## 12.3 Norwegian Sea ecoregion – Aquaculture Overview

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### Executive summary

Aquaculture in Norway is governed under national legislation with social, economic, and environmental objectives.

Marine aquaculture relies on high quality environmental conditions. Facilities in the Norwegian Sea ecoregion are located in coastal areas, which are generally characterized as low nutrient environments. Aquaculture production is dominated by salmonids, which account for around 50% of national and 25% of global salmon production. Production of other finfish species, seaweed, and molluscs is low.

Salmon lice is the major issue for farmed salmon production, and it is also the major threat to wild salmon from aquaculture in the ecoregion. Reducing the occurrence of sea lice serves profitability, animal welfare, and the environment and is the main driver of aquaculture regulations in the region today. Genetic introgression between farmed and wild salmon is another major threat.

Aquaculture is an important industry for coastal communities in the ecoregion. In the past, industry growth has been governed by profitability concerns; currently, however, environmental concerns are governing aquaculture developments. Competing interests from other human activity sectors and recreational uses in coastal areas is changing the outlook for the industry.

Sustainable aquaculture growth requires innovative production technologies to reduce the environmental impact, development of sustainable feed ingredients for fish farming, and expansion and diversification to lower trophic organisms and fish species other than salmonids. Future aquaculture development should also consider the impacts of climate change and interactions with other human activities in the sea.

### Introduction

Marine aquaculture activity occurs along the coast in the Norwegian Sea ecoregion (Figure 1), with sites generally located within one nautical mile from the coast.

Coastal waters in the ecoregion have variable but generally low nutrient concentrations, and the majority of aquaculture sites are located in moderate to high wave exposed areas with moderate to high currents. Monitoring at coastal hydrographic stations in the ecoregion has been in place for multiple decades, while more detailed fjord water quality monitoring has only started relatively recently.

There are four spatial scales relevant to aquaculture activities in the ecoregion: the broader jurisdictional scale (i.e., the entire Norwegian coastline); the ecoregion scale; the Norwegian county and municipality scale, at which official aquaculture statistics are reported and licensing occurs (including allocation of aquaculture sites and area planning); and the aquaculture production zones (PZs), the scale at which production capacity is regulated for salmon and trout farming, on the basis of salmon lice-induced mortality on wild salmon post-smolt. ICES considers the ecoregion scale as the relevant spatial scale to inform ecosystem-based management.

This overview provides:

- a summary of regional and temporal information on aquaculture activities, practices, and production of the cultured taxa;
- a description of the relevant policy and legal foundation;
- considerations of the environmental and socioeconomic interactions of aquaculture activities and practices;
- insights on the interaction of environmental, economic, and social drivers; and
- considerations of future projections and emerging threats and opportunities.

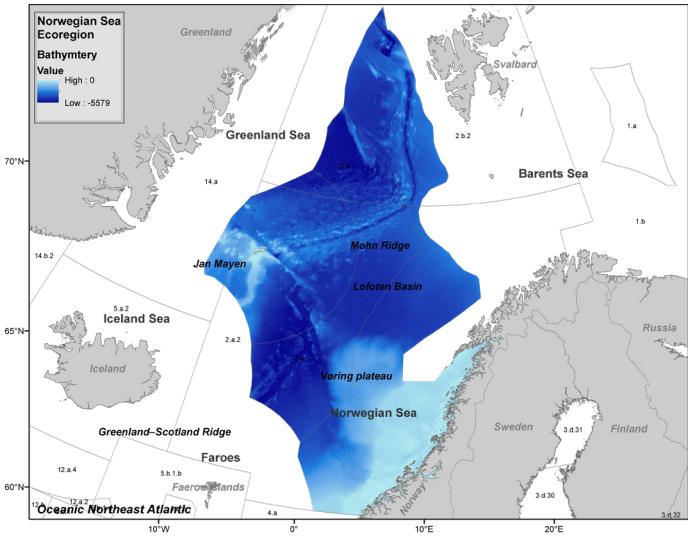


**Figure 1** The Norwegian Sea ecoregion. For locations of active aquaculture sites in the ecoregion, see Figure 2.

## Description and location of aquaculture activities and practices

The Norwegian Sea ecoregion is an important area for aquaculture production in Norway. A total of 446 sites are allocated for Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), 20 for other fish species, 81 for molluscs (including crustaceans and echinoderms), and 37 for algae (Table 1). Official aquaculture statistics are reported at the county level, and there are three counties that border the ecoregion. The farming of salmon represents the dominant aquaculture activity in the ecoregion. The ecoregion, however, also accounts for the majority of Norway's blue mussel (*Mytilus edulis*) production.

Salmonid production commences in land-based hatcheries (and nurseries) from where smolts are relocated to sea cages (usually circular floating net pens) for rearing to harvest (grow-out). Production at each site may last from 14 to 22 months, and each site typically contains between six and ten net pens with a combined maximum capacity of 3000–4000 tonnes. The duration of culture depends on multiple factors, such as the size of smolts introduced, environmental conditions, seasonal timing (spring or autumn), and licence conditions. Net pens, typically of 50 m in diameter, can have a depth of 20–50 m depending on the stage of production and water depth at the site. One net pen can hold up to 200 000 fish. The maximum stocking density is 25 kg/m$^3$. Sites are located in both relatively sheltered waters in fjords and in more exposed areas along the coast. There are also some facilities for grow-out on land in addition to the use of semi-enclosed systems in sheltered coastal areas.

Atlantic cod (*Gadus morhua*) production uses similar marine net pen systems to salmonids and relies on a combination of wild caught or hatchery-produced juveniles. Atlantic halibut (*Hippoglossus hippoglossus*) are cultured both in land-based systems and in the sea from hatchery-produced juveniles.

The most important criteria for selecting blue mussel production sites are food supply and temperature, but limiting conditions such as predation and the presence of both toxin-producing algae and harmful chemical substances are also considered. Mussel culture is typically carried out on lines suspended from longlines held at the surface by floats. Wild seed settles from the water column onto the lines. Stock is thinned out as it grows and thereby the area under culture will increase during the production cycle. Mussel farms are located in sheltered and relatively shallow (< 200 m) inshore waters.

Algae production typically uses longline systems similar to mussel longline. The source of stock is primarily from hatcheries where sporlings are seeded onto lines.

**Table 1** Marine aquaculture sites by county in Norway (Norwegian Sea ecoregion counties are shown in **bold**, they account for 46% of the total aquaculture sites in Norway). Molluscs, crustaceans, and echinoderms includes blue mussel (*Mytilus edulis*), great scallop (*Pecten maximus*), European oyster (*Ostrea edulis*) and other shellfish, and sea urchin. Other fish species includes, amongst others, Atlantic cod (*Gadus morhua*), Arctic char (*Salvelinus alpinus*), Atlantic halibut *(Hippoglossus hippoglossus)*, turbot (*Scophthalmus maximus*), wrasse (*Labrus* spp.), and lumpfish (*Cyclopterus lumpus*). Algae includes sugar kelp (*Saccharina latissima*), winged kelp (*Alaria esculenta*), and other species.

| County | Atlantic salmon and rainbow trout | Other fish species | Molluscs, crustaceans, and echinoderms | Algae |
|---|---|---|---|---|
| Troms og Finnmark | 196 | 6 | 3 | 3 |
| **Nordland** | **203** | **8** | **39** | **19** |
| **Trøndelag** | **163** | **9** | **40** | **10** |
| **Møre og Romsdal** | **80** | **3** | **2** | **8** |
| Vestland | 272 | 8 | 45 | 47 |
| Rogaland | 62 | 2 | 5 | 3 |
| Agder | 10 | 0 | 6 | 3 |
| Other counties | 0 | 0 | 1 | 0 |
| **Total** | **986** | **36** | **141** | **93** |

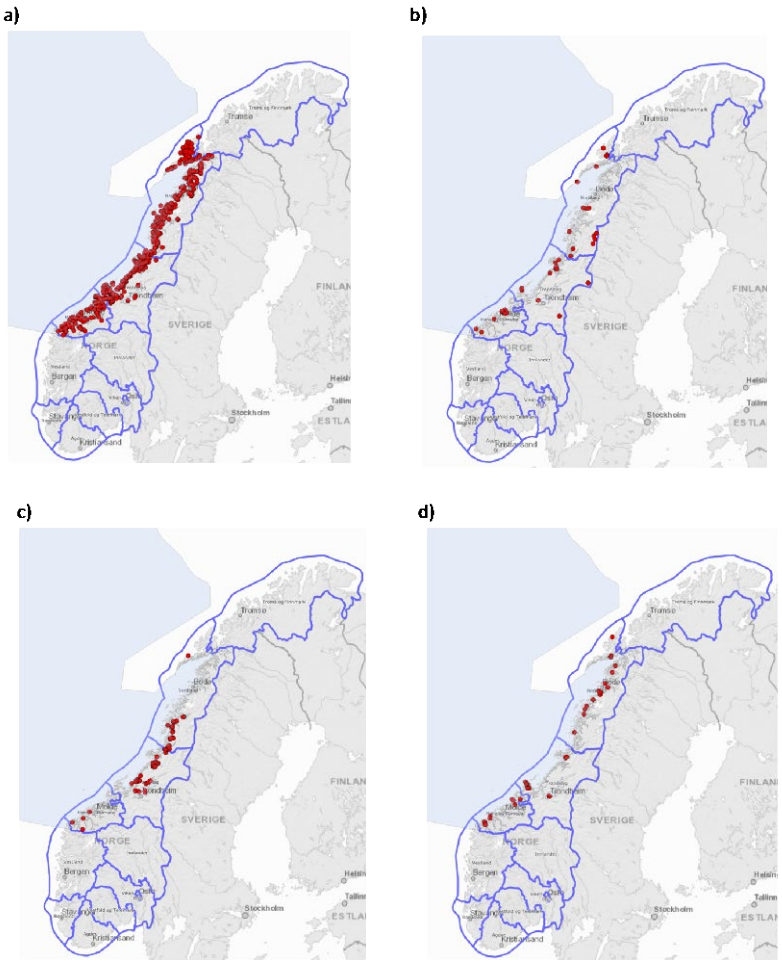


**Figure 2** Location of aquaculture sites in counties bordering the Norwegian Sea ecoregion (marine- and land-based). The three counties bordering the Norwegian Sea ecoregion are (light blue area): Møre og Romsdal, Trøndelag, and Nordland. Panels display aquaculture sites by species type: (a) Atlantic salmon and rainbow trout, (b) other fish species, (c) molluscs, crustaceans and echinoderms, and (d) algae.

## Production over time

Aquaculture production in the ecoregion commenced in the 1970s with low production in the early years, but began to grow more rapidly in the 1980s. In 2019, aquaculture production in the Norwegian Sea ecoregion (counties of Møre og Romsdal, Trøndelag, and Nordland) constituted about 50% of the overall aquaculture production in Norway (Table 2). The production of Atlantic salmon in the ecoregion has generally increased over time (Figure 3a) and in addition to accounting for 50% of national production, the ecoregion accounts for up to 25% of global production. Since 2010 this increase is driven primarily by greater production in the northernmost county, Nordland. The production of rainbow trout has remained low relative to salmon and has decreased marginally since 2008 (Figure 3a).

The production of other fish species in the ecoregion peaked during 2008–2011, primarily driven by Atlantic cod production (Figure 3b). However, since 2011 the production of cod decreased sharply primarily due to disease, early maturation, and low profitability.

Production of molluscs, crustaceans, and echinoderms in the ecoregion has been around 2000 tonnes since 2004. The temporal dynamics of production for this species category are primarily driven by the production of the blue mussel (around 2000 tonnes; Figure 3c). Algal production in 2019 in Norway was 117 tonnes (Table 2).

**Table 2** Aquaculture production in Norwegian Sea ecoregion (by county and total) and in total in Norway in 2019. Numbers are given in metric tonnes. Other fish species includes Atlantic cod, Arctic char, Atlantic halibut, and minor quantities of other species. Molluscs, crustaceans and echinoderms include blue mussels, scallops, oysters and other shellfish.

| Species | Norwegian Sea ecoregion | | | | Norway |
|---|---|---|---|---|---|
| | Nordland | Trøndelag | Møre og Romsdal | Total | |
| Atlantic salmon | 305301 | 201575 | 186766 | 693641 | 1364042 |
| Rainbow trout | 4395 | 2592 | 12992 | 19979 | 83290 |
| Brown trout | 0 | 0 | 0 | 0 | 199 |
| Other fish species | 1145 | 201 | 0 | 1346 | 3230 |
| Molluscs, crustaceans, and echinoderms | 839 | 1243 | 8 | 2090 | 2164 |
| Algae | | | | | 117 |
| Total | 311680 | 205611 | 199766 | 717056 | 1453042 |

Aquaculture production also includes the production of juvenile fish, primarily salmonids (Figure 4) and species used as cleaner fish (lumpfish [*Cyclopterus lumpus*] and to a lesser extent, ballan wrasse [*Labrus bergylta*]). Production of juveniles has increased steadily since the year 2000. This increase has been driven primarily by higher production over the last decades in the ecoregion.

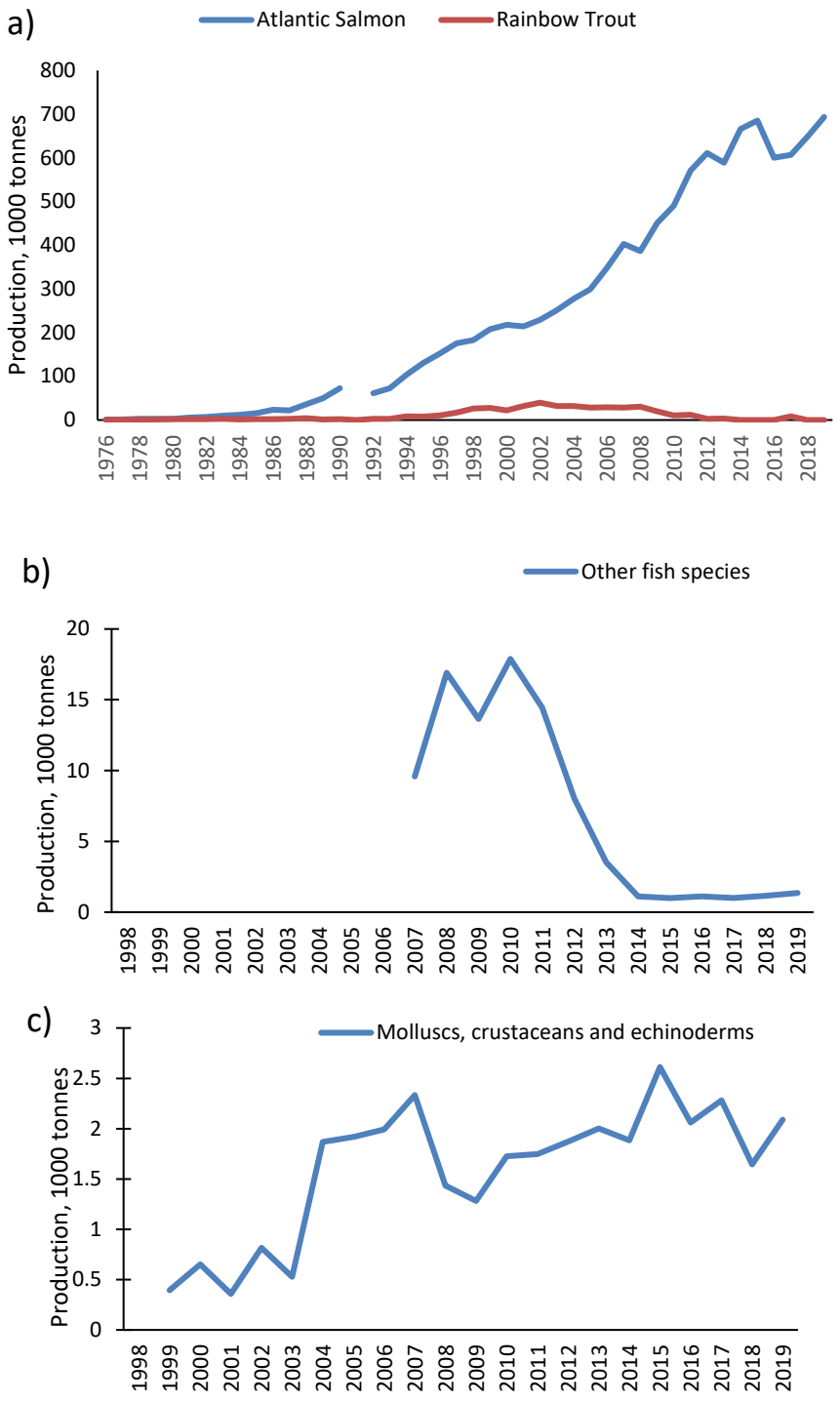


**Figure 3** Aquaculture production in the Norwegian Sea ecoregion (counties of Nordland, Trøndelag and Møre og Romsdal) of (a) Atlantic salmon and rainbow trout, (b) other fish species, and (c) molluscs, crustaceans, and echinoderms (all in thousand tonnes).

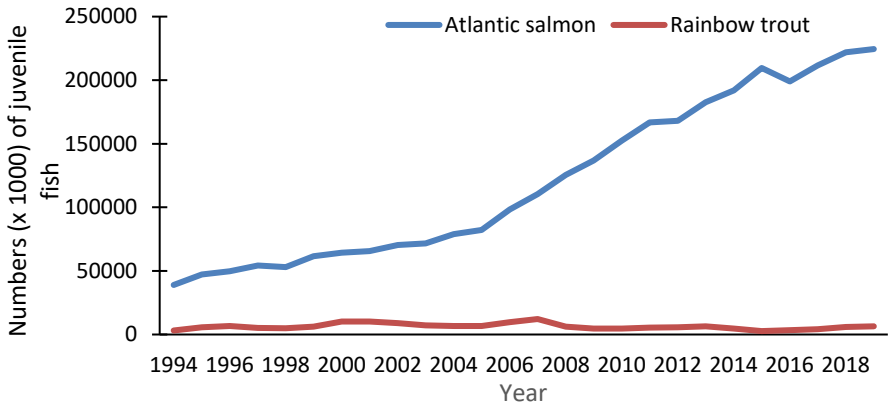


**Figure 4** Production of juvenile Atlantic salmon and rainbow trout (numbers in thousands) in the Norwegian Sea ecoregion (counties of Nordland, Trøndelag, and Møre og Romsdal).

## Policy and legal foundation

Aquaculture management in Norway is conducted under the Aquaculture Act of 2005, with the general objective '*to promote the profitability and competitiveness of the aquaculture industry within the framework of a sustainable development and contribute to the creation of value on the coast*'. As of April 2021, there were 25 formal regulations authorized under the Aquaculture Act, including the production zones (PZs) regulation. PZs represent defined areas where salmonid aquaculture production capacity is regulated, and these were delineated based on hydrodynamics modelling and the associated probability of salmon lice spread. PZs are used to achieve a more predictable system for growth in aquaculture production, while taking environmental sustainability into account. There are 13 PZs along the Norwegian coast (Figure 5).

Area planning for aquaculture activities within the coastal zone (i.e. the area within the first nautical mile from the baseline) is regulated based on the Planning and Building Act of 2008, with municipal councils responsible for the planning. A fish farm must be located within a predefined aquaculture zone in the relevant municipal land-use plan, or may be located somewhere else by exemption. Currently, area planning for aquaculture outside of the coastal zone is not regulated, but relevant policy is provided for major ocean areas, including for the Norwegian Sea, under Norway's Integrated Management Plans.

Aquaculture production in Norway requires a licence (Table 3), which gives the right to produce a certain species within a predefined aquaculture zone. Special licences are also required for juvenile production and broodstock and slaughter cages, as well as for research, development, education, and viewing. The issuing of licences is regulated under the Aquaculture Act and separate, additional regulation.

**Table 3** Aquaculture licences by county in Norway (counties within the Norwegian Sea ecoregion are shown in **bold**).

| County | Atlantic salmon, sea trout, and rainbow trout* | Other fish species** | Molluscs, crustaceans, and echinoderms | Algae | Sea ranching |
|---|---|---|---|---|---|
| Troms og Finnmark | 267 | 29 | 13 | 6 | 0 |
| **Nordland** | **293** | **41** | **41** | **173** | **0** |
| **Trøndelag** | **270** | **48** | **46** | **23** | **1** |
| **Møre og Romsdal** | **162** | **29** | **8** | **12** | **1** |
| Vestland | 381 | 85 | 72 | 280 | 0 |
| Rogaland | 104 | 26 | 18 | 3 | 3 |
| Agder | 27 | 14 | 12 | 14 | 2 |
| Other counties | 36 | 18 | 5 | 0 | 0 |
| Total | 1540 | 290 | 215 | 511 | 7 |
| Norwegian Sea | **725 (47%)** | **118 (41%)** | **95 (44%)** | **208 (41%)** | **2 (29%)** |

* Atlantic salmon, rainbow trout, and trout include commercial grow-out and juveniles, broodstock, education, research, development, and viewing licenses.
** Other fish species includes grow out- and brood stock licenses.

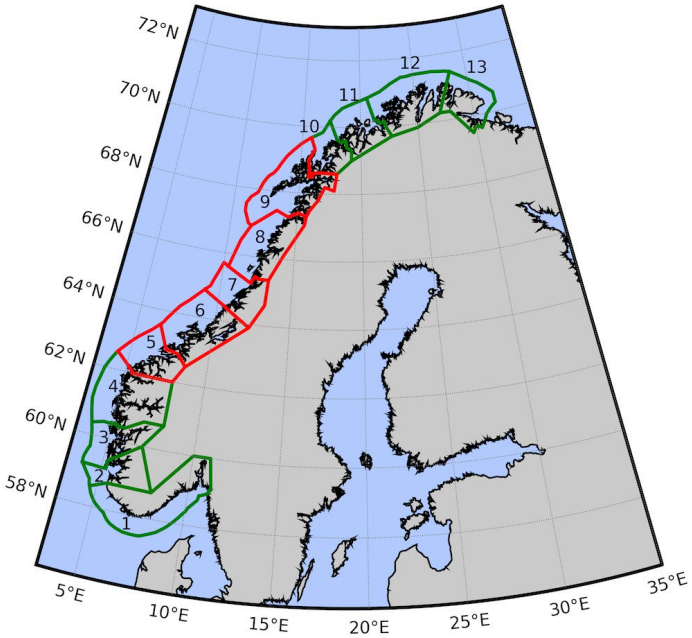


**Figure 5** Location of production zones (PZs) for regulation of farming capacity of Atlantic salmon, sea trout, and rainbow trout. The PZs within the Norwegian Sea ecoregion (in red) are: 5 – Stadt til Hustadvika, 6 – Nordmøre og Sør-Trøndelag, 7 – Nord-Trøndelag and Bindal, 8 – Helgeland to Bodø, and 9 – Vestfjorden and Vesterålen.

***Management measures***

The risk of salmon lice spread from farmed salmon to wild salmonid species (e.g., salmon, sea trout, Arctic char) is currently the primary environmental metric used by the Norwegian government for managing aquaculture production in the ecoregion. Production capacity for salmon, sea trout, and rainbow trout aquaculture is regulated by ministerial decision every second year at the scale of individual PZs using a traffic light system implemented in 2017. Regular assessments of estimated sea lice induced mortality on wild post-smolts from aquaculture are used to categorise PZs as either "green" (less than 10% mortality), "yellow" (between 10–30% estimated mortality), or "red" (above 30% mortality). Production capacity can increase by 6% in "green" PZs and must decrease by 6% in "red" PZs, while remaining unchanged in "yellow" PZs. This traffic light system is currently under review with the intent to address a broader range of environmental impacts from aquaculture.

Work is ongoing to develop a mortality indicator for use in the management of animal welfare in salmonid farms, to remove escaped farmed fish from the wild to minimize genetic introgression with wild populations, and to mitigate the impacts of aquaculture facilities on other species including seabirds (e.g. covering of net pens with bird mesh, video monitoring [above and below the water surface], reduced use of lighting, return of waste to mainland, and reduced speed of operating vessels).

## Ecosystem/environment interactions

Aquaculture activities within the Norwegian Sea ecoregion result in a range of ecosystem and environmental interactions. The focus is on the environmental interactions of salmonid farming as this represents the dominant form of aquaculture production within the ecoregion.

### Salmonid aquaculture

Salmon lice

The salmon louse (*Lepeophtheirus salmonis*) is the most abundant parasite that affects farmed Atlantic salmon and is considered the major threat to wild salmon from aquaculture within the ecoregion. There is an increased risk of additional

mortality in migrating post-smolt salmon in southern areas due to a combination of high lice levels within southern PZs combined with increased contact time with migrating smolts, which exacerbates the problem. Currently, the estimated lice-induced additional mortality of wild salmonids is the primary environmental metric used to manage salmon aquaculture production (i.e. the traffic light system) in the PZs, and there are regulations on the total allowable number of sea lice per fish.

Genetic introgression

Genetic introgression between farmed and wild salmon has been well-described and is considered a main threat. More than 300 000 farmed salmonids escaped in the ecoregion during 2015–2019; more than half of these within PZ 7. In the past, poor construction and/or maintenance of net pens combined with bad weather was the main cause of escapes. Currently, handling operations like delousing or harvesting are responsible for most escape events.

Disease transmission

According to the Norwegian Veterinary Institute, viral diseases are a serious problem in fish farming in Norway, and disease transmission from salmon farms to wild salmon is considered a threat. However, the occurrence of viral diseases in wild salmon populations has been monitored since 2012 and although infected farmed fish have been found in salmon rivers, so far no major disease outbreaks in wild salmon populations have been reported. Despite this, the most common pathogenic viruses cause 400 to 500 outbreaks of disease in fish farms along the entire coast each year.

Farm effluents

Emissions of dissolved nutrients and particulate organic matter (faeces and spillover feed) are released directly into the environment from open net pens. Emissions of dissolved nutrients in this ecoregion are not considered to be an environmental challenge with today's production level, primarily because of the oligotrophic (nutrient deficient) status of waters and local hydrodynamic conditions. Impacts from particulate wastes on the seabed are highest closed to the farm, especially in low current locations and are managed on a site-by-site basis via monitoring programmes. Wild fish can be attracted to open-cage fish farms due to spillover feed, which might have both negative and positive effects.

Copper is a concern because of its toxicity to marine biota with particular risk to early life stages, infauna, and sedentary benthic organisms. Copper-based compounds are frequently used as an antifoulant in netting at salmon farms and have been found to contribute to copper accumulation within sediments over time.

The use of antibacterial agents and drugs against internal parasites on salmon farms in the ecoregion, has been at a low level for many years, and therefore from an environmental perspective, the therapeutics of concern are the drugs used in the treatment of salmon lice. Salmon lice are crustaceans, and drugs that kill salmon lice can potentially affect other crustaceans, ranging from planktonic organisms to crabs and lobsters. Both in-feed drugs and bath treatments are used against sea lice, but although these have been proven to be toxic to many non-target crustaceans, no major environmental impacts have so far been documented.

Use of cleaner fish

The use of cleaner fish for delousing is common in the salmon industry and is considered as a low impact method of lice control. Cleaner fish also pose little direct welfare risk to the salmon compared to chemical delousing and especially mechanical and thermal delousing. In general, the current use of cleaner fish by the industry is not considered sustainable, mainly due to very high mortality rates and thus animal welfare concerns. Also, increased fishing in the wild (for ballan wrasse in particular) may impact on local populations. Finally, relocating cleaner fish over long distances presents risks to local wild fish populations in terms of the transmission of pathogens and genetic introgression in the event of cleaner fish escapes.

Farmed salmon welfare

The welfare situation for farmed salmon within the ecoregion is considered to range from bad to moderate. Indicators of poor welfare are disease, parasites, wounds and injuries, poor growth and weight loss, and deviant behaviour, all of which can be linked to increased mortality.

**All aquaculture**

Marine mammals

There is some evidence of interactions between marine mammals and aquaculture in the ecoregion, including reports of entanglement of whales (minke whales [*Balaenoptera acutorostrata*] and humpback whales [*Megaptera novaeangliae*]) in the anchor lines of the farms. Additionally, seals (harbour seal [*Phoca vitulina*]) and otters (*Lutra lutra*) frequently feed near fish farms, possibly increasing stress levels in the fish. Marine mammals like seals can damage fish pens, potentially resulting in net pen failure and mass escapes of fish.

Seabirds

The environmental impacts of aquaculture activities on seabirds may include risk of entanglement (in the net pens and bird netting) or interactions with marine debris. In addition, the productivity and health of seabirds can be affected by their foraging on fish feed or cultured species like mussels and oysters. Possible hazards to seabird populations include disturbance from farm activities such as noise and through collision with farm vessels and lighting.

Seaweed and bivalve shellfish farming

Seaweed cultivation is considered to have fewer negative environmental impacts compared to finfish farming, while longline mussel production has local impacts on benthic communities and habitats, local hydrodynamics, plankton abundance, and pathogen transmission. Seaweed and bivalve shellfish farming can provide environmental benefits, such as habitat for wild fish and invertebrates as well as nutrient removal.

## Social and economic context

The nature and extent of aquaculture activities, practice, and production are influenced by social and economic considerations. Aquaculture in the Norwegian Sea ecoregion, as elsewhere in Norway, is managed under the social and economic objectives stated in the Aquaculture Act – specifically profitability, sustainable development, and value creation on the coast.

**Profitability**

Profitability can vary substantially over time as a result of biological factors (e.g. disease outbreaks) and economic factors, including feed prices and other production costs, market demand and prices, and import tariffs to major international markets. Concerns for the profitability of salmon and trout farming in Norway have historically motivated limitations on new licences or production, but today environmental concerns are more important. In recent years, profitability measured as the operating margin has been high for companies operating within the Norwegian Sea ecoregion (Figure 6). High profitability is linked to growing international market demand and a limited number of new licences being issued out of environmental concerns, mainly salmon lice. Profitability has increased despite a general increase in production costs, namely the cost of feed and other costs related to salmon lice and disease treatments (Figure 7).

Sales value is related to production volume and the average price received by species or species groups, which can vary considerably over time and within short timespans. In 2019, counties located within the Norwegian Sea ecoregion accounted for 50% of total Norwegian sales of Atlantic salmon (total sale: 68.0 billion NOK), 21.4% of total sales of other fish species, exclusive of salmon and rainbow trout (total sale: 238.8 million NOK), and 94% of total sales of molluscs, crustaceans, and echinoderms; the sales of the latter being dominated by blue mussels (total sale: 28.7 million NOK). Among other fish species, farmed Atlantic halibut had by far the highest sales value (accounting for 65% of the total national value of sale of other fish species in 2019).

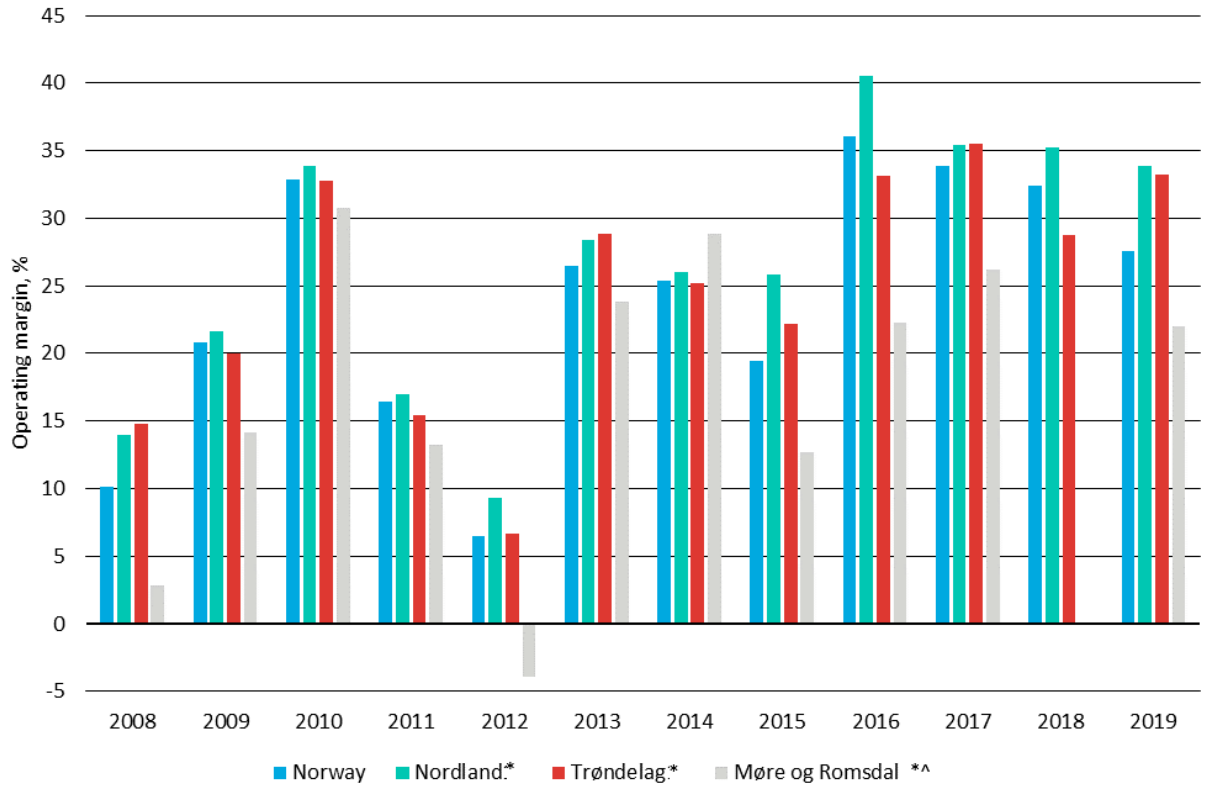


**Figure 6** Operating margin (operating profit divided by operating revenues) for farming of salmon and trout (%) for all Norwegian companies and for companies operating only in the three counties located within the Norwegian Sea ecoregion.

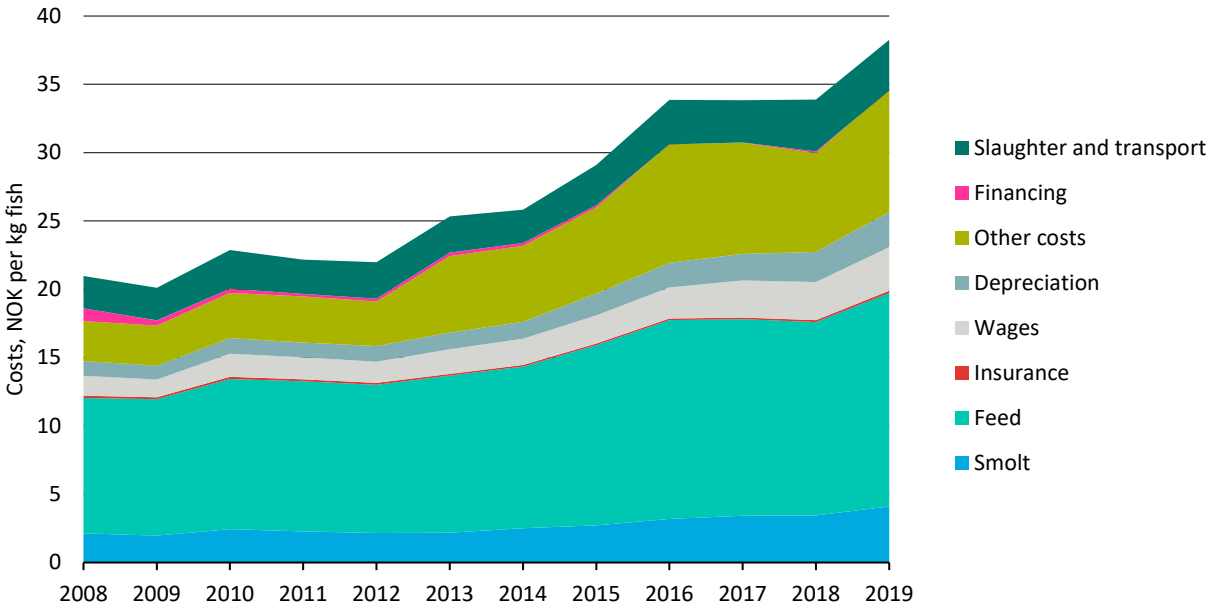


**Figure 7** Temporal trend in production costs per kg fish (salmon and trout) produced, average for Norway (in Norwegian kroner, NOK). Other costs are related to salmon lice and disease treatments.

**Value creation on the coast**

Norwegian aquaculture is to a large degree a rural and coastal industry. Aquaculture is seen as one of the few industries that can create high-paying jobs in coastal communities in the future and provide income for both private consumption

and public welfare. The employment related to aquaculture has increased over time, concurrent with the increase in production. In 2019, the aquaculture value chain including core production (breeding, juvenile production, and grow-out), slaughter and fish processing, and trade and export employed about 12 000 full-time equivalents (FTEs). Suppliers delivering services, goods, and equipment to the aquaculture value chain were estimated to employ around 30 000 FTEs.

The value added is the total revenue of a company minus the cost of the physical inputs. The total value added of Norwegian aquaculture increased from 2012 to 2019, mainly as a result of higher international prices for salmon (which also led to salmon exports dominating the total seafood export). In 2019, the value added per employee in Norwegian aquaculture was estimated to be more than double the value added per employee in fisheries – and more than three times the national average value added per employee (not including the petroleum industry).

Norwegian municipalities are now receiving a much larger share of the value added in aquaculture than they did before 2016. The concentration of ownership of the aquaculture industry, with fewer administrative centres and larger and fewer slaughter plants with more automated operations, reduces employment opportunities as well as the economic returns from salmon farming to coastal municipalities. Foreign ownership of the aquaculture industry (estimated at about 47% in Norway) also affects the distribution of benefits. Efforts are ongoing to ensure that the social and economic benefits from aquaculture reach coastal municipalities; including the establishment of the Aquaculture Fund in 2016. Whether enhanced benefits from aquaculture to municipalities will lead to further aquaculture development remains uncertain due to competing interests for natured-based recreation (clean, pristine environment) and second home owners, which have been generally favoured by municipalities over the last couple of decades.

**Social acceptability**

The public perception of aquaculture varies across the Norwegian landscape and human activity sectors. Fishers generally have a negative perception of aquaculture. Among the general public, there are widespread concerns regarding the environmental impacts of salmon farming but the general perception is that access to space for other activities like fisheries and tourism are not much affected by aquaculture. In Nordland county, the general public thinks the aquaculture industry has a positive socioeconomic effect on their municipalities. In Arctic Norway, there is a strong division on the social acceptability of aquaculture between rural and urban areas, with rural areas perceiving it more positively (possibly shaped by local employment opportunities provided by the aquaculture industry).

## Interaction of environmental, economic, and social drivers

A number of sectors operate in the coastal region of the Norwegian Sea and provide a regional context for interactions among environmental, economic, and social drivers relevant to the management and further development of aquaculture. These sectors include commercial fisheries, recreational fisheries, tourism, shipping, energy (hydropower and petroleum activities), and mining. Interactions between sectors include direct interactions through competition for space and indirect interactions through impacts on the environment as well as social and economic interactions across different spatial scales.

Regulated navigation areas cover extensive areas in the Norwegian ecoregion and along the Norwegian coast. Aquaculture contributes to shipping activity in PZs together with fisheries, petroleum, and transportation of goods and people. Shipping activity is high within PZs with 41% of total sailed distances across all PZs in 2019 and increasing over time (by 43% in the period 2015–2019).

Interactions between aquaculture and fisheries are both related to access to space and fishing grounds and the possible impact on behaviour and physiology of wild fish living close to farms. Also, the potential effects of delousing agents on non-target species, and harvested coastal shrimp populations specifically, remains a topic of concern and interest. In 2011–2019, the relative importance of coastal fisheries (e.g. vessels < 15 m in length) in terms of proportion of total catch increased from south (on average 19% of the catches in PZ 5 in 2011–2019) to north (on average 42% of the catches in PZ 9) in the ecoregion. Marine recreational fishing activities are extensive along the Norwegian coastline with a total of over 500 tourist fishing companies currently registered. Recreational activities also include some of the largest wild salmon river fisheries, with national annual revenues of 1.3 billion NOK.

Aquaculture production zones in the ecoregion intersect with the energy sector. Over 500 hydropower production facilities (30% of all hydropower facilities in Norway with 24% of hydropower energy production) is based in the PZs. In addition to

aquaculture, hydropower regulation of rivers has reduced habitat quality and inflicted high mortalities on wild salmon. Hydropower alters circulation patterns and distribution of planktonic organisms within fjords and this may influence fjord water ventilation and drift patterns of salmon lice – and therefore also salmon farming capacity. Petroleum activity is mostly located outside the PZs, although both seismic and electromagnetic surveys extend into the more offshore parts of these zones. Offshore wind farming is a sector in development and may intersect with offshore aquaculture development in future.

Land-based mining activity for deposits currently takes place in four fjords within the ecoregion with a fifth location currently under planning. Interactions between mining and aquaculture are not well understood. Environmental concerns relevant to aquaculture include the disposal of environmental pollutants, particulate matters, and sand and gravel, with impacts on the fjord environments beyond the disposal site.

## Future projections and emerging threats and opportunities

Sustainable aquaculture is a vital part of a future solution for global food security and nutrition, as well as in terms of contribution to the socioeconomic development of rural areas. Sustainable aquaculture development should consider diversifying the industry, potential impacts of climate change, and any interactions with other human activities affecting the marine environment. Table 4 summarizes information needs to support the effective management of ongoing environmental impacts of aquaculture in the Norwegian Sea ecoregion.

### Diversifying the industry

Diversification of the aquaculture industry can mainly occur through two mechanisms: 1) new production concepts and technologies for farming of salmonids and other finfish; and 2) expansion towards low-trophic species.

The environmental impacts of current culture practices of salmonids (net pens) necessitate the consideration of other production methods. These include the development of new rearing systems on land and sea and improved and sustainable sludge management technologies, as well as methods addressing challenges related to salmon lice, escapees, and other environmental impacts (e.g. closed systems and the use of sterile fish). Alternative solutions also come with challenges, for example, closed systems may accentuate problems related to fish welfare, water quality, and disease/stress. Moving fish farms onto land will require the development of large areas along the coast and will be associated with increased energy consumption due to the need for power to operate the facilities (e.g. pumping sea water).

Diversification of aquaculture practices to finfish species other than salmonids requires the elaboration of breeding, disease control, and welfare programmes, together with advanced production methods that minimize environmental impacts.

Aquaculture practice focusing on lower trophic species that do not rely on feed inputs, such as those of seaweed and mollusc, can play a significant role in nutrient recycling, and these species can act as efficient nutrient scrubbers that could assist in the management of eutrophication of coastal water.

Fishmeal availability is a global concern. Research and development efforts are needed to focus on developing third generation feed ingredients for finfish farming. These should focus on valorizing organic streams produced in the food chain with less extensive production requirements (i.e. large inputs like arable land, fertilizer, and freshwater are not required). Examples include insects fed on organic waste, yeast fed on cellulose-rich waste material, microalgae fed on captured $CO_2$, and low-trophic feed material produced in the oceans.

### Impacts of climate change

Climate change can hamper sustainable growth and existing capacity for aquaculture in the ecoregion and alter interactions with other sectors. This may lead to an unsuitable temperature regime for cold-water fish, oxygen changes in the water, and outbreaks of known and unknown disease infections. This requires, amongst other things, consideration of future temperature and hydrodynamic forecasts in area planning as well as exploring breeding and rearing technologies for more temperature tolerant species and breeding lines.

**Coastal integrated ecosystem assessment**

The future growth of the aquaculture industry in the Norwegian Sea ecoregion will require more space, likely cause increased pressure on the marine ecosystem, and elevate interactions between different human activities. While the environmental risk assessment for salmonid aquaculture is already operational, no similar risk assessments are established for the other aquaculture practices or other human activities operating in coastal areas. Future developments should consider the incorporation of ecosystem services and social and economic indicators in order to enable assessments of synergies and trade-offs among coastal sectors and to investigate consequences across environmental, ecological, and socioeconomic dimensions. Efforts are ongoing to support cross-sector assessments and facilitate coastal integrated ecosystem Assessments within the nationally funded CoastRISK project

**Table 4** Summary of main knowledge gaps and data needs regarding environmental impacts of aquaculture within the Norwegian Sea ecoregion.

| Impacts of salmonid farming | Knowledge gaps and data needs |
|---|---|
| Salmon lice impacts on wild salmonids (i.e., salmon, sea trout, and Arctic char) | • Data on tolerance limits of sea lice infestations on wild salmonids<br>• Migration routes of salmon smolts<br>• Behaviour mechanisms of early return migration in sea trout and Arctic char |
| Disease transmission to wild salmon | • Underlying mechanisms of disease transmission and infection from farmed to wild fish<br>• Predictive capacity (development of modeling tools) to investigate spatiotemporal variation in emission, spread, and dilution of pathogens from farmed fish |
| Genetic introgression in wild salmon | • Reliable escape data<br>• Reliable data on number of escaped farmed salmon at spawning grounds<br>• Vulnerability assessment of wild salmon populations to genetic introgression |
| Nutrient and waste emissions | • Coastal water quality monitoring data<br>• Environmental impacts of fish farming particulate waste on hard-bottom communities |
| Copper pollution | • Sediment monitoring and modeling of copper dispersal and dilution to understand accumulation in sediment<br>• Assessment of copper concentrations in the water column and effects on pelagic organisms, especially early life stages |
| Therapeutic drug use | • Sensitivity of non-target organisms to therapeutic drugs<br>• Predictive capacity (dispersal and dilution modeling to investigate local and regional impacts of drug use in fish farms) |
| Cleaner fish (wrasse and lumpfish) | • Reliable data on escapes of cleaner fish<br>• Effects of high fishing pressure on local wild wrasse populations<br>• Genetic introgression from escaped cleaner fish<br>• Disease transmission from cleaner fish to wild fish populations |
| Farmed salmon welfare | • Development of animal welfare indicators (e.g. acceptable mortality rates) for production management |
| General impacts | |
| Marine mammal interactions | • Evaluation of farmed fish stress levels due to presence of predatory marine mammals near aquaculture facilities<br>• Data on interaction levels between marine mammals and aquaculture activities (i.e. entanglement, collisions etc.) |
| Seabird interactions | • Data on interaction levels between seabirds and aquaculture facilities<br>• Risk assessment of environmental impacts of aquaculture on seabirds |
| Impacts of seaweed and bivalve shellfish farming | • Risk assessment of environmental impacts of seaweed and shellfish farming |

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