Introduce a maximum allowable number of non-medicinal delousing treatments per production cycle to reduce stress on the salmon.
- Implement stricter requirements for infection prevention measures and preparedness to prevent the development and spread of the most common viral diseases, incorporating biosecurity considerations into the licensing system.
- Investigate and implement measures to minimize the spread of infections during live fish transport, as moving smolts and fish for harvest between open sea facilities is considered the greatest risk factor for disease transmission.
- Including mortality as a pre-qualification requirement in the traffic light system; in areas with a green light, increased production can only be permitted if the average mortality rate is at or below 5%.
- Coordinate management and authorities to ensure that regulations for fish health and welfare are safeguarded on an equal footing with legislation relating to the environment and permission for increased production.
- Further develop good reporting systems for causes of fish losses during the sea phase of production. This will serve as a foundation for new tools to improve fish health and welfare that can be adopted across industry.
- Strengthen the Norwegian Food Safety Authority's capacity for supervision and follow-up of regulations that ensure fish health and welfare.
- Conduct life-cycle analyses (LCA) for salmon mortality to better understand the carbon footprint associated with fish losses.

Bellona will:

- Monitor developments in regulations on production losses closely. This includes staying updated on the latest knowledge regarding the causes of losses and mortality, as well as preventive farming methods that can reduce the need for delousing treatment.
- Work politically and with regulatory authorities for stricter requirements to safeguard animal welfare and reduce mortality in production.

2.5. Aquaculture sludge

The annual amount of sludge produced by Norwegian aquaculture is estimated somewhere between 695,480 and 817,494 tons [29]. Sludge has long been considered a waste product in the aquaculture industry, but it is an underutilized resource with significant potential.

Fish sludge holds significant potential as a resource for various applications, including substrates for insect production, soil enhancers and biogas**.** To future-proof Norway, strengthen job and food security, and deliver significant climate and environmental benefits, the social mission for sustainable feed ingredients and the Raw Materials Initiative, highlight the importance of circular products in Norwegian produced raw food ingredients. The social mission objective is to strengthen food supply security in Norway by, e.g., producing feed ingredients based on circular resources. One good example is the production of insects or other invertebrates, using sludge as a substrate, with insect proteins serving as sustainable feed ingredient. Despite this potential, large amounts of valuable nutrients that could be utilized for a range of different purposes are, for now, being released into sea via sludge.

Each year, approximately 14,000 tons of phosphorus is released into the ocean by Norwegian aquaculture, posing a significant challenge to international environmental goals. This practice contradicts key initiatives like the EU's *Farm to Fork Strategy* under the Green Deal and Target 7 of the Kunming-Montreal Global Biodiversity Framework adopted at COP15 in 2022. Both aim to cut nutrient loss to the environment by 50% by 2030. [30,31]. Furthermore, phosphorus is considered a finite resource, critical to reuse in circular value chains, to ensure global food security. For example, particulate phosphorus discharged from net-pens, when not utilized by low-trophic organisms, could be repurposed as animal feed[32], instead of being imported from other countries. It is, therefore, essential to harness this resource to further develop the Norwegian bioeconomy and promote green value creation.

An expected increase in salmon and trout production will significantly increase sludge discharge within Norwegian fjords. To mitigate environmental impacts and increase circular resource utilization, it is crucial to be at the forefront of technological developments by developing and investing in innovative technologies that collect sludge. This will be critical for the sustainable growth of the aquaculture industry. However, several practical and technological challenges must be addressed before sludge can become a commercially viable resource on a large scale. Furthermore, there remains a significant knowledge gap regarding the point at which these discharges cross environmental thresholds and begin to cause substantial impact to ecosystems. It is also necessary to evaluate current monitoring methods used to assess the environmental impact of fish farming to confirm their suitability to be farmed over different substrate types, e.g., soft bottom vs hard bottom substrate.

At present, only recently built or expanded hatcheries are required to collect and treat sludge, while no such obligations exist for the sea phase of production. Although initiatives and test facilities for the collection and utilization of sludge exist, there is a need for larger incentives and facilitation across the industry to build large-scale value chains for fish sludge. Achieving this will require increased political and regulatory awareness. If the future of aquaculture is to be sustainable, it is necessary to integrate circularity as a key component of the industry's development.

2030 Vision:

Sludge has gone from environmental challenge to a commercial resource via collection and product development.

Key-measures:

- Development of a political strategy for managing aquaculture sludge.
- Initiate feasibility studies for optimal aquaculture sludge resource use.
- Develop a broader range of incentives to stimulate investment in environmental technologies and practices that address the sludge issue. This will foster a more holistic approach to sustainability and environmental challenges in the aquaculture industry, while encouraging innovation and development.
- Generate more knowledge to better understand the environmental impacts of sludge accumulation beneath fish farms.
- Identify where fish sludge utilization can have the greatest sustainability impact.
- Require mandatory sludge collection for fish production in all closed or semi-closed net pen systems.

Bellona will:

- Work to establish research and scientific documentation on the food safety of using sludge as a substrate for insect production.
- Clarify the scope and amount of scientific documentation required to recommend changes to current regulations.
- Engage with politicians and government bodies to make sludge collection mandatory during the sea phase of production across all of Norway.
- Work actively with the industry and R&D environments to identify and verify sustainable commercial value chains for sludge.
- Implement obligations for the allocation of new or expanded licenses, such as introducing sludge collection requirements for sites that have reached a “poor,” or “very poor” environmental status (class 3 and 4) based on MOM-B surveys. Currently, about 10% and 5% of sites are classified as “poor” or “very poor,” respectively, which can serve as both an incentive and a starting point to accelerate technological advancements and the implementation of sludge collection solutions. This approach will enable the gradual introduction of stricter collection requirements in the future.

2.6. Plastic waste

The aquaculture industry uses enormous amounts of plastic. A single fish farm location with 10 cages, it is estimated that 360 tons of plastic equipment are used. Of this, the cages account for three-quarters of the mass, while nets and mooring lines account for approximately 10% each. [33]. Most of the equipment used in the aquaculture industry is of high quality and can be used for several years. Regardless of this, around 30,000 tons of plastic waste is produced every year [20]. Most of the waste is collected and sent to waste management facilities, but almost two-thirds of this collected waste ends up being incinerated or in landfills [34]. A smaller proportion is lost at sea due to poor equipment handling, wear and tear in storms, repair and replacement of equipment, or failure to secure equipment during transportation by boat. This results in marine plastic litter along the Norwegian coast.

Beach clean-up efforts regularly find plastic items from the aquaculture industry including ropes, feed pipes, and parts of net-pens. Such objects from marine activities make up on average 46% of the plastic waste found on Norwegian beaches [35]. A considerable proportion of marine litter originates from relatively localized sources, leading to large regional variations in litter composition. While personal care products dominate in South-Eastern Norway (Østlandet), the contribution of plastic waste from fisheries and aquaculture increases significantly as latitude increases[36]. What waste is found on beaches, however, represents only a minor part of the problem. Up to 94% of all plastic that ends up in the ocean sinks to the bottom, while only 1% floats on the ocean surface. And 5% washes up on beaches [37], which means there is far more plastic in the ocean than is visible to us.

Microplastics presents another challenge that is rarely visible to the naked eye. Microplastics are defined as pieces of plastic that are less than half a centimeter in size. Microplastics can either be deliberately produced in small sizes for specific purposes, such as in cosmetics or rubber granules on soccer fields, or they can be fragments, broken off from larger plastic objects in nature. In the aquaculture industry, microplastics come predominantly from equipment exposed to natural wear and tear such as sun, wind, waves, and seawater. Microplastics from worn ropes is an obvious source, but microplastics can also come from wear and tear from feed pellets blown through feed pipes. In addition, microplastics can form during maintenance activities, such as cleaning of the nets and cutting of the feed pipes. Since microplastics are very difficult to remove after they are released to nature, it is crucial to prevent new releases by handling the equipment carefully.

The regulatory landscape for plastics in Norway is fragmented, with several overlapping global, regional, and industry-specific initiatives. Negotiations within the UN, on a global treaty against plastic pollution, will commit all countries to introducing new rules for the use and production of plastic, aiming to stop plastic pollution. The treaty should be in place by 2025 [38]. In Norway, a new Extended Producer Responsibility (EPR) scheme, concerning plastic equipment from fisheries, aquaculture, and recreational fishing, should also be implemented towards the end of 2024. The EPR will ensure that producers cover the necessary costs associated with the separate collection and treatment of discarded equipment, thereby increasing the amount of plastic waste from the aquaculture industry that is reused and recycled [39]. In 2021, the Directorate of Fisheries launched an action plan against marine littering, which contains measures to reduce littering in marine areas from commercial fishing, recreational fishing, and aquaculture. The action plan includes clean-up measures, preventive work, and investment in research and development, aiming to reduce marine litter by the end of 2026 [40].

With operations along most of the Norwegian coast and large consumption of plastic equipment, the aquaculture industry has a responsibility to ensure operations and routines do not lead to the spread of plastic waste. This includes raising awareness about reducing plastic consumption and focusing on reusing plastic equipment. It is important to ensure that plastic waste is handled responsibly and that valuable resources remain part of the circular economy.

2030 Vision:

A holistic approach to circular management of plastic waste in the aquaculture industry. This includes the longest possible use and reuse of equipment and no littering or material resources being lost to the environment, including microplastic emissions.

Key measurements:

- Focus on environmental design of aquaculture equipment to extend its service lifespan and increase reuse or recycling, as a last resort. To optimize circular handling it is crucial to start in the product development phase and practice sustainability by design, because the production phase has the greatest potential to minimize the use of raw materials.
- Improving routines and performing regular checks of equipment to minimize plastic being lost to the environment.
- The industry must report all plastic waste and its waste management, including downstream handling of the various waste fractions.
- Determine which recycling solutions are best and how to further utilize this material through dialogues with all relevant players in the value chain: manufacturers, subcontractors, fish farmers, waste companies, and R&D institutions.
- Minimize microplastic emissions by conscious handling of the equipment, including replacing equipment before it becomes worn out, using underwater feeding solutions, and ensuring that small particles from cutting feed pipes and other equipment are collected and do not end up in the environment.
- Introduce an Extended Producer Responsibility for plastic equipment for the fishing and aquaculture industry to increase the reuse and recycling of equipment and reduce littering and microplastic emissions to the environment.

Bellona will:

- Work to highlight good plastic handling during operation to extend the lifespan of plastic equipment and increase the recycling of plastic waste, as demonstrated in the online course Bellona has helped to develop; “Plastic Management in Aquaculture” [41].
- Work with relevant authorities to ensure plastic that ends up in landfills is phased out.
- Communicate ambitions and best practice solutions for handling and minimizing plastic in the industry.
- Work to increase knowledge and awareness of the various players in the aquaculture industry.
- Work towards increasing knowledge regarding the sources of microplastics from aquaculture amongst operators, including the effects of microplastics in the marine environment.
- Work to ensure that suppliers of plastic products to the aquaculture industry consider reuse and recycling before the products are put into production.

3. Scaling up low-trophic aquaculture

In the future, the demand for biological resources will increase, as more food, feed, energy, industrial products, and carbon storage are needed. To contribute to growth in the Norwegian bioeconomy, the aquaculture sector has a unique opportunity to utilize the marine environment for future-proofing production of several species, especially from lower levels of the food chain, "Low-trophic species" encompass a wide range of organisms, including sea urchins, sea cucumbers, tunicates, oysters, mussels, and seaweed. These species can be grown without using topsoil, fresh water, or fertilizers. These organisms have great potential as a sustainable food source, or as contributors to bioenergy, carbon storage, and the production of animal feed with a low carbon footprint. Transitioning to a bioeconomy with increased use of low-trophic aquaculture can potentially create valuable new resources, increase employment rates, increase food and nutrition security, and reduce greenhouse gas emissions. Diversifying our resources will also make us less vulnerable to future challenges in the agriculture industry and other food production systems [42]. Meeting the challenges society faces requires a fundamental transformation in the production and consumption of resources.

Limiting temperature rise to 1.5°C by 2050 will require proactive policies, industry efforts, and innovation. The bio-based industry must expand by approximately 50% by 2050, with significant growth needed in bioplastics and fiber production. At the same time, macroalgae production must double by 2050 to reduce the protein deficit in Europe [43]. Biomass from various low-trophic sources has great potential to meet the growing demand for resources, but availability is limited. In the future, we need to increase the production of bioresources and the development of efficient biotechnological methods to achieve the biggest climate and social benefits possible.

So-called “biorefinery concepts” can be crucial in realizing large-scale marine biomass production [44]. A biorefinery sustainably processes biomass for different purposes, such as food, feed, chemicals, materials, and bioenergy, where different biological material components are used for various purposes to maximize revenue streams and resource efficiency. Several challenges remain in establishing the necessary infrastructure and efficient processing, but large-scale kelp cultivation represents a significant opportunity for bioenergy production without competing with the need for food production. Coastal versus offshore production will require different regimes and frameworks, but both will be important in low-trophic biomass production in the future.

2030 Vision:

A Norwegian aquaculture industry that has realized a wide range of profitable and sustainable production systems based on low-trophic species that deliver new food sources, feed ingredients, bioenergy, and materials to a society that implements and demands bold climate actions.

Key measures:

- Establish a technology development program to promote industrialized and automated systems to monitor and cultivate areas for low-trophic production, including joint operation between offshore installations and seaweed production. Ministry of Climate and Environment and Ministry of Trade, Industry and Fisheries develops a roadmap that includes how Norway will use low-trophic aquaculture in response to the growing need for sustainable biomass.
- The government establishes a dedicated fund to stimulate commercial development to subsidize cultivating, harvesting, and utilizing low-trophic organisms.
- Develop and establish a politically anchored value hierarchy for the utilization and application of biomass.
- Establish a framework for the co-location of various marine industries.

Bellona will:

- Inform authorities, politicians, and the public about opportunities to facilitate increased diversification and low-trophic production in the aquaculture industry.
- Further develop the knowledge base and map both barriers and opportunities associated with producing low-trophic bioresources and their associated application areas.
- Through its ownership of Ocean Forest, Bellona will conduct the cultivation and processing of various low-trophic species to increase the knowledge base and identify commercial potential.

3.1. Coastal low-trophic aquaculture production

Today's Norwegian coastal aquaculture is predominantly focused on salmon production. Diversifying the aquaculture industry, by including organisms from lower trophic levels, will lead to significant benefits. Low-trophic species improve water quality and the surrounding environment by sequestering carbon, nitrogen, and phosphorus. This sequestration can have a regenerative effect on the local environment. These species do not require feed or fertilizer, which eases the pressure on feed production and makes Norwegian aquaculture more efficient. Coupling farming of two or more non-feed (low trophic) species with salmon farming can also capture nutrients that would otherwise go unused. The latter concept, known as multitrophic aquaculture, will ensure more efficient use of aquaculture areas and valuable resources.

Although developing “new aquaculture species” has been a political ambition for several decades, low-trophic species production has only marginally increased. Mussel farming reached a short peak in 2005 with 4,885 tons but has since stabilized at around 2,000 tons per year with only minor annual variation. Mussels are currently mainly used for human consumption but have good potential as a feed ingredient. There are some challenges to overcome, like establishing predictable production, lowering costs, ensuring efficient processing, and access to spaces for facilities at sea. In 2023, Norwegian tunicate production began to grow, with investments in coastal aquaculture and land-based production facilities. Tunicates were initially only seen as a potential source of raw material for sustainable feed, but products for direct human consumption were also developed. Kelp is the fastest-growing group of organisms in low-trophic aquaculture in the world and has gained an increasing interest in Norway over the past decade. The latter has triggered a significant R&D effort and a growing start-up business along the coast.

The potential for increased low-trophic production is enormous, especially in response to the Norwegian social mission for sustainable feed. The initiative set a target to increase the production of sustainable Norwegian feed ingredients with 500,000 tons per year by 2034 [14]. However significant challenges for low-trophic production remain, which the aquaculture industry and authorities must address before large-scale cultivation of low-trophic species can be realized along the Norwegian coast. The latter includes streamlining and automating seedling production and planting, access to spaces for facilities at sea, harvesting, processing, dewatering and drying technology, product development, and market development and access.

The environmental conditions along Norway's coast can enable the production of far more low-trophic species than currently produced. For many species, however, there are significant biological challenges that must be solved before commercialization can be realized, which requires basic research and targeted R&D. For other species, production protocols have been established, while technology, business models and value chains are immature, resulting in a correspondingly weak profitability. Another challenge is the lack of knowledge and experience regarding low-trophic aquaculture among authorities, especially concerning permits and allowing access to spaces for facilities at sea. At present, there are few incentives for existing aquaculture stakeholders to invest in low-trophic aquaculture. Moreover, a significant challenge for established players is that future applications will extend beyond food and feed, necessitating new expertise and the development of entirely new value chains. One “new” value chain that recently emerged is the usage of kelp as bait for sea urchin traps, which will require large quantities of kelp.

2030 Vision:

A large proportion of the growth in the Norwegian aquaculture industry up to 2030 will come from the cultivation of low-trophic species, which significantly improves the industry's environmental and climate accounting.

Key measures:

- The ministry of Trade, Industry and Fisheries prepares a national strategy and a roadmap to increase low-trophic production.
- The ministry of Trade, Industry and Fisheries develops financial incentives to advance low-trophic aquaculture development.
- Establish reasonable maximums for security deposits for space acquisition, for low-trophic aquaculture production, that reflect the current potential profit that can be made.
- Allocate the required space for the start-up and upscaling of low-trophic aquaculture in coastal municipalities in their coastal zone-use plans.
- By the end of 2025, a national plan for the development and space allocation of low-trophic aquaculture must be established, in which municipalities are required to support the industry. Space allocation should be prioritized where low-trophic species can have a positive impact on the marine environment.
- Develop guidelines for each species that can be cultivated and the areas where they can be cultivated.
- Diversify aquaculture into a broader range of value chains and markets, with a focus on developing products for a wide range of low-trophic aquaculture applications and industries.
- The Norwegian Environment Agency establishes and ensures that systematic LCAs are performed for all low-trophic production methods.
- Increased R&D investment to further develop low-trophic aquaculture product processing technology, with a focus on drying technology, including opportunities to utilize residual heat from existing industrial plants.
- Significantly increased focus on low-trophic organisms as raw feed ingredients for aquaculture and agriculture, through the Norwegian social mission for sustainable feed to utilize sustainable feed materials.

Bellona will:

- Through its work in Ocean Forest, develop multitrophic aquaculture systems as environmental quality improvement measures. The aim will be to offer proven, scalable concepts.
- Investigate tools that can promote possible value creation for low-trophic products. An example of this could be setting up a monetary reward system, based on the provided ecosystem services, such as environmental and water quality improvement effects or carbon sequestration.
- Develop criteria and a best practices method, by conducting an LCA for each low-trophic organism raw material ingredient, for feed production.
- Increase the understanding of the potential for the inclusion of low-trophic organisms as raw feed ingredients in Norwegian aquaculture and agriculture feed products.
- Be active in dialog with key stakeholders to develop regenerative low-trophic aquaculture. The goal will be to ensure society benefits from its associated ecosystem services, to ensure that authorities develop appropriate regulations and measures to advance the industry.

- Through Ocean Forest, facilitate increased production of low-trophic species. This will be accomplished by improving knowledge, increasing access to sea-based farming areas, and creating more market opportunities, based on the Norwegian social mission for sustainable feed.
- Investigate new value chains and markets for seaweed and kelp, for example, the use of kelp as bait in sea urchin traps.
- Communicate the benefits of low-trophic aquaculture to a wider range of stakeholders, such as politicians, managers, industry, and the public.

3.2. Low-trophic aquaculture and bioindustry

With the world's second-longest coastline and a leading position in aquaculture technology, Norway's aquaculture industry has the potential to produce large quantities of sustainable biomass. Our R&D groups possess a great deal of expertise in bioprocessing and bioprospecting. This gives Norwegian industry the prerequisites for developing products and technology, which can lead to increased value creation from marine resources, within the bioeconomy.

To achieve profitability, it is essential to reduce production costs by adopting more efficient cultivation techniques and optimizing the use of raw materials, enabling the production of additional products through biorefining. This usually involves prioritizing the most valuable main products, while facilitating maximum utilization of materials in less profitable side streams. Including new low-trophic organisms in biorefining will require varying R&D efforts and investment to develop the feedstock base, optimize chemical composition, and/or demonstrate process lines.

Large-scale production and cost reductions are essential for the profitability of biorefining low-trophic aquaculture products. To ensure the supply of biomass is a profitable industry requirement, it is necessary to consolidate industrial production and land utilization. Co-location, where different marine industries operate together, can be a viable solution. For example, low-trophic organisms, such as kelp, can be cultivated near oil platforms, offshore wind farms, or in the vicinity of offshore fish farms. Today's offshore industry consists of large facilities at sea, but knowledge of the seafood industry and the bioindustry at sea, is lagging. Co-location will require harmonization between regulations and current laws, as well as a new approach in the management plans for Norwegian marine areas.

Biofouling presents a significant challenge in industry, especially in commercial kelp farming, as it degrades the kelp quality and reduces its biomass value [45,46]. Fouling mainly occurs in the summer months, with coastal kelp farming, requiring additional measures to maintain clean biomass. While additional measures lead to higher production costs, a cleaner biomass results in higher-quality products with more value. For offshore kelp farming, it may be beneficial to allow fouling to occur, while sustaining permits for larger biomass volumes, which will reduce costs. This approach could also promote higher biodiversity in the surrounding area and provide additional ecosystem services. This approach requires that the biorefining process can handle “impure” biomass. But this “impure” biomass has great potential for applications such as biostimulants, which improve plant health. Other promising applications of low trophic biomass with fouling lie in the production of energy and biochar.

The biostimulant market is projected to grow at an annual rate of 11%, with macroalgae emerging as a promising source of biomass due to its positive impact on plant health. Biostimulants present several benefits to plant health, including the extraction of polysaccharides in soil. Biostimulants have applications across industrial, pharmaceutical, and food-related products. Although the use and effect of biostimulants are not as well documented or prevalent in Norway, as in other countries, they can be useful in combination with biofertilizers. Some studies also look at using *Ciona intestinalis* (tunicates) as a biofertilizer, which can be reused for various purposes, such as soil improvement, animal feed, compost, or as a building materials [47].

Biorefining processes with low trophic organisms can produce biochar, along with other useful by-products, such as proteins and biogas. Biochar improves the soil's ability to store water, increases biomass production and soil carbon content, and has a liming effect. Biochar is made using pyrolysis, which makes it highly stable against biodegradation. Although biochar, made from seaweed, only stores a minor amount of CO_2, it can reduce $N_2 0$ (nitrous oxide) emissions and improve plant nutrient utilization, when combined with manure or compost. Further research is required to assess the use of kelp biochar as a soil-improving component, and use in other applications, such as air and water purification, and in building materials.

The transition to bioenergy is a crucial factor in achieving Norway's climate goals, according to the Norwegian report "Klimakur 2030"[16]. Bioenergy can also contribute to economic growth in rural areas and secure energy supply. Currently, bioenergy accounts for 60% of Europe's renewable energy supply. However, growing concerns about the sustainability of bio-resources and their availability, amid rising demand, underscore the need for alternative solutions.

Marine resources, such as kelp, are gaining attention as a sustainable option, to meet the bioenergy demand. Kelp can potentially sequester significant amounts of carbon through energy production or long-term carbon storage. While scaling up kelp cultivation could contribute substantially to carbon sequestration, strategies for its long-term storage are essential. Bio-CCS (Bioenergy with Carbon Capture and Storage), particularly from kelp-based bioenergy production, is regarded as a promising tool for achieving net-zero emissions. A strategy for long-term carbon storage, using Norwegian low-trophic aquaculture resources, is needed. This should include carbon storage potential from different marine organisms and diverse production methods.

2030 Vision:

In 2030, offshore production of low-trophic biomass will deliver significant volumes of raw material to marine biorefineries, serving various needs in a strengthened Norwegian bioeconomy.

Key-measures:

- Develop a roadmap and establish a national initiative to realize biorefining of low-trophic marine organisms towards 2030.
- Establish value and logistics chains for mass production of offshore-cultivated macroalgae.
- Utilize experience from terrestrial material biorefinery to develop the first industrial-scale refinery based on marine raw materials.
- Further develop R&D activities to map the potential of utilizing marine resources to produce biostimulants, biochar, and bioenergy combined with CCS.
- Develop integrated offshore concepts that combine the cultivation of multiple marine species adjacent to wind farms or oil platforms.
- The Ministry of Trade, Industry, and Fisheries establishes requirements for investigating opportunities for co-locating seaweed production with offshore wind farming when awarding licenses.
- Establish support schemes for pilot projects concerning the production and processing of biomass from offshore low-trophic aquaculture production.
- Mapping technology and value chains that enable carbon capture and storage from low-trophic marine aquaculture.

Bellona will:

- Investigate whether established refinery concepts, current stakeholders, and other existing industries can accelerate the development of marine biorefineries.
- Identify barriers and opportunities for establishing relevant technologies that process the cultivated marine raw materials.
- Participate in developing biorefining solutions for macroalgae through the Ocean Forest project.
- Work to make exploring opportunities for co-location of low-trophic aquaculture a requirement in the design of offshore wind farms.
- Be a driving force for realizing large-scale offshore low-trophic biomass production, potentially co-located with offshore wind, oil, and gas installations.
- Develop feasibility studies and roadmaps for including low-trophic marine resources in future Norwegian bioenergy production.
- Establish support among political decision-makers and the Norwegian industry for using marine biomass as part of the national plan for bioindustry.

Bellona's bio-team

Jessica Hough, Advisor, marine biology

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Jessica Hough has a master's degree in marine biology from the University of Oslo. She has worked as a department engineer and lab leader in the Norwegian Institute of Marine Research, where she has been on several cruises, including in the Barents Sea, West Africa and Morocco. Here, she has been responsible for providing training to local researchers in, among other things, sampling and reporting collected data. Jessica has also been involved in the organization «Lei en Biolog," where she has worked with marine restoration, communication and fieldwork. She has lived most of her life in the Philippines and in England and has worked for several international voluntary organizations.

Michele Legernes, Advisor, aquaculture

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Michele Legernes is employed as a marine biologist in Bellona and will strengthen the Bio team to deliver on a number of exciting projects, including those related to marine restoration and low-trophic aquaculture. Michele has a Masters in Marine Ecology from the University of the Virgin Islands. She comes from the position of system controller in Brim Explorer and is also the leader of the association "Marea", which focuses on low-trophic organisms and regenerative aquaculture in the Oslofjord. Michele has 10 years of experience in marine research and consultancy, as well as experience from environmental projects, both at management and operational level.

Alexander Ugland, Project Manager Bioeconomy

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Alexander has an academic background from NTNU, where he obtained a bachelor's degree in Biomarine Innovation and another bachelor's degree in Marketing and Management, specializing in innovation and entrepreneurship. Furthermore, he holds a master's degree from NMBU, where he studied Innovation and Entrepreneurship with a specialization in business development. Alexander previously worked at a landbased salmon farm and comes from a position as a business developer responsible for aquaculture at the supplier company Motek. At Bellona, Alexander works as a project manager in the bio-team, where he is responsible for projects within the bioeconomy.

Marina Hauser, LCA-Advisor

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Marina Hauser works as an LCA-advisor in Bellona's bio team, where she identifies and promotes environmental solutions through life cycle assessment and material flow analysis. Marina came to Bellona after being a postdoctoral researcher at the Department of Environmental Impacts and Sustainability at the Norwegian Institute for Air Research (NILU). She has a solid academic background with a bachelor's degree in environmental science from the University of Wisconsin - Green Bay, a master's degree in residual resource engineering from the Technical University of Denmark (DTU) and the Norwegian University of Science and Technology (NTNU), and a PhD in environmental systems science from the Swiss Federal Institute of Technology (ETH).

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Olav Fjeld Kraugerud works with sustainable solutions for Norwegian agriculture and aquaculture, and how to accelerate the development of the Norwegian bioeconomy. He has a particular focus on sustainable feed for the future. Olav has extensive experience in the field of feed from both business and academia, as well as a researcher and operational manager. At Cargill, Olav was a senior researcher working with raw materials for the blue and green sectors. Themes there included optimal processing for the best possible feed performance of alternative raw materials. Before that, he worked as a section manager at the Center for Feed Technology (NMBU), where the customers were the European feed industry and many of the assignments involved innovation projects in new raw materials. It was also at NMBU that he took his PhD (process and nutrition) and before that he took a master's degree in biotechnology, focusing on the carbohydrate molecules in seaweed.

Joakim Hauge, Global Head of Science and Strategy

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As Global Head of Science and Strategy, Joakim has primary responsibility for Bellona's strategy development, and for strengthening interaction, coordination and synergies between departments and the various offices in Bellona. The position also has primary responsibility for defining and implementing an overall direction and structure for the foundation's scientific and technological work. Joakim holds a MSc in biology from the Center for Ecological and Evolutionary Synthesis at the University of Oslo. He has broad experience with strategy development, innovation processes and environmental technologies from organizations, the private sector and through consulting for international institutions. Previous roles include CEO and President of the Sahara Forest Project and head of Bellona's bioeconomy team.

Silje Båtsvik Risholm, Senior Advisor, aquaculture

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Silje has a master's degree in ecological economics from Nord University and a bachelor’s degree in comparative politics together with a Chinese language degree from UiB & UiO. She has worked in various parts of the aquaculture industry since 2009 and has extensive international experience, mainly from Asia. She has previously worked both with marketing of seafood in the Seafood Council in China and sales and exports in Lerøy. In Sett sjøbein / FHF she worked within communication and recruitment to the industry. Before joining Bellona, she was project manager at Tekna, where she led the Havåker project, tackling new challenges in the aquaculture industry.

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Kari holds a bachelor’s degree in biology in marine resources and aquaculture from the Norwegian University of Science and Technology (NTNU), and a master’s degree in aquatic medicine from the Norwegian School of Veterinary Science (NVH). Before she joined Bellona, she worked with aquaculture insurance as well as with fish health services. In Bellona, Kari works with aquaculture and Ocean Forest.

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