Report 36/2012 • Published November 2012

Aquaculture in the Arctic – a review

Øystein Hermansen (Nofima) & Max Troell (Beijer)

Nofima is a business oriented research institute working in research and development for the aquaculture, fisheries and food industry in Norway.

Nofima has about 420 employees. The main office is located in Tromsø, and the research divisions are located in Averøy, Bergen, Sunndalsøra, Stavanger, Tromsø and Ås.

Main office in Tromsø
Muninbakken 9–13
P.O. box 6122
NO-9291 Tromsø
Norway
Tel.: +47 77 62 90 00
Fax: +47 77 62 91 00
E-mail: post@nofima.no

Internet: www.nofima.no

Nofima AS
P.O. box 6122
NO-9291 Tromsø, Norway
Visiting address:
Muninbakken 9–13,
Tel.: +47 77 62 90 00
Fax: +47 77 62 91 00
post@nofima.no
www.nofima.no

Business reg. no.:
NO 989 278 835 VAT

Report

	ISBN: 978-82-8296-028-1 (printed) *ISBN:* 978-82-8296-029-8 (pdf)	*Report no:* 36/2012	*Accessibility:* **Open**
Title: **Aquaculture in the Arctic – a review**		*Date:* 26.11.12 *Number of pages and appendixes:* 32	
Author(s): Oystein Hermansen and Max Troell		*Project no.:* 21204	
By agreement with: EU-project “ACCESS” grant agreement no 265863		*Contractors ref.:*	
Three keywords: Implications, global warming, socio-economics			

Summary:

Aquaculture in the Arctic region contributes with 2% of global production. This may seem small, but is of same magnitude as EUs total aquaculture production. Norway is by far the dominant producer in the Arctic. There is some activity in Iceland and Russia, while production in Sweden and Finland is very small. In the other Arctic countries we have not noted any activity. Production mainly constitutes of salmonids with additional limited production of a few other species.

There is considerable uncertainty associated with the projections of future climate. This is also true for the Arctic region. Models predict increase in water temperature within the range of 0.5 to 2.5 degrees. Detailed impact studies for aquaculture are scarce, and even fewer analyse this from an Arctic perspective. The direct effects from a temperature change on the aquaculture industry can to some extent be modelled with fairly good accuracy, including both the effects on fish growth as well as how a whole industry may be affected. These models show how production will change and also socio-economic consequences. From these models it becomes clear that aquaculture in the Arctic will see positive effects from warming water temperatures. Other direct effects such as from storm frequencies and intensities can be relatively well anticipated, but the uncertainty regarding how these parameters will change is high.

Other indirect effects such as diseases and pest species, freshwater runoff etc are very hard to predict, aggravating the uncertainty related to climate change. What is certain is that the environmental conditions will change and that the industry will have to adapt to these changes. For enabling the industry to do so there is a need to look over existing regulatory frameworks and start a multi-stakeholder dialogue to find out where and how aquaculture operations can move or change their operations.

Table of contents

1 Introduction

1.1 Aquaculture and climate change

The climate change is already a reality in many parts of the world and the effects are particularly obvious in the Arctic region (Symon *et al.,* 2008). This will have considerable implications for the marine arctic ecosystems and as these are tightly coupled to the economic and social system (social -ecological systems) the anticipated effects may impact negatively on food production, livelihoods and overall welfare.

Aquaculture, the aquatic counterpart of agriculture, has grown rapidly in recent decades and is the fastest growing animal sourced food producing sector in the world, with a growth rate averaging about 8.8% per year the recent decade (FAO, 2012). Today about half of all seafood products we eat originate from farming and cultivations, and in 2020, aquaculture is expected to account for 60% of seafood consumed worldwide (FAO, 2007; 2012). Even if we manage to improve governance of global fisheries, capture fisheries will only to some limited extent have the capacity for increased production. Thus, this makes aquaculture our only option for obtaining more food from our aquatic environments.

Aquaculture is an economic activity that uses and transforms natural aquatic resources into commodities valued by society and in so doing it may also generate environmental impacts (Naylor *et al.,* 2000; Boyd *et al.,* 2005; Diana, 2009). Looking at the diversity of farming systems it is easy to appreciate that the biophysical impacts of aquaculture activities, that is, magnitude and spatial scale, can vary significantly. Technical and economic inputs, such as construction materials and energy, in many traditional aquaculture systems form only a small part of the inputs needed. The main and critical inputs in those systems are instead locally available natural resources and labor. Intensive production systems that earlier predominated in temperate aquaculture are also rapidly increasing in the tropics. These cultures rely instead more on technical investments and nutritionally complete commercial feeds containing e.g. fishmeal, fish oil and vegetable alternatives like soy. The magnitude and type of resource use and impacts of aquaculture are, however, very much dependent on species cultured, farming system, intensity of farming methods, and management. Small-scale faring systems are today not the same as extensive as these farms may also depend completely on formulated commercial feeds and run their farming operation in intensive mode (examples are e.g. small shrimp farms and pangasius farms).

In assessing the aquaculture - climate change nexus, it is important to have a value chain perspective, which considers not only the production process itself (and the local socio-ecological system it is embedded in), but also all the up and downstream activities like seed and feed production, transportation, processing, distribution and marketing activities. Aquaculture contributes to global warming potential by the release of carbon dioxide and this primarily through energy use for supplying essential inputs and through on-farm processes, processing and distribution. However, aquaculture is not a significant contributor to climate change, but, nonetheless, should strive for reducing energy consumption through-out the whole value chain. Considering future changes in energy prices, aquaculture systems need to optimize performance to stay competitive and build resilience against fluctuating energy prices. Changes in energy usage, together with other resources and environmental impacts may be achieved through adoption of codes of practice, encouraged by fiscal and economic incentives and ethical consumers. The need for tools measuring environmental performance, i.e. an activities environmental footprint, is needed for making comparisons between production systems. LCA has been suggested to be one such a tool and is increasingly used also for aquaculture production.

A key challenge for aquaculture from climatic change involves changes in water temperature; this will impact on the overall aquatic environment that supports aquaculture production, as well as the performance of the farming operations itself. The temperature range will define where production can take place and possible impacts on productivity. Increased temperature above some critical points will stress existing farmed species, impacting on survival, and growth, and possibly also increase risks for pest species from surrounding ecosystem. Changed water temperature may also open up for other aquaculture species having different tolerance and temperature optima. The overall impact from climate change will depend on present structure of the aquaculture industry, i.e. its capacity to adapt to new circumstances, accessibility to new water and land suitable for production, existing regulations and markets. At the larger scale, changes in temperature and precipitation pattern will affect global crop production and there are uncertainties with respect to its effects on the availability of fish meal and oil. This may affect aquaculture production significantly changes in prices and availability of feed.

This report is part of the European Commission 7th framework programme project ACCESS (www.access-eu.org). A bearing element in this large project is to study the implications of climate change for Arctic ecosystems - including both the native people deeply embedded in the social-ecological system as well as outside people being dependent or linked to arctic activities and functions. This report focuses on the aquaculture industry in the Arctic region and forms the first part in a broader evaluation of how aquaculture activity there will be directly influenced by climate change effects and also how it will be indirectly affected by other climate change effects.

More specifically this first report aims at giving a general overview of the present aquaculture industry within the Arctic region. A shorter review of present knowledge on climate change implications with relevance for Arctic aquaculture is also included, that will be further described in subsequent analyses. Aquaculture production in the Arctic region will then also be viewed from a larger governance perspective where the industry's capacity to adapt to new and evolving conditions will be evaluated.

1.2 The Arctic

An important starting point is to coin the geographic limits of the rather poorly defined term "The Arctic". Several definitions are in use; the area north of the Polar Circle, the polar treeline, the July 10°C isotherm among others. These are shown in Figure 1, and clearly show that the geographic differences are rather large, depending on the boundary definition that is employed. Aquaculture is quite limited in these relatively cold areas, and this work therefore takes an inclusive approach and limits the research area to the least restrictive of the limits. Data availability for individual countries may also force the analysis to make adjustments of what areas to include. In the review of present production, areas just outside the defined boundary may be discussed as this will be important for making predictions of possible expansions or relocation of current activity into the Arctic.

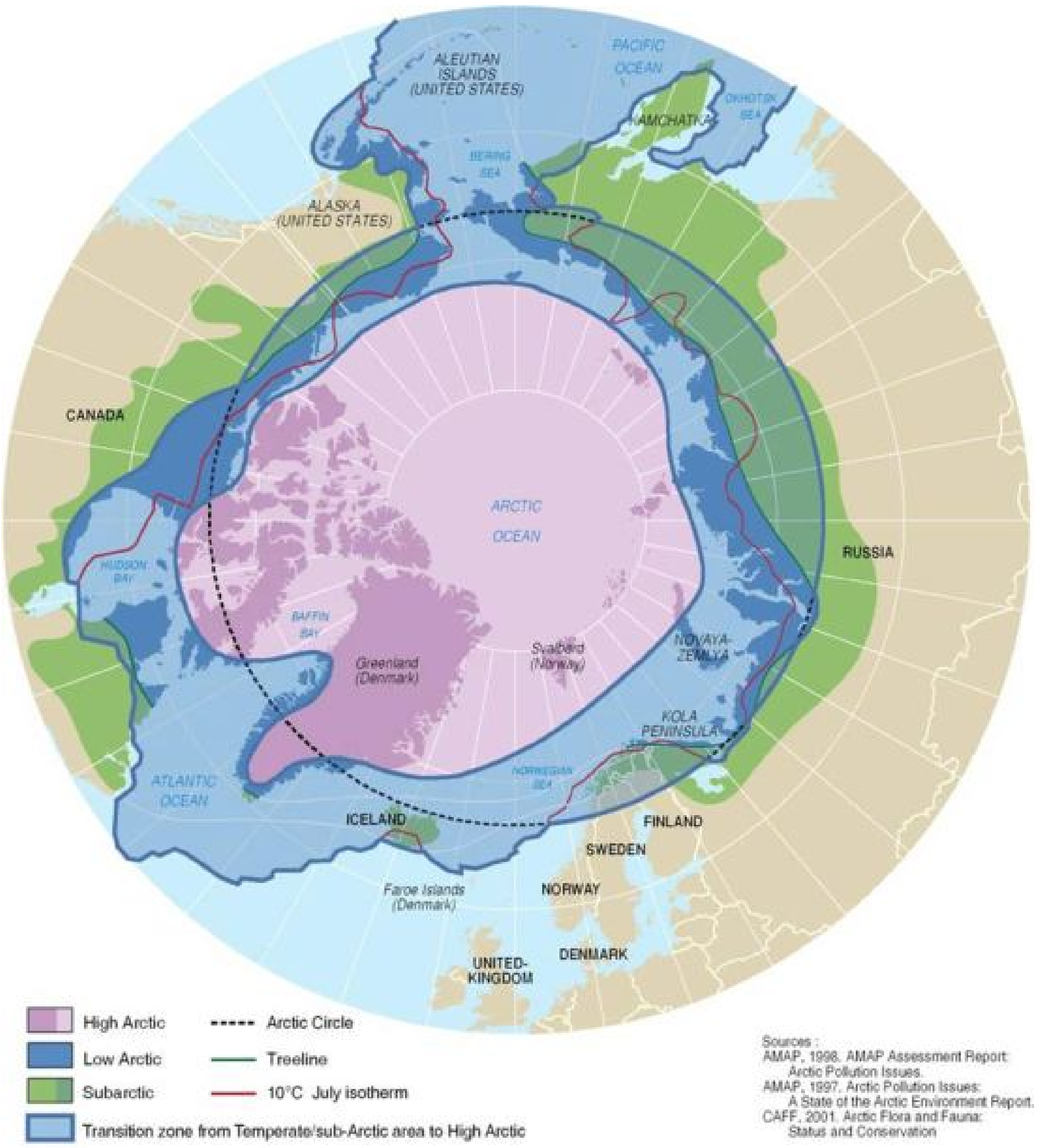

Figure 1 Definitions of the Arctic (Source: Philippe Rekacewicz, UNEP/GRID, http://www.grida.no/graphicslib/detail/definitions-of-the-arctic_12ba)

2 Aquaculture production in the Arctic

This section presents details about present aquaculture activities within the Arctic region as this will form a needed basis for subsequent predictions about climatic effects on the industry. The review builds on production data obtained through official national statistics. Industry data or other sources have been utilized where such data not been available or quality of data been poor. Data been collected and presented as values of annual production measured in USD and is presented country wise. Focus is on production quantities, values, geographic location and physical parameters such as sea temperature range in the areas of the farming activity. For comparison and reasons discussed above, aquaculture activity in neighboring areas is also presented.

2.1 Regional overview

Aquaculture is already an important economic activity in some limited parts of the Arctic region. In particular, production of salmonids in Norwegian waters is large and besides generation of high export revenues it is a significant contributor to rural economies and employment. Salmonids have been introduced for farming in the Kola Peninsula in Russia, but so far production is limited. There are also long traditions for farming freshwater species in Sweden and Finland, and farming of Atlantic cod and halibut has been developing for some years in e.g. Norway. Total aquaculture production in the Arctic constitutes about 2% of both global production volumes and global values of fish and shellfish (Source of global figures: FAO 2010).

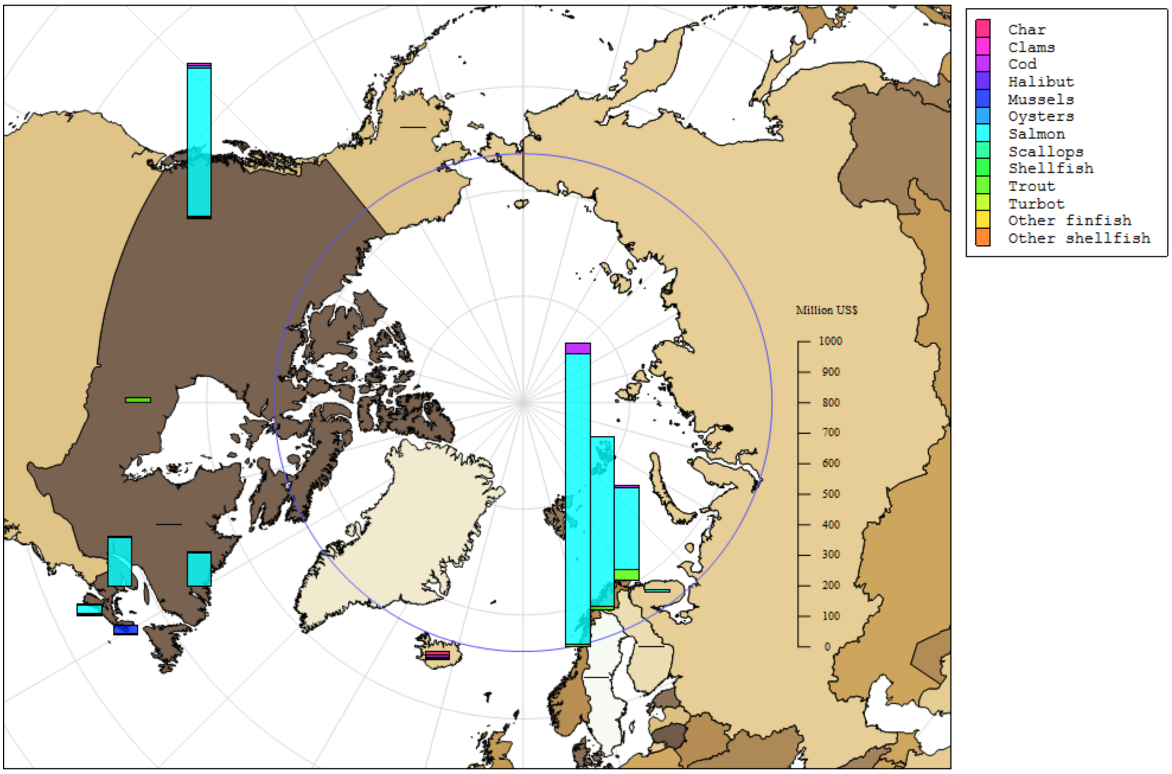

Figure 2 Aquaculture production in the Arctic and selected surrounding areas by location, specie and value (Source: National and State Aquaculture authorities, FAO)

Figure 2 provides an overview of the geographic species distribution of aquaculture in the region, including the production in some areas being close to the Arctic. The vast majority of aquaculture in the Arctic is made up of salmon culture in Norway. This represents 93% of the total value of aquaculture in the region. Norway is also home to the second and third largest species, trout and cod bringing the Norwegian share of Arctic aquaculture to 98%.

To get a better overview of the contribution of other species and countries, the Norwegian production has been excluded in Figure 3. It then more clearly shows that Iceland has a significant production of arctic char and cod, and that Russia and Iceland both produce smaller volumes of salmon. In Finland and Sweden the production is dominated by small volumes of freshwater species.

If accounting also for the surrounding areas; there is a considerable salmon production in Newfoundland, Canada. Here there is also some production of mussels. In the southern parts of Alaska there are some mussel and scallop production.

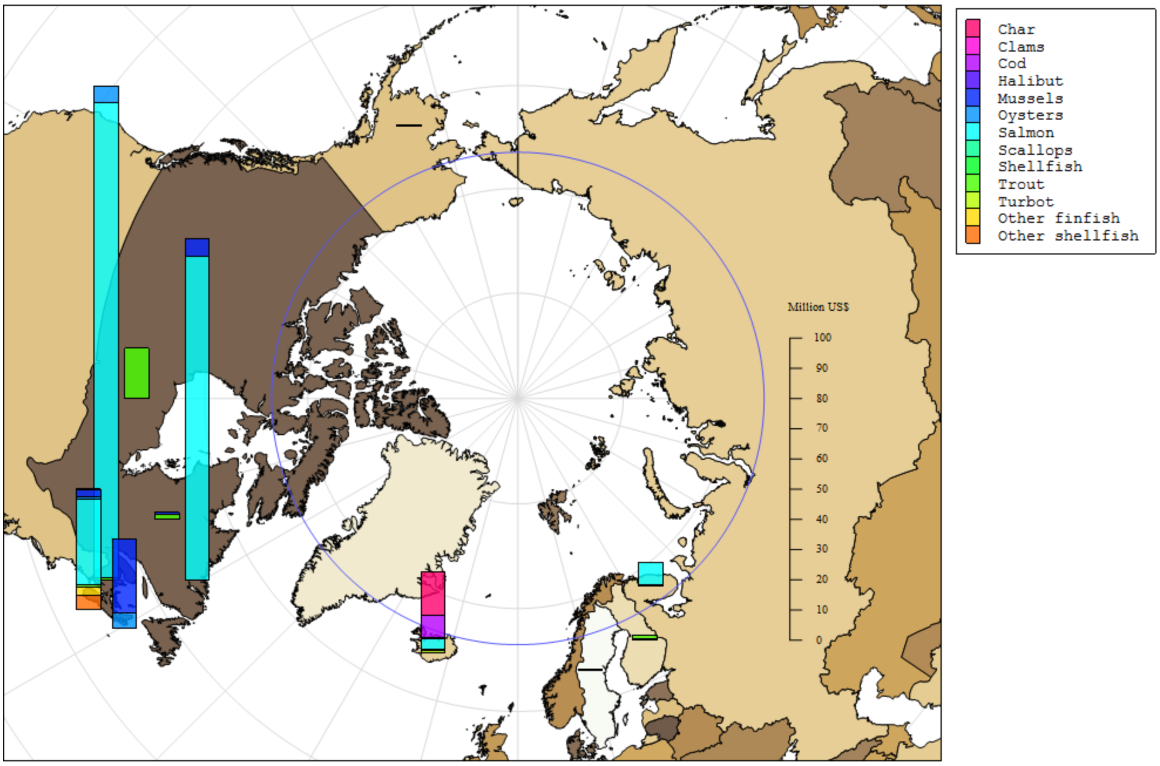

Figure 3 Aquaculture production in the Arctic and selected surrounding areas, excluding Norway and British Columbia. (Source: National and State Aquaculture authorities, FAO)

2.2 Iceland

According to Figure 1, only a small part of Iceland is south of the July isotherm, hence the whole country is included in the present survey of aquaculture in the Arctic. Iceland has limited coastline that is protected and suitable for aquaculture, hence production is relatively small. FAO data on 2009 production is shown in Table 1. Arctic char (*Salvelinus alpinus*) is by far the largest specie at about 50% of total production. This is followed by Atlantic cod (*Gadus morhua*) and Atlantic salmon (*Salmo salar*). There is some minor production of flatfish, trout and mussels. It is noteworthy that a large share of the overall production is land-based.

Table 1 Value of Icelandic aquaculture production in 2009 (1,000 USD)(Source: FAO Fishstat)

	Inland	Sea
Arctic char	14430	
Atlantic cod		7220
Atlantic salmon		3570
Atlantic halibut		441
Turbot	544	
Rainbow trout	300	
Blue mussel		98
Total	15274	11329
Total		26603

Icelandic aquaculture has gone through several phases, rapid growth in the 1980ies, stable production in the 1990ies, rapid growth until 2006 and then a sharp decline. This development is shown in Figure 4. Salmon has been the major species until the decline from 2006 to 2007 when production was reduced from about 7.000 to about 500 tonnes. Arctic char has had a relatively steady growth through the whole period. Cod culture started to develop first after the turn of the century.

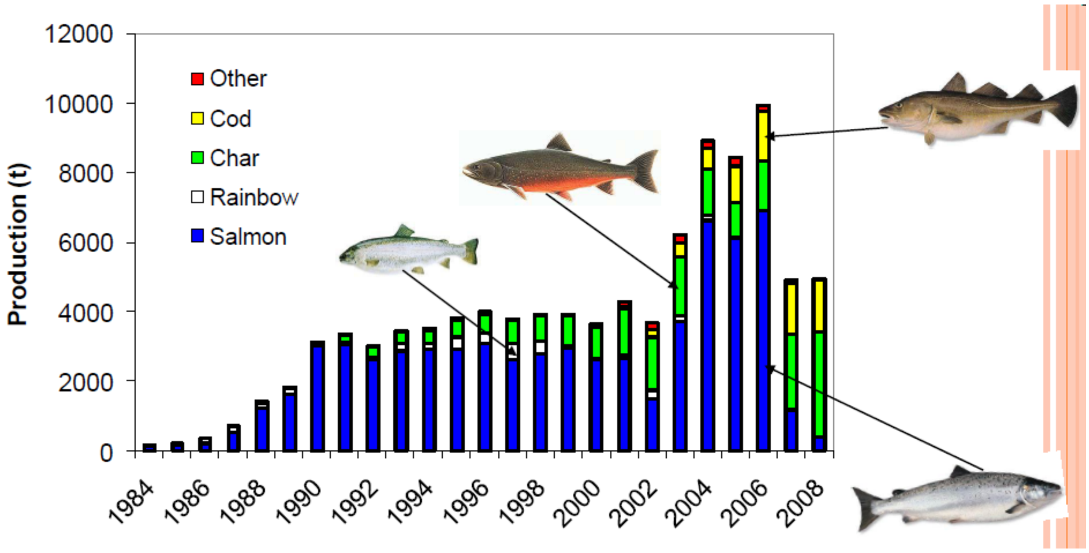

Figure 4 Icelandic aquaculture production from 1986 to 2008. (Source: Gunnarson, 2009)

Figure 5 shows the detailed geographic locations of the Icelandic aquaculture sites (mussel farms omitted). The sites are distributed across the coastline, with the cod farms relatively concentrated in the east and west. There is only one location for farming of salmon, rainbow trout, halibut and turbot.

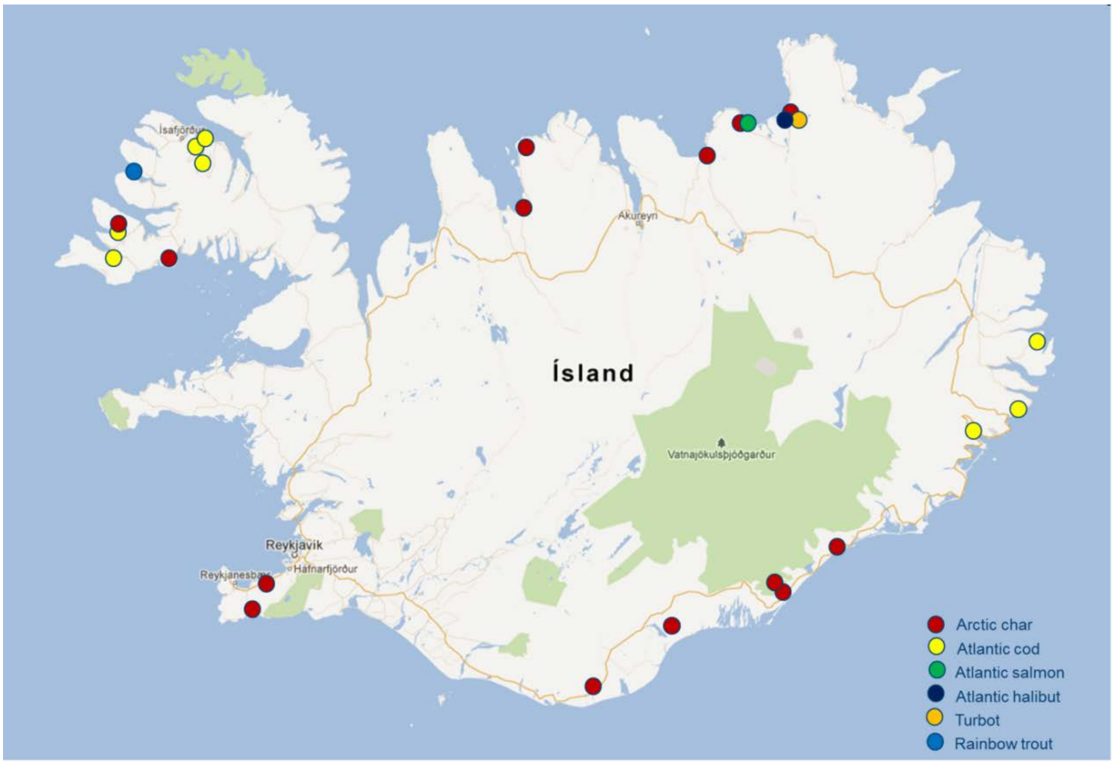

Figure 5 Locations for Icelandic aquaculture sites (Based on Gunnarson, 2009). Map from Google Maps, maps.google.com.

2.3 Norway

From the map of the Arctic it becomes obvious that only a fraction of Norway is to the north of the treeline and July isotherm. The Polar circle, however, leaves about 1/3 of the country in the Arctic area. In terms of aquaculture, Norway is the world's largest producer of Atlantic salmon (*Salmo salar*) and also has significant production of sea trout (*Oncorhyncus mykiss*) and smaller production of a number of other species. A significant amount of this production takes place in the Arctic area.

Detailed information on production quantities, values and geographic location of farms been obtained through the Norwegian Directorate of Fisheries. The locations are shown in Figure 5. The sites are relatively evenly distributed in the bottom two thirds of the area and less frequent in the remaining area. This is primarily due to historic reasons, reflecting the distribution when the entry into salmon farming was closed, but also because conditions for farming are better in the lower parts with higher sea temperatures.

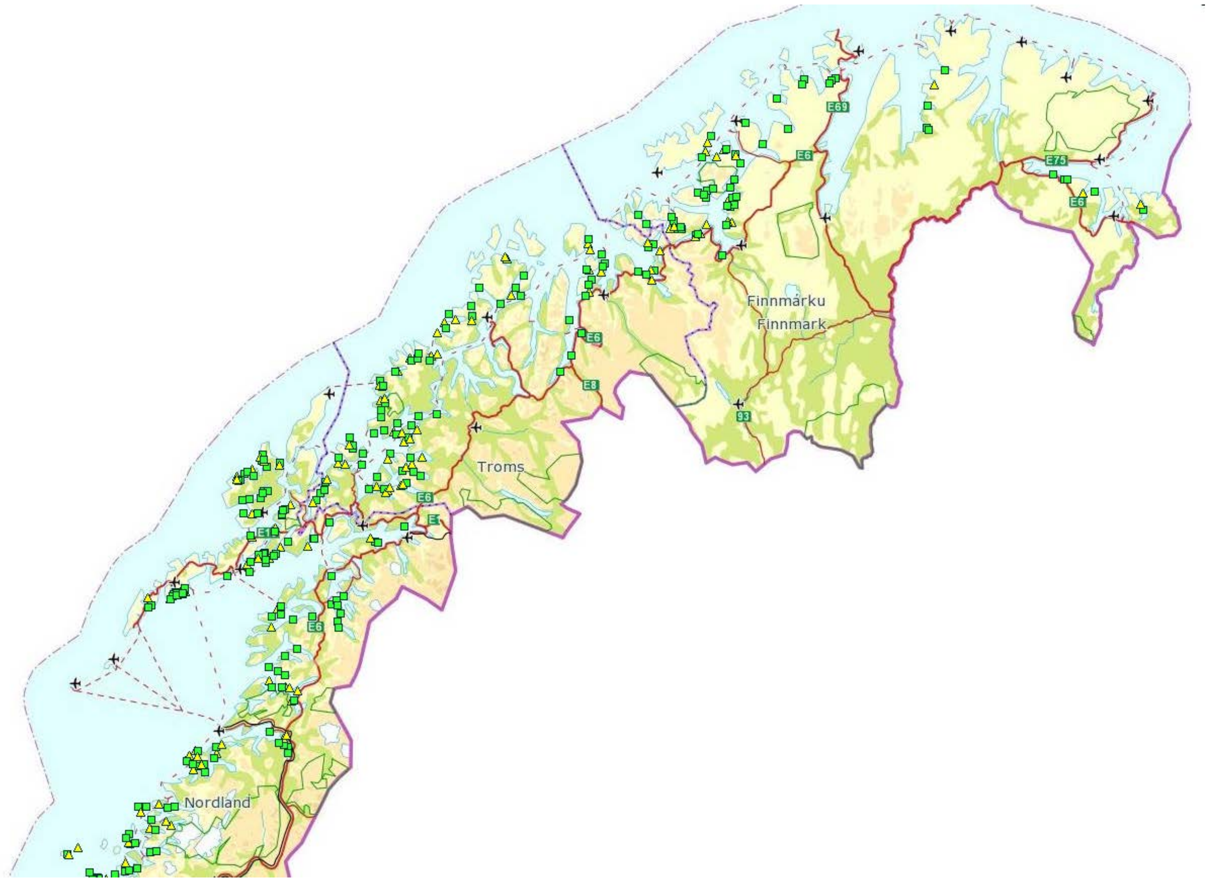

Figure 6. Detailed map of aquaculture sites in the Norwegian Arctic area. Green squares indicate sites with current production and yellow triangles sites that are idle (Source: Norwegian Directorate of Fisheries).

Norway is divided into 19 counties and this is the scale that much of the statistical data are reported on. The Arctic border splits one county, Nordland, in two. For simplicity, the whole of this county is included in the geographical representation of the Arctic.

Present aquaculture in the Arctic is shown in Table 1. Salmon dominates at about 1,7 billion USD, constituting 95% of the total value. Trout and cod constitute 3 and 2% of production, respectively. Nordland is the dominating producer county, with Troms second and Finnmark third.

Table 2 Value of Norwegian aquaculture production by county 2010 (1,000 USD) (Source: Norwegian Directorate of Fisheries)

	Nordland	Troms	Finnmark	Total
Salmon	951,587	554,845	268,282	1,774,714
Trout	8,234	14,638	32,489	55,361
Cod	32,681		4,933	37,614
Shellfish	379		1,149	1,528
Arctic char	2,456			2,456

Salmon farming was introduced in the Norwegian Arctic area around 1970. Figure 7 shows the development since 1994 and thus excludes the initial phase. Salmon has dominated during the whole period and the value of production accelerated after 2000. Several other species have been introduced, but these have not experienced the same growth as salmon. Norwegian authorities invested considerable R&D funds to develop farming of halibut and cod, but none have proven commercially viable to any significant scaling up. Halibut was primarily in focus during the early 1990ies and cod in focus during the latest part of 1990ies. Farming of blue mussels has also been attempted to scale up, but again unsuccessfully due to, among other reasons, occurrence of toxic algae (Winther *et al.,* 2010).

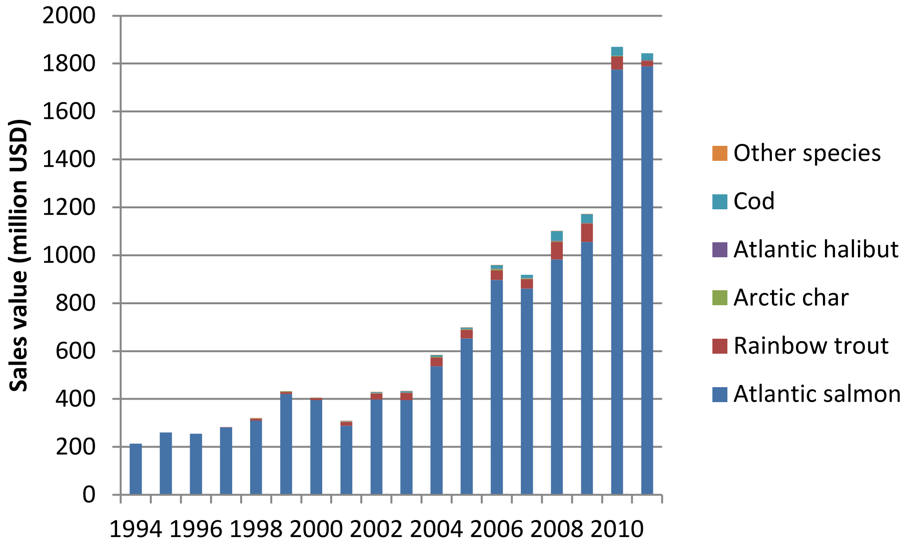

Figure 7 Aquaculture production in Nordland, Troms and Finnmark 1994-2011. Source: Norwegian Directorate of Fisheries

2.4 Sweden

Sweden's aquaculture production is out from a global perspective very minor, and this also compared to neighbouring countries like e.g. Norway. However, there is an ongoing initiative to investigate the possibilities for vitalising Swedish aquaculture production so it can be a part of the government's vision of Sweden becoming more self-sustained with food. The Government has since December 2007 carried out an investigation for analysing the prospects for development of aquaculture in Sweden and this resulted in the report "Det växande vattenbrukslandet" SOU 2009:26. During 2012 MISTRA (The Swedish Foundation for Strategic Environmental Research) has carried out a scooping survey to identify stakeholders' perspectives on Swedish aquaculture trajectory, i.e. possibilities and challenges as well as needed investments in research and production infrastructure. This work is led by internationally renowned aquaculture scientists, including people from both Norway and Finland. The work is expected to be finalised during 2012 and compiled in a report. The analysis, however, seems not to involve any in depth consideration of potential impacts from climate change.

The Swedish aquaculture production of finfish was 9,260 metric tonnes in 2010 (wet weight). The dominating species was rainbow trout (*Oncorhyncus mykiss*) (7,859 tonnes), constituting

85% of the total production of fish for consumption. Production of Arctic char (*Salvelinus alpinus*) amounted to 1,307 tonnes and blue mussels to 1,382 tonnes. In addition some smaller volumes of eel and crayfish are also produced. The total value of the Swedish aquaculture production of food fish amounted to USD 38 million, of which rainbow trout generated 28 million. Sweden also produces fish for stocking at a total value of 12 million. In 2006 there were 219 companies registered and the number of active farming sites was 300. Around 400 people are employed in the Swedish aquaculture industry, including both part and full time employment.

In Sweden, rainbow trout constitute the main cultured species, both out from both volume and value. Thus, there is a long tradition in farming rainbow for food and sport fishing and the species is relatively easy to farm and show high growth rate in relatively higher temperatures. Its expansion is thus restricted by temperature, something that is slowly changing with effects from climate warming. Today farming is mainly conducted in the southern and middle part of Sweden, but some farms exist further north (Storuman, Lycksele and Höga kusten) but here the temperature conditions are not optimal.

Farming of Arctic char is performed in freshwater and compared to e.g. Norway the many lakes and reservoirs in Sweden may constitute suitable environments for expansion. The farming is mainly performed in cages and production is limited southwards by the temperature that needs to stay below 15°C for most of the time. The farming practice needs to fulfil environmental criteria, involving among other things limits to how much nutrients that can be emitted. The water reservoirs with their oligotrophic status, may therefore be of special interest for expansion of Arctic char farming. Thus, the large reservoirs in Norrland may constitute new farming sites and some preliminary estimates indicate that the production of char in these waters could be at least 50,000 tonnes per year. However, if this is realistic also from a structural and economic perspective needs to be evaluated, as many of these areas are quite remote and lack access to established processing facilities and transportation infrastructure.

The actual production within the Arctic region in Sweden i.e. Norrbotten county is small and is represented by Rainbow trout only. There are 10 Rainbow farms producing 181 tonnes and one non-producing Arctic char farm. The production in the county constitute only 2% of the Swedish production at a value of USD 0.53 million.

2.5 Finland

In 2010 the total Finish aquaculture production of food fish was 11,800 tonnes, generating a value of USD 56.6 million. Rainbow trout dominated the production, 11,000 tonnes, followed by European whitefish (700 tonnes). Other species cultured for food included trout, char, brook trout, sturgeon and pikeperch (58 tonnes). Aquaculture in Finland also includes culture of fry for stocking into the wild, including additional species like Baltic salmon, sea trout, brown trout, grayling, cyprinids, pike, vendace and crayfish. The overall number of fish farm enterprises was 485 and of these were 178 farms involved in production of food fish. Due to strengthened environmental regulation in Finish waters recent Rainbow farms established in Sweden have co-owners from Finland.

Finish aquaculture production within the Arctic region constitutes of Rainbow trout farming and only adds up to 300 tonnes. This is 2.7% of total Finnish aquaculture, generating a value estimated to about USD 1.3 million. Around 11 farms are located within the Finnish Arctic region.

2.6 Russia

Russia has a relatively large aquaculture production, but most is inland culture of freshwater species in the southern parts of the country. Production was severely set back during the turbulent 1990ies when it fell by about two thirds. The Arctic section of Russia includes the Kola peninsula, northern parts of Archangel, Nenets and Siberia. Information on the activity in these areas is difficult to obtain, but production in the latter two is very limited due to the very cold winter temperatures experienced. Some aquaculture production is however ongoing and under development in the Kola peninsula. Hence, focus in this report is on this area.

Trout culture has earlier been an important part of aquaculture in this region, and production was 1,350 tonnes in 1991 (Anokhin *et al.,* 2011). Since then, production has declined sharply and was in 2010 down to 40 tonnes, exclusively from freshwater culture. Salmon is considered a promising candidate for culture in Russia based on the successful experiences from Norway. Sales of salmon and trout from farms in Arctic Russia was in 2011 2,916 tonnes (Tolkacheva, pers comm), but companies are granted licenses and have at present cages stocked with smolts that will considerably increase this production in the coming years. The current production is to a very large extent delivered by only one company, “Russian Salmon” with activities in the Pechenga area. No data on value of production has been obtained, but employing the Norwegian average salmon prices the estimated value amounts to 14.5 million USD.

“Russian Salmon” and the company “Russian Sea” have large expansion plans for salmon aquaculture in the Murmansk area. The latter company secured tenders for several sites in 2011. So far, one site is developed and 1.2 million smolts were put to sea in june 2012. This will yield a planned harvest of 3-4,000 tonnes in 2014. Three more sites per year are planned to be developed in the coming period.

There are challenges to scaling up Russian production in the Arctic. In particular military restrictions apply to most of the fjords attractive for farming. This can limit and slow down the expansion. Importing key inputs such as smolts and production systems can also be challenging due to tariffs and other trade restrictions.

Small-scale trout farming is performed in freshwater at several sites in the Kola peninsula and rainbow trout at only one site in the White Sea. A company is also utilizing cooling water from a nuclear power plant to grow sturgeon, but at experimental scale (Klochkov, pers comm, Mordal, pers comm).

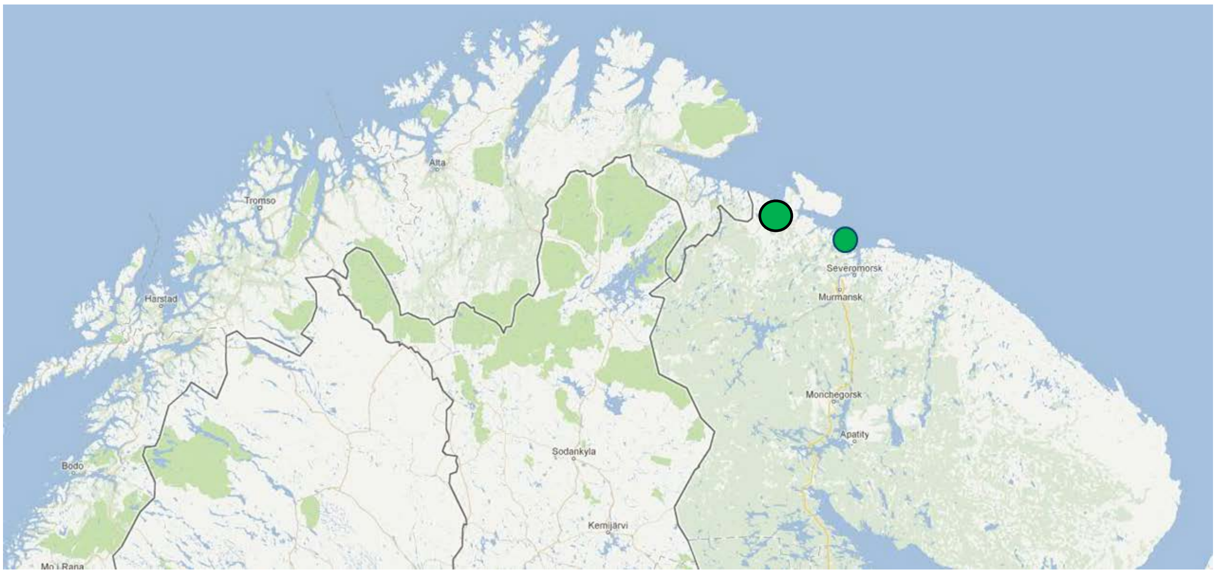

Figure 8   Salmon farming areas in Murmansk oblast

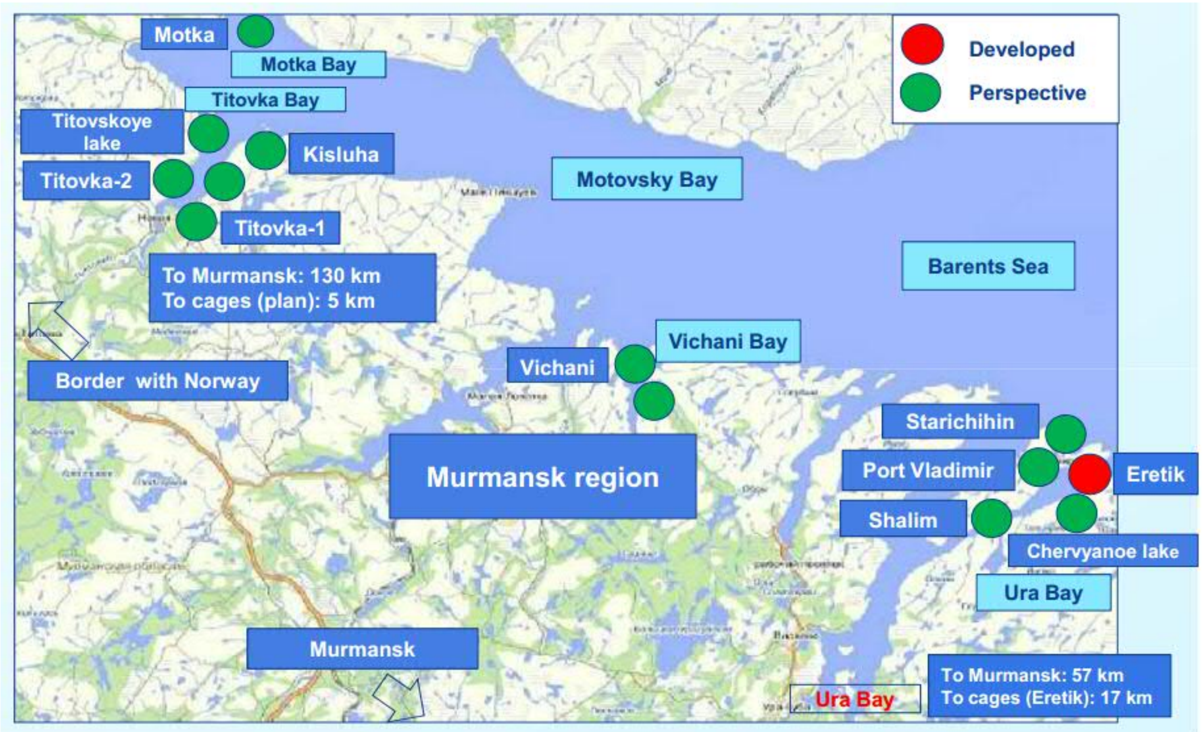

Figure 9   Map of current and planned aquaculture sites for the company Russian Sea Group. (Source: Russian Sea Group, 2012)

3 Review of climate change impacts on Arctic aquaculture

The abiotic environmental conditions are of fundamental importance for the success of aquaculture. Both growth and health of fish and shellfish are dependent on variables such as water temperature, salinity, oxygen content and water quality (Mydlarz *et al*., 2006). Adding to this is the physical processes associated with waves, currents, tides, ice and river inputs that may influence farming conditions (Callaway *et al*., 2012). A number of international studies have investigated how aquaculture production may become influenced by climate change (Handisyde *et al.,* 2006, Cochrane *et al*., 2009), but the detailed research carried out on this issue is still limited. These studies have in large looked at aquaculture in isolation from other effects from to climate change, i.e. effects on agriculture production, on finance markets, on demographic structures, changes in capture fisheries etc. This sub-task within the Arctic ACCESS project will look at current knowledge on climate change effects on aquaculture production in the Arctic. Focus is both on environmental and socio-economic impacts and emphasis is on salmon culture as this by far is the largest aquaculture production system in the region.

The links between environmental changes and aquaculture are of both direct and indirect nature. It is often difficult to discern the causative links and in most cases the impacts are attributed to a chain of effects (de Silva & Soto 2009). The temperature-growth relationship for finfish is an example of a direct effect and so is also increase in extreme weather events. Indirect effects may be increased risks for diseases or pathogen infections due to increased temperature. Potential indirect effects may also be changes in input factors, especially those linked to capture fisheries and agriculture through feeds and also energy inputs. Also changes in demand for aquaculture products will be of importance. This study will put emphasis on the direct effects but also try and identify indirect effects of significant importance for aquaculture in the Arctic. Predictions of environmental changes due to climate change are obtained from existing climate models and scenarios. According to Handisyde *et al*. (op cit), the climatic drivers that are most likely to impact on aquaculture production systems can be grouped as shown in Figure 10. Air and water temperature and sea level are self-explanatory. Oceanograpic variables represent water current, wind, waves, ice, salinity and others not covered by temperature and sea level. Extremes are a category that captures changes in the severity and number of occasions where the oceanographic variables are beyond their normal ranges, i.e storms and temperature extremes. These changes can influence aquaculture through physiology parameters such as growth, reproduction and disease outbreaks, ecology through e.g. organic cycles and parasites and operation of the farms such as sites and technologies applied.

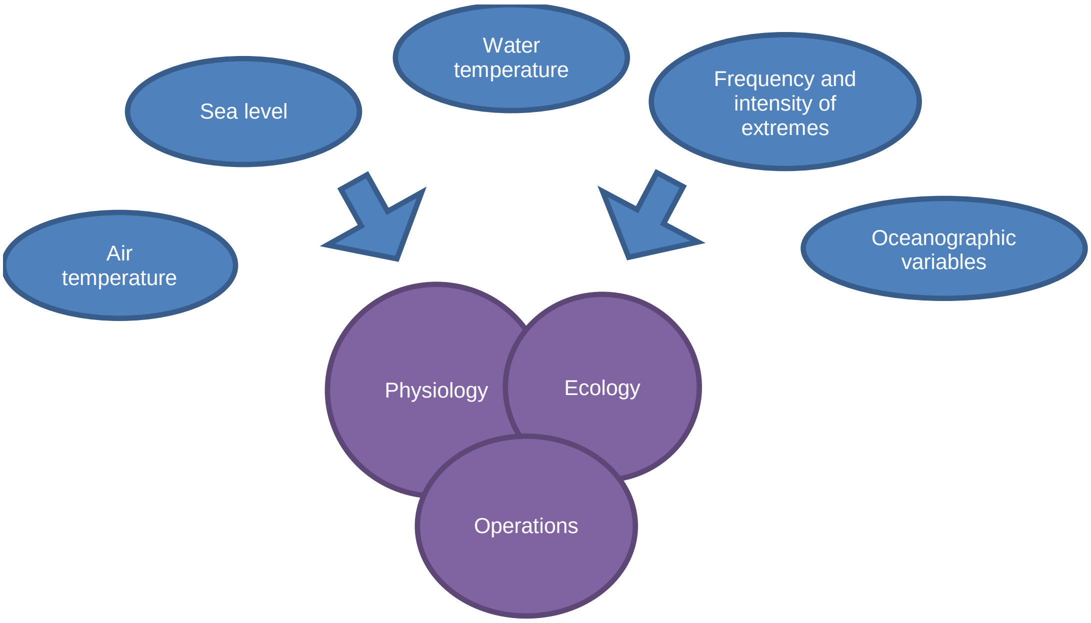

Figure 10 Climate change drivers and the production system

Several models are utilized to predict future climate. On a global scale this is done through the global coupled models, i.e. IPCC AR4. Their resolution is coarse and they often lack important physical properties close to coasts. To provide better estimates and resolution, downscaling models are also run. The predictions from different models vary and there is considerable uncertainty. Downscaling models are found for the North Sea (Ådlandsvik, 2008), Barents Sea (Ellingsen *et al.,* 2008) and all Norwegian sea areas (Melsom *et al.,* 2009). The estimates for future sea temperature vary between a rise of 0.5 °C (2051-65), 1°C (2059) and 1.7°C. Figure 11 shows a geographical distribution of forecasted sea temperatures. In general, the Arctic areas in Norway are expected to warm by 0.5 to 1.5°C during the whole year. The results for the Russian Arctic areas (Kola peninsula) are more variable, some areas warm from 0.5 to 1.5°C and others between 1.5 and 2.5°C.

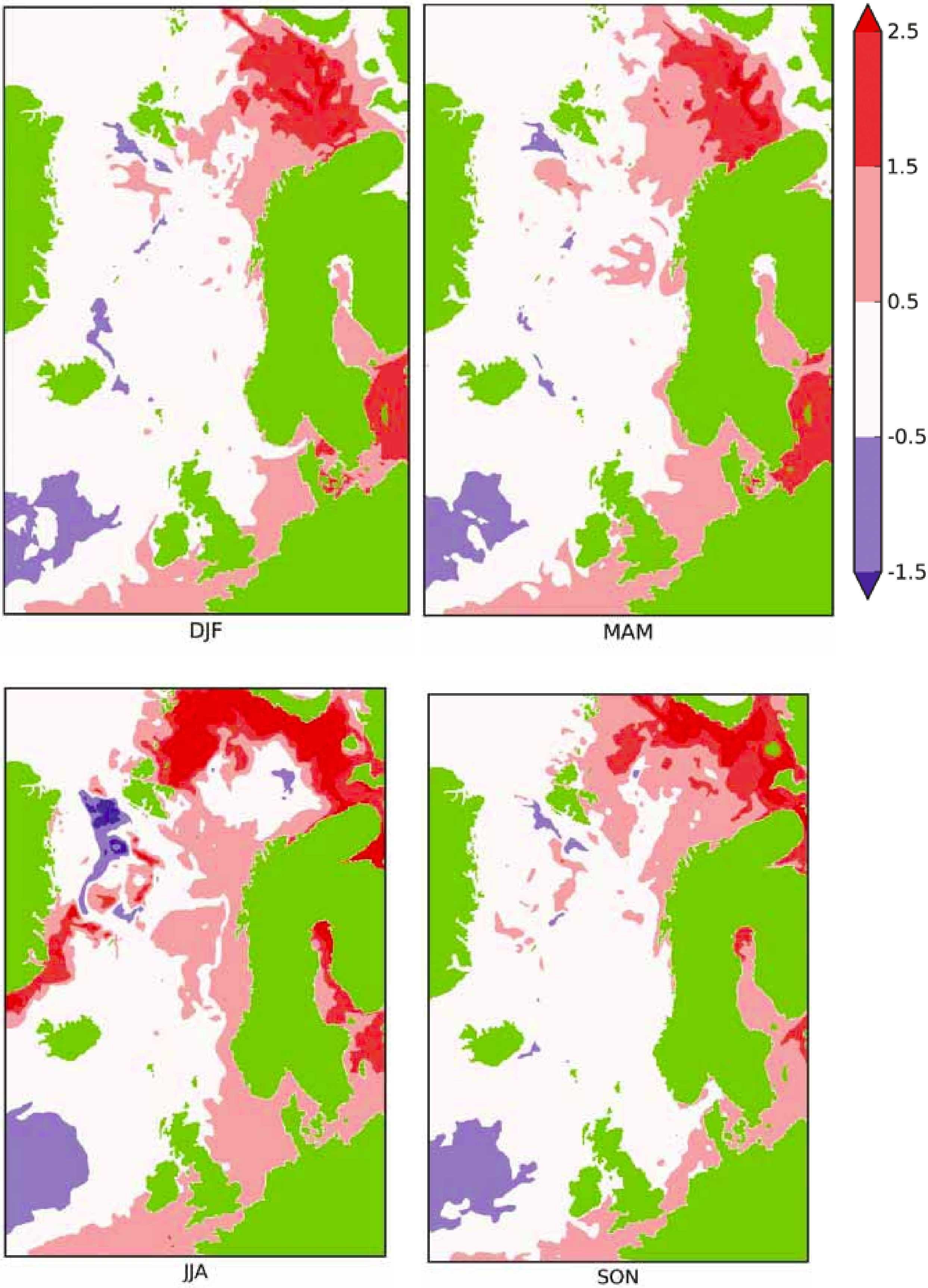

Figure 11 Forecasted sea surface temperature anomalies by quarter (Dec, Jan and Feb upper left, Mar, Apr and May upper right, Jun, Jul and Aug lower left, Sep, Oct and Nov lower right) (Source: Hanssen-Bauer et al. 2009)

The Norwegian Institute of Marine Research has temperature stations spaced along a north-south axis along Norway's coast. Mean observed and predicted temperature in March and August for the stations in year 2070 are shown in Figure 10. Station 1 is furthest south and station 19 is the northernmost. The Arctic, as defined in this study is from Nordland and north. During both winter and summer temperatures are generally decreasing with increasing latitude, although the stations to the far north have relatively even winter temperature.

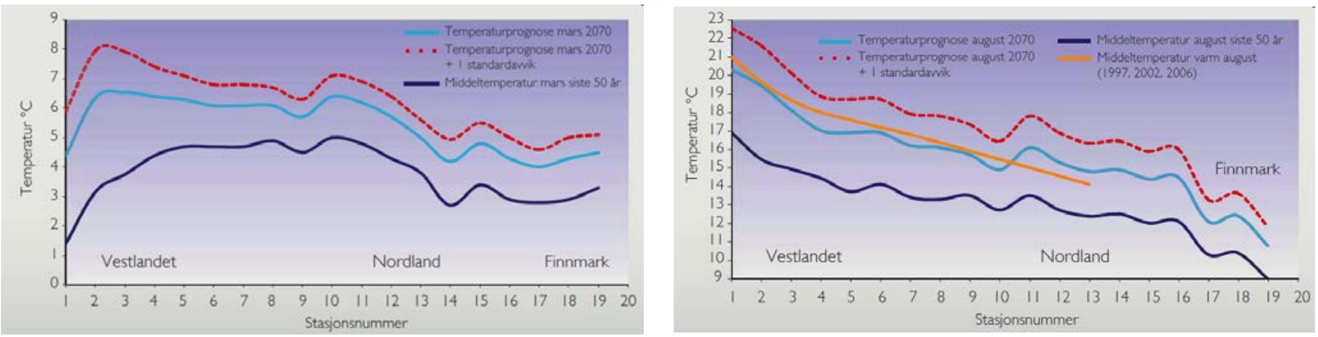

Figure 12 50-year means and predicted 2070 temperatures along the Norwegian coast. March in left and August in right panel (Source: Asplin et al., 2008).

Haugen et al (2008) predicts increased precipitation in Norway, especially in the coastal areas and during autumn and winter. Predictions of changes in wind patterns are, however, not clear. Some results show upon increased numbers of storms with increased intensity (Furevik *et al.,* 2002, Matulla *et al.*, 2007) while others only show small changes in average wind parameters (Haugen *et al.,* op cit).

Wave action is to a large degree wind dependent and hence also uncertain. Debernard and Røed (2008) establish a model to forecast wave height in the North Atlantic and Barents Sea, but the results for the Arctic area relevant for aquaculture are not statistically significant.

3.1 Water temperature

3.1.1 Growth and productivity

This section explores current knowledge about the relationship between temperature and productivity for the main species presently being farmed in the Arctic. Sea temperature is of particular interest as fish generally are poikilothermic and temperature thus has a direct influence on metabolism and growth. Fish most often have an optimal temperature for growth and temperatures deviating from this optimum will therefore restrict growth.

Salmonids have a relatively narrow range of temperatures for optimal growth (Ficke *et al.,* 2007). Presently, the optimum conditions for salmon farming in Norway are found at about 62–64 degrees along the Norwegian coast. Sites further south generally experience summer temperatures that are higher than optimum and sites further north experience too low temperatures throughout the year. Increased sea temperatures will generally move this optimum zone further north. Lorentzen (2008) estimates that output from a fish farm experiencing less than optimal temperature conditions can expand by 11–15% for a one degree increase in temperature. For farms that are at optimum or higher temperatures, production will decrease. This emphasises the strong economic impacts that can be expected from a temperature change. Salmon farms in the Arctic generally experience lower than optimum temperatures, and will likely experience improved productivity.

Other species, such as cod and halibut, have more narrow temperature ranges (Levesque *et al.,* 2005, Imsland *et al.,* 2000). Depending on the existing temperature regime at current farm sites, increase in temperature can have both positive and negative influence on fish growth and productivity. The temperature optimum also decreases with increasing size of the fish which further complicates the predictions of actual impacts from changes in temperature. In the Arctic, the production of these other species is quite small and limited by economic constraints. Farmers that today run operations in areas that will experience significant temperature changes can mitigate adverse effects through re-siting/re-establishing their farms in areas with better temperature range. But to what extent this will occur depends on production loss from the changes in temperature, costs involved in moving operations, property rights, permits and existing infrastructure at new sites.

3.1.2 Oxygen content

The solubility of oxygen decreases with increased temperature. Combined with the higher metabolic rates and oxygen consumption associated with higher temperature, this may have significant impacts on the carrying capacity of a site. The farmers have to plan their stocking densities so that the maximum oxygen demand does not exceed the availability at any time. Locations with insufficient water exchange may have to reduce the density of fish in order to avoid oxygen depletion that will hamper fish growth.

3.1.3 Disease

Higher sea temperature not only influences growth in fish, but may also result in increased losses of fish due to diseases. Climate models indicate longer and more frequent periods of extreme temperatures. If these extremes are close to the tolerance levels of the fish, and in combination with oxygen depletion, this result in physiological stress and thus increased susceptibility to disease (Gubbins, 2006).

Diseases occur in most living organisms, and maybe increasingly so in farmed animals. This is because farms, with their high biomass concentration, provide attractive breeding grounds for pathogens. Changes in temperature can have several effects on an aquaculture operation through changes in disease occurrence and spreading patterns, but these are usually difficult to predict (Gubbins, op cit). In general, pathogens have shorter generation times in higher temperatures (Duguid *et al.,* 1978). In salmon and cod aquaculture, several common diseases such as fransicellosis, vibriosis and furunculosis are associated with high water temperatures (Lillehaug *et al.,* 2003, Samuelsen *et al.,* 2006). These can be expected to be more abundant with increased temperature and also occur more frequently throughout the year. High temperatures generally influence the immune system of the farmed species negatively, but some diseases such as winter ulcers and cold-water vibriosis are associated with low temperatures and will hence be less frequent with higher temperature. In addition, some parts of the immune system may actually function more effectively at higher temperatures (Le Morvan *et al.,* 1996, Eggset *et al.,* 1997) resulting in improved ability to resist infections.

Most disease outbreaks occur at “extreme” temperature events. The predicted increase in average temperature is not likely going to influence the disease risk noteworthy, but the increased incidence of periods with high temperature will increase the risk of disease (Bergh *et al.,* 2007).

Pathogens are generally found within a specific temperature range and climate change may shift the distribution of particular pathogens, leading both to introduction of exotic diseases and removal of others.

Parasite infestion is a common problem in aquaculture and the occurrence and growth of parasitic organisms are also temperature dependent. A shorter generation time is associated with increased temperature which means higher production of parasites resulting in subsequent losses in production and increasing costs for mitigation efforts. However, the life cycles of many parasites are complex, making it difficult to predict the actual effect from increased temperature. Different species also have different temperature ranges that they thrive within. Increasing temperature could hence result in some parasites dropping out of the area and others moving in. The most common parasite in salmon farming is sea lice (*Lepeophtheirus salmonis*) (Boxaspen, 1997). It is currently more of a problem in the southern, warmer areas than in the Arctic. With increased temperature, its distribution will most probably move north. The spread of sea lice is dependent on current patterns and the larval stage and increased temperature is shortening the larvae stage. Currents are influenced by the expected increase in freshwater runoff. In conclusion, the combined effects from sea lice are difficult to predict. However, it is likely that infestion will increase and that this results in increased costs for treatment to avoid mortality and reduced productivity of farmed fish, as well as elevated infection rates among wild salmon (Bergh *et al.,* 2007).

3.1.4 Algal blooms

The effects from temperature change on phytoplankton communities are also hard to predict. The abundance of flagellates and dinoflagellates is predicted to increase relative to diatoms (Sætre *et al.,* 2003). As potentially toxic species are found in both of these two groups, algae blooms of these can cause mortality or reduced growth of farmed fish and shellfish.

Climate models also predict increased precipitation that will probably lower the salinity of coastal water, strengthening the stratification and influencing the availability of nutrients for algae. Together with changing zooplankton communities that graze on phytoplankton, which further increases the complexity of the system, predictions will be hard to make (Gubbins, 2006).

Again, changes in temperature may not only shift algal community towards flagellates and dinoflagellates but other alga groups may also be favored by changes in temperature due to their temperature optima. The resulting algae community and their dynamics are difficult to foresee.

3.1.5 Area available for farming

Temperature changes may influence the area (land/water surface) that is available for farming. In the Arctic, the available area may be limited by the minimum water temperature that allows economically sustainable farming. For species where the upper temperature bound is not reached by warming, the temperature increase will have a positive effect on the area available in the Arctic. For species that are close to their upper temperature limits, the net change ina available area depends on the gain and loss of areas.

The incidence of ice cover is mainly temperature-related and restricts where cage cultures can be placed. Cage cultures requires more or less ice-free conditions year-round as ice can cut the nets and lead to fish escapes. Increase in water temperature therefore, from an ice perspective, imply more available waterways being suitable for cage farming.

3.1.6 Opportunities for new species

Along with other site-specific environmental factors (i.e. currents, wind/wave fetch, upwelling, salinity, etc), sea temperature is of prime importance for determining which species that can be farmed where. Increased water temperature also imply that introduction of new species with higher temperature optima will be possible.

An approach for identifying candidate species and an indication of possible rearing volumes is to look at what species being farmed in Sub-Arctic areas. Along the southern coast of Alaska shellfish and aquatic plants are dominating farming. Production here is, however, limited with a sales value of about 400,000 USD in 2010. With increased sea temperatures, farming can expand into the current Arctic, but the volume is not likely to be large considering the limited activity in the Sub-Arctic areas. It should however be noted that Alaska has banned finfish farming, and a lift of this ban could possibly trigger introduction of fish farms in the current farming areas, as well as into the current Arctic.

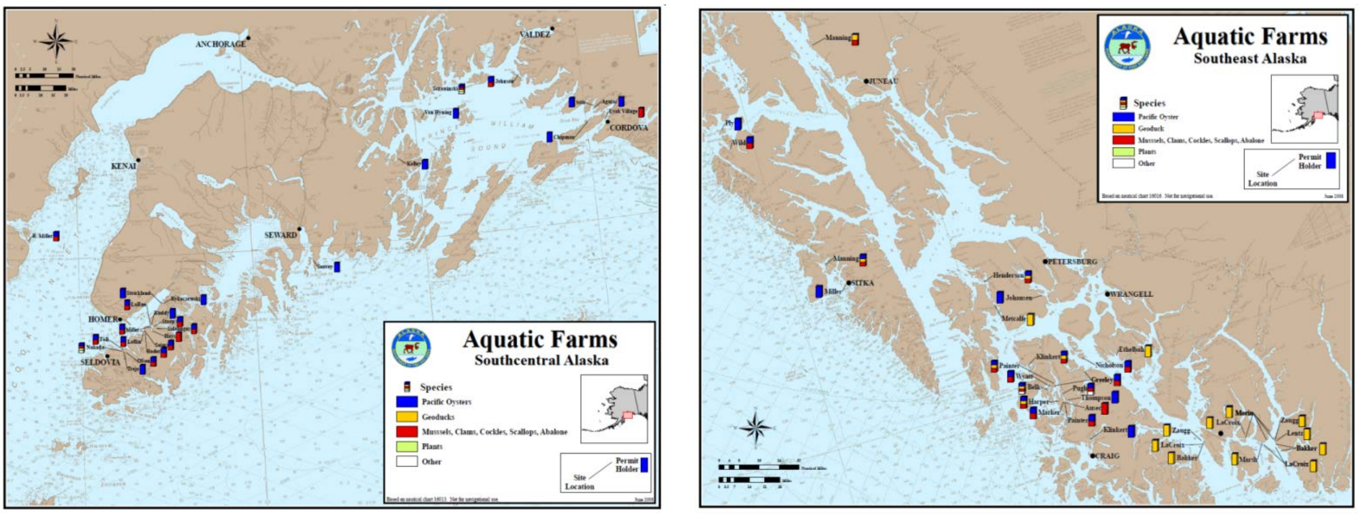

Figure 13 Aquaculture sites in Alaska (Source: Alaska Department of Fish and Game, http://www.adfg.alaska.gov)

Canada also has some aquaculture activity relatively close to the Arctic (shown in Figure 12). The tree line and isotherm runs through the northern parts of Labrador and aquaculture activity is currently only found in north Quebec and in Newfoundland. Atlantic salmon is the main species at USD 107 million in 2010, but also some shellfish culture is found in the northern parts of Quebec and Newfoundland. With increasing water temperatures, it is likely that the industry will expand northwards. However, reaching as far as the current Arctic requires relatively large increases in temperature.

Figure 14 Aquaculture areas in eastern Canada (Source: Various government agencies in Canada)

Iceland has no close "neighbors" that can provide inputs for potential future aquaculture species expansion. For the Norwegian and Russian Arctic the remaining part of Norway may be a good reference to look at. The production here is, however, not very different as shown in Table 3. The differences are limited to a considerably higher production of rainbow trout in the south. There is also more production of Atlantic halibut. Both these species have a higher temperature preference than salmon. In case of warming conditions in the Arctic, it is likely that these species to a greater extent will be farmed here. Other marine fish is turbot that is grown on a land-based facility, utilizing warm water from a metal plant. Oysters and scallops are primarily grown in the far south. The anticipated warming is not sufficient to bring temperatures in the Arctic to comparable levels.

Table 3 Aquaculture production in North- and South-Norway 2010 (1,000 USD)(Source: Norwegian Directorate of Fisheries)

	Arctic	*South*
Salmon	1,787,996	3,061,438
Trout	23,090	271,539
Char	1,502	442
Halibut	2,742	27,859
Other marine	-	3,126
Blue mussels	481	941
Scallop	-	113
Oyster	-	40
Other shellfish	2,449	499

3.2 Other oceanographic variables

3.2.1 Storms

How climate change will influence wind and wave conditions in the Arctic are most uncertain. However, models predict more frequent and more intense storms in the northeast Atlantic (Leckebusch *et al.,* 2006, Frost *et al.,* 2012), although this shift will take long time to evolve (Weisse *et al*., 2005).

Storms can impact severely on the aquaculture industry, particularly on the sea-based farms. Land-based facilities are less exposed to such forces. For cage farms at sea, the majority of breakdowns occur during storms, mainly caused by strong waves and icing. This cause structural damages as well as loss of fish through mortality or escapees. Fish escaping to the wild and breeding with native populations can cause hybridization and loss of genetic diversity (Walker *et al.,* 2006).

The anticipated slow change in storm patterns gives the industry sufficient time for adaptations. As a response, structures can be strengthened or moved to less exposed sites. The first measure implies higher costs and the second may be difficult due to lack of available sites. In addition, production may have to take place at suboptimal sites in terms of fish growth, thus reducing productivity and profits. This might, however, be an accepted trade-off to make considering the economic and ecological losses a damaged farm could result in.

3.2.2 Precipitation

Climatic models predict increased precipitation in Norway (Bergh *et al.,* 2007). Increased river discharges create a strong stratification in the fjords, characterized by a thick surface freshwater layer. The stronger freshwater stratification will increase the temperature of the fjord system and the increased run-off will increase surface currents.

The fjords will also experience higher nutrient discharges from increased land run-offs. The direct implications from changes in precipitation for Arctic aquaculture are, however, not likely to be large. Smolt production may benefit from increased rainfall, as their production often is limited by the supply of freshwater from rivers during peak season in May/June. The indirect effect on water temperature will exacerbate the effects as described earlier. The current changes will influence the farms directly through the provision of oxygenated water and removal of waste products from the cages.

3.2.3 Ocean acidification

The rise of atmospheric carbon dioxide content is expected to lower oceanic pH by 0,3 to 0,5 and carbonate saturation by about 45 % (IPCC 2007, Andersson et al 2008).

Finfish are well adapted to changes in ocean acidity, indicating that the impacts will be small for this group of species (Callaway 2012).

Lowering of the ocean pH will mainly impact on organisms with calcium shells or skeleton and in aquaculture it involves all shellfish species being farmed. These will experience difficulties particularly during their early life stages (Callaway *et al.,* op cit). However, as shellfish culture does not constitute any significant share of current aquaculture in the Arctic, the socio-economic impacts will be small. This will, however, have consequences for future expansion of shellfish farming.

3.2.4 Sea level

Climate change, is expected to result in a net sea level rise and this due to several direct and indirect effects. The sea water volume is positively linked to water temperature, and hence warming will result in higher sea levels. Warming will trigger melting of ice caps, such as Greenland and Antarctica (Parry *et al.,* 2007). Through a reduction in the gravitational pull from the reduced mass, melting in Greenland will yield reduced sea levels in the Arctic. Melting in Antarctica latter will yield the opposite effect, thus the net effect depends on where melting occurs and to what extent. In some areas, such as the Nordic parts of the Arctic, landmasses are still rising due to the withdrawal of the icecap from the last ice age.

The estimates for how much future sea levels will be are uncertain, but Simpson *et al.* (2012) estimate that the sea level will change between -20 and +30 centimeters along the Norwegian coast. The influence on aquaculture is difficult to predict but if the sea level rise stay within such modest levels then it is not likely to have any significant effects on sea based aquaculture.

3.3 Economic implications

Socio-economic impacts resulting from climate change effects on the aquaculture sector may be significant but as with the many environmental parameters it is difficult to foresee how the overall effects will play out. The overall effects will also be linked to how other sectors in the Arctic will change and what effects these changes will have on aquaculture.

Acknowledging the uncertainty most economic modeling of the climatic effects on aquaculture has focused on the impacts related to increased temperature. The most advanced modeling attempts on salmon aquaculture in Norway has been carried out by Lorentzen & Hanneson (2005, 2006), Lorentzen (2008) and Steinshamn (2009). Lorentzen & Hanneson (2005) investigated different development scenarios for Norwegian salmonid culture with and without warming. The model that included a growth functions for salmon showed a positive effect on fish growth from increased water temperature. However, a relatively strong negative impact on sales prices was found due to expected increase in overall Norwegian salmon production.

Lorentzen & Hannesson (2006) further investigate the implications of faster growth by developing a Faustmann-type model that estimated optimal harvest time, both with and without rotation of crops. Increased temperature resulted in all cases in higher slaughter weight and reduced rotation time. Steinshamn (2009) expanded this model to also include weight-dependent prices with the same qualitative results. At present, Norwegian fish farmers are quite limited in terms of where production can take place. For aquaculture management, Norway is divided in five regions. The licenses are granted to one region and are not permitted to be moved to other regions. Hence, they are forced to adapt to the various effects from climate change. Also Hermansen & Heen (2012) investigated the relationship between temperature and productivity and developed a bio-economic model to predict how temperature change could lead to shifts in the geographic distribution of salmon farms and production. Not surprisingly, the model predicts a significant improvement in productivity for the northern farms and vice versa for the farms furthest south and a corresponding northwards shift in production if the restrictions are lifted.

4 Governance systems

This chapter provides an overview of the present regulatory systems for aquaculture in the Arctic. We focus mainly on the main producing countries or those that are expected to expand their production when climatic effects change the conditions for farming. Thus, the latter includes Norway, Russia, Iceland, Canada and the US. Both official legislation and informal voluntary industrial arrangements related to environmental impacts, production planning, area use, disease management, site locations and reporting are included. If possible also new emerging international legislations being developed specifically for the Arctic region, impacting or related to aquaculture development, will be identified and discussed out from existing national legal frameworks.

Extensive knowledge about present regulations will be helpful in developing scenarios for both governance and individual farmer's responses to climate change. National legislation may become an obstacle for adaptations to a changed environment, with likely pressure mounting for policy reform. Background knowledge about the basis for the regulations in question may also be helpful in assessing the likelihood of change and possibly identification of new regulations that are needed. Challenges for governance lie also at a higher level than aquaculture itself and needs to address the complexity of actors and stakeholders, involving such issues as power structures and global drivers. Aquaculture need to be a part of this larger perspective as one stakeholder and interest party. Thus, there is a need for giving attention to and, in a transparent way, involves all Arctic stakeholders in the process, particularly including also the indigenous people. Only when multiple human activities are included will an integrated assessment be possible, where risks and cumulative and interacting impacts are accounted for. Planning for aquaculture, together with other coastal or near coastal activities, should follow an ecosystem-based approach.

4.1 Norway

Norwegian aquaculture is managed through several laws and a number of provisions. Management is primarily concerned with environmental sustainability, but also economic sustainability and appropriation of area are of importance. This section gives a broad overview of the legislative and management systems. For more details, consult FAO's legislation overview (http://www.fao.org/fishery/legalframework/nalo_norway/en). In legal terms, aquaculture is considered as total production of aquatic organisms, where production relates to interventions that influences weight, size, number or characteristics. This is a relatively broad definition also defines sea ranching as aquaculture.

Several areas of regulation are relevant for aquaculture. The following are of particular importance to the sector:

- The Aquaculture Act of 2005 and provisions give sector specific regulations on starting and running aquaculture.
- The Food Safety Act of 2003 regulates animal health, food safety and quality.
- The Act on Prevention of Cruelty to Animals of 2003 sets standards for the keeping and treatment of live animals, including fish and crustaceans.
- The Act on Planning and Construction

4.1.1 Licensing system

The Ministry of Fisheries and Coastal Affairs administers the Act on Aquaculture and issue detailed provisions. The Directorate of Fisheries, an executive body within the ministry, is responsible for administration and enforcement of the regulations. A key element of the regulations is that a license is required for aquaculture activities.

The prime condition for allocation of a license is that the activity is environmentally responsible. This is a relatively vague terminology, but it involves explicit need for permissions related to pollution and waste management. Discharge of waste into the environment requires permits from the County Governor. Such permits are based on the documented environmental status of the receiving water body and state a permitted level of discharge. Licensing is also dependent on satisfying area use criteria such as local authorities land use plans and waterways plans. The land (also water areas) use planning is decided by the municipalities, thus local authorities can limit aquaculture through the allocation of areas.

Applicants also have to document professional competence in running the operation. This relates to technical operations as well as management of fish escapes and fish welfare.

The authorities also have the option of capping the number of licenses to limit production, ensure fish welfare, promote geographic distribution considerations or other criteria. Presently this is being applied to salmon and trout culture.

The licenses are in most instances given as a permit to hold a maximum biomass at a given location. For fry production, licenses are restricted in terms of the number of individuals produced annually. If criteria are violated, the authorities may amend or revoke granted licenses.

Environmental considerations apply also after a license is granted. By law, the operations are required to be conducted in an environmentally sustainable manner. To ensure this, the farmers have to document a range of environmental parameters at the aquaculture site, involving both water quality and benthic ecosystems.

4.1.2 Land and water use

Each municipality along the coast is required by this act to prepare a land use plan that includes the coastal zone. Unless the municipality council gives consent, aquaculture sites have to be located to these zones. The Directorate of Fisheries handling applications for aquaculture also represent the interests of other stakeholders and need to take their perspectives into consideration, e.g other than aquaculture and fisheries. Provisions within the Act on Harbours and Fairways ensure that aquaculture sites cannot be established in areas where traffic is impeded or defence interests will suffer.

4.1.3 Disease control

The Food Safety Act contains an obligation for all to avoid development or spread of animal diseases. Aquaculture facilities require permit from the Food Safety Authority for establishment and expansion. A risk assessment of disease spreading has to be conducted. Distance requirements between farms are important measures to reduce risk. If disease breaks out or is suspected, the Food Safety Authority can impose measures to limit disease spreading such as destruction or slaughter. For daily farming operations there are hygiene and disease preventing requirements. Slaughter is not to take place at the farm site, but is to be carried out at approved plants.

4.1.4 Drugs

Only veterinaries and specially qualified fish health biologists are permitted to order prescription drugs. Specific withdrawal times define when fish can be used for food production.

4.1.5 Food safety

The Food Safety Act prohibits trade or distribute unsafe food. To a large extent the control is based on own-control, but the Food Safety Authority conducts inspections of particularly processing plants.

4.1.6 Animal welfare

The Act on Prevention of Cruelty to Animals states that animals shall be treated well and shall not suffer unnecessarily. They shall receive sufficient food, care and attention. Killing of animals shall be done so to limit their suffering. Artificial modification of genes is also restricted.

4.1.7 Adaptation issues

The regulations are relatively detailed and are relatively mature, as the industry has developed since the early 1970s. This implies that there are no major areas where legislation is severely missing. In terms of climate change, a potential drawback for adaptation is the stringent geographical bindings to the licenses. When issued, they cannot be moved between relatively large regions. This, however, is a topic for a present evaluation of the legislation, although not directly climate change related. The areas that open up may, however, be in need of special protection and not being suitable for farming. This needs to be evaluated.

4.2 Russia

According to FAO, Russia does not have systematic aquaculture legislation, as there at present is no general aquaculture law. A draft of a federal law containing fish farming is available and under evaluation by the Russian Parliament. Until this federal law is adopted, aquaculture is regulated by regional laws, federal special programs and regional special programs. Fish farming requires a license from the Federal Fisheries Committee or its territorial branches. Licenses are given for a period of not less than three years. Apart from this limited information, no details of the management systems in place have been obtained.

5 Conclusions

Aquaculture in the Arctic region contributes with 2% of global production. This may seem small, but is of same magnitude as EUs total aquaculture production. Norway is by far the dominant producer in the Arctic, and production from other countries within the region is negligible compared to Norway. However, any production in this region is providing important employment opportunities as these usually remote areas are characterised by few alternative livelihoods. Production mainly constitutes of salmon with additional limited production of a few other species.

Even though there is a consensus about a general temperature rise caused by climate change, there is no consensus about the exact temperature. This is also true for the Arctic region and the coastal areas where aquaculture production takes place. Different sub-models, especially focusing on the Norwegian coasts, predict increase in water temperature within the range of 0.5 to 2.5 degrees. A change that will play out differently during different parts of the year.

There is considerable uncertainty associated with the projections of future climate. Relatively few detailed studies have been undertaken in modelling impacts for aquaculture, and even fewer analyse this from an Arctic perspective.

The direct effects from a temperature change on the aquaculture industry can to some extent be modelled with fairly good accuracy, including both the effects on fish growth as well as how a whole industry may be affected. These models show how production will change and also socio-economic consequences. From these models it becomes clear that aquaculture in the Arctic will see positive effects from warming water temperatures. Other direct effects such as from storm frequencies and intensities can be relatively well anticipated, but the uncertainty regarding how these parameters will change is high.

Other indirect effects such as diseases and pest species, freshwater runoff etc are very hard to predict, aggravating the uncertainty related to climate change. What is certain is that the environmental conditions will change and that the industry will have to adapt to these changes. For enabling the industry to do so there is a need to look over existing regulatory frameworks and start a multi-stakeholder dialogue to find out where and how aquaculture operations can move or change their operations.

To identify the possible effects from climate change on aquaculture in the Arctic Region is a useful exercise and also important for increasing our understanding about challenges for present and future aquaculture production. However, as the Arctic Region currently are undergoing a multitude of changes, involving activities and changes in economic conditions for different sectors and stakeholders, as well as large scale environmental changes, the different ways that aquaculture in the Arctic can adapt will be linked to the overall changes occurring in the region. Thus, a broader integrative approach is needed for successful governance of the Arctic system.

6 References

Andersson, A.J., F.T. Mackenzie & N.R. Bates (2008). Life on the margin: implications of ocean acidification on Mg-calcite, high latitude and cold-water marine calcifiers. *Marine Ecology Progress Series,* **373**, pp. 265–273.

Anokhin, V.S, E.V. Sjosjin & P.P. Krajevetz (2011). The potential for aquaculture in north-european Russia.

Anon. (2009). Det växande vattenbrukslandet. SOU 2009:26.

Asplin, L., J. Aure & S. Sundby (2009). Klima og klimaendringer i fjordene og på kysten. In Boxaspen, K.K., E. Dahl, J. Gjøsæter, B.H. Sunnset (eds.). *Kyst og havbruk 2008*. *Fisken og havet 2-2008*, Havforskningsinstituttet, Bergen.

Bergh, Ø., L. Asplin, K. Boxaspen, T. Lorentzen, A. Nylund , K. Ottem & S. Sundby (2007). Klimaendringer – konsekvenser for akvakultur I Norge. Havforskningstema 2-2007. Havforskningsinstituttet, Bergen.

Boxaspen, K. (1997). Geographical and temporal variation in abundance of salmon lice (Lepeophteirus salmonis) on salmon (Salmo salar L.). *ICES Journal of Marine Science*, **54**: 6, pp. 1144–1147.

Boyd, C.E., A.A. McNevin, J.W. Clay & H.W. Johnson (2005). Certification issues for some common aquaculture species. *Reviews in Fisheries Science*, **13**, pp. 231-279.

Callaway, R., A.P. Shinn, S.E. Greenfell, J.E. Bron, G. Burnell, E.J. Cook, M. Crumlish, S. Culloty, K. Davidson, R.P. Ellis, K.J. Flynn, C. Fox, D.M. Green, G.C. Hays, A.D. Hughes, E. Johnston, C.D. Lowe, I. Lupatsch, S. Malham, A.F. Mendzil, T. Nickell, T. Pickerell, A.F. Rowley, M.S. Stanley, D.R. Tocher, J.F. Turnbull, G. Webb, E. Wootton & R.J. Shields (2012). Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems,* **22**, pp. 389–421.

Cochrane, K., C. De Young, D. Soto & T. Bahri (eds.) (2009). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530, FAO Rome.

de Silva, S.S. & D. Soto (2009). Climate change and aquaculture: potential impacts, adaptation and mitigation. In Cochrane, K., C. De Young, D. Soto & T. Bahri (eds.). Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530. FAO, Rome.

Diana, J.S. (2009). Aquaculture production and biodiversity conservation. *Bioscience*, **59**, pp. 27-38.

Duguid, J.P. (1978). *Medical microbiology 13th ed*. London and New York: Churchill Livingstone, Edinburgh.

Eggset, G., H. Mikkelsen & J.E.A. Killie (1997). Immunocompetence and duration of immunity against Vibrio salmonicida and Aeromonas salmonicida after vaccination of Atlantic salmon (Salmo salar L.) at low and high temperatures. *Fish and Shellfish Immunology*, **7**: 4, pp. 247–260.

Ellingsen, I. H., P. Dalpadado, D. Slagstad & H. Loeng (2008). Imppact of climatic change on the biological production in the Barents Sea. *Climatic Change*, **87**, pp. 155-175.

Ficke, A.D., C.A. Myrick & L. J. Hansen 2007. Potential impacts of global climate change on freshwater fisheries. *Reviews in Fish Biology and Fisheries*,**17**: 4, pp. 581–613.

FAO (2007). The state of world fisheries and aquaculture 2006. FAO Fisheries and Aquaculture, FAO, Rome.

FAO (2010). The state of world fisheries and aquaculture. FAO Fisheries and Aquaculture, FAO, Rome.

FAO (2012). The state of world fisheries and aquaculture. FAO Fisheries and Aquaculture, FAO, Rome.

Frost, M., J.M. Blaxter, P. Buckley, M. Cox, S. Dye & N. Withers Harvey (2012). Impacts of climate change of fish, fisheries and aquaculture. *Aquatic Conservation: Marine and freshwater Ecosystems*, **22**, pp. 331–336.

Furevik, T., Drange, H. & A. Sorteberg (2002). Anticipated Changes in the Nordic Seas Marine Climate. *Fisken og havet*, **4**: 2002, pp 1–13.

Gubbins, M. (2006). Impacts of climate change on aquaculture. In Buckley, P.J., S.R. Dye & J.M. Blaxter (eds.) Marine climate change impacts annual report card. Online summary reports, MCCIP, Lowestoft.

Gunnarson, V.I. (2009). Aquaculture in Iceland and coastal zone management. Presentation at University Centre of the Westfjords, 7. Sept 2009. Available at www.hsvest.is/skraarsafn/skra/266/.

Handisyde, N.T., L.G. Ross, M-C. Badjeck & E.H. Allison (2006). The effects of climate change on world aquaculture: a global perspective. Department for International Development, London.

Hanssen-Bauer, I., H. Drange, E.J. Førland, L.A. Roald, K.Y. Børsheim, H. Hisdal, D. Lawrence, A. Nesje, S. Sandven, A. Sorteberg, S. Sundby, K. Vasskog og B. Ådlandsvik (2009). Climate in Norway 2100. Background material for NoU on Climate adaptation (in Norwegian). Norsk Klimasenter, Oslo.

Haugen, J.E. & T. Iversen (2008). Response in extremes of daily precipitation and wind from a downscaled multi-model ensemble of anthropogenic global climate change scenarios. *Tellus*, **60A**, pp. 411-426.

Hermansen, Ø. & K. Heen (2012). Norwegian salmonid farming and global warming: socioeconomic impacts. *Aquaculture Economics and Management,* **16**: 3, pp. 202–221.

Imsland, A.K., T.M. Jonassen, S.O. Stefansson, S. Kadowaki & M.H.G. Berntsen (2000). Intraspecific differences in physiological efficiency of juvenile Atlantic halibut. *Journal of the World Aquaculture Society,* **31**: 3, pp. 285–296.

Klochkov, Dimitry. Manager and owner of Fishnet.ru, a news and industry online publication. www.megafishnet.ru.

Le Morvan, C., P. Deschaux & D. Trotaud (1996). Effects and mechanisms of environmental temperature on carp (Cyprinus carpio) anti-DNP antibody response and non-specific cytotoxuc cell activity: a kinetic study. *Developmental and Comparative Immunology,* **20**: 5, pp. 331–340.

Leckebusch, G.C., B. Koffi, U. Ulbrich, J.G. Pinto, T. Spangehl & S. Zacharias (2006). Analysis of frequency and intensity of European winter storm events from a multi-model perspective, at synoptic and regional scales. *Climate Research,* **31**, pp. 59–74.

Levesque, H.M., J. Bondy, C. Short, J.S. Ballantyne, W.R. Driedzic & T.W. Moon (2005). Effects of seasonal temperature and photoperiod on Atlantic cod. *Canadian Journal of Fisheries and Aquatic Sciences*, **62**: 12, pp. 2864–2873.

Lillehaug A., B.T. Lunestad & K. Grave (2003). Epidemiological description of bacterial diseases in Norwegian aquaculture - a description based on antibiotic prescription data for the ten-year period 1991 to 2000. *Diseases of Aquatic Organisms,* **53**, pp.115–125.

Lorentzen, T & R. Hannesson (2005). Climate change and future expansion paths for the Norwegian salmon and trout industry. Working paper 59/05, Institute for Research in Economics and Business Administration, Bergen.

Lorentzen, T & R. Hannesson (2006). Climate change and productivity in the aquaculture industry. Working paper 02/06, Institute for Research in Economics and Business Administration, Bergen.

Lorentzen, T. (2008). Modeling climate change and the effect on the Norwegian salmon farming industry. *Journal of Natural Resource Modeling*, **21**: 3, pp. 416–435.

Lorentzen, T. (2008). Modeling climate change and the effect on the Norwegian salmon farming industry. *Natural Resource Modeling*, **21**: 3, pp. 416–435.

Matulla, C., W. Schoner, H. Alexandersson, H. von Storch & X.L. Wang (2007). European storminess: late nineteenth century to present. Climate Dynamics, DOI 10.1007/s00382-007-0333-y.

Melsom, A., V. Lien & W.P. Budgell (2009). Using the Regional Ocean Modeling System (ROMS) to improve the ocean circulation from a GCM 20th century simulation. Ocean Dynamics. DOI 10.1007/s10236-009-0222-5.

Mordal, Christen. Consultant and owner of CA Mordal Consulting.

Mydlarz, L.D, L.E. Jones & C.D. Harwell (2006). Innate immunity, environmental drivers and disease ecology of marine and freshwater invertebrates. *Annual Review of Ecology, Evolution and Systematics*, **37**, pp. 251–288.

Naylor, R.L., R.J. Goldburg, J.H. Primavera, N. Kautsky, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney & M. Troell (2000). Effect of aquaculture on world fish supplies. *Nature*, **405**, pp. 1017-1024.

Parry, M.L., O.F. Canziani, J.P. Palutikov, P.J. van Linden & C.E. Hanson (eds.) (2007). *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge and New York: Cambridge University Press.

Russian Sea Group (2012). Status update presentation June 2012. Available at http://www.russianseagroup.ru/uploads/tx_drblob/storage/Status_update_presentation_RSG_June_2012_01.pdf

Sætre, R., J. Aure & D.S. Danielsen (2003). Long-term hydrographic variability patterns off the Norwegian coast and in the Skagerrak. *ICES Marine Science Symposium,* **219**: pp. 150–159.

Samuelsen, O.B., A.H. Nerland, T. Svåsand, M. Schrøder, T. Jørgensen & Ø. Bergh (2006). Viral and bacterial diseases of the Atlantic cod (Gadus morhua), their prophylaxis and treatment: a review. *Diseases of Aquatic Organisms* , **71**, pp. 239–254.

Simpson, M., K. Breili, H.P. Kierulf, D. Lysaker, M. Ouassou & E. Haug (2012). Estimates of future sea-level changes for Norway. Technical report of the Norwegian Mapping Authority, Statens Kartverk, Oslo.

Steinshamn, S.I. (2009). Climate change and marine aquaculture (in Norwegian). Working paper 33/09, Institute for Research in Economics and Business Administration, Bergen.

Symon, C., L. Arris & B. Heal (eds) (2008). Arctic climate impact assessment. Cambridge: Cambridge University Press.

Tolkacheva, Victoria. Officer responsible for aquaculture in Murmansk oblast.

Walker, A.M., M.C.M. Beveridge, W. Crozier, N. Maoileidigh & N. Milner (2006). Monitoring the incidence of escaped farmed Atlantic salmon, Salmo salar L. in rivers and fisheries of the United Kingdom and Ireland: current progress and recommendations for future programmes. *ICES Journal of Marine Science,* **63**, pp. 1201–1210.

Weisse, R., H. von Storch & F. Feser (2005). Northeast Atlantic and North Sea storminess as simulated by a regional climate model during 1958-2001 and comparison with observations. *Journal of Climate* **18**, pp. 465–479.

Winther, U., T. Olafsen, I.J. Aarhus & R. Tveterås (2010). Strategy for Norwegian blue mussel farming (in Norwegian). Report SFH80 A106001, SINTEF, Trondheim.

Ådlandsvik, B. (2008). Marine Downscaling of a Future Climate Scenario for the North Sea. *Tellus*, **60A**, pp. 451–458.

ISBN 978-82-8296-028-1 (printed)
ISBN 978-82-8296-029-8 (pdf)
ISSN 1890-579X