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Angelica T. Tungland

(signature author)

Author:

Angelica Thorsen Tungland

Course coordinator:

Hannah Hondebrink

Supervisor(s):
Mark van der Giezen

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The infectious diseases that pose a threat to the Norwegian farmed salmon industry in the coming years due to climate changes.

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Abstract

What emerging diseases can we expect as a threat to the rapidly growing and important farmed salmon industry in Norway due to anthropogenic environmental changes? This question will be answered as best as possible based on published studies in the field. First, basic knowledge of the current salmon industry in Norway is provided and the impact of climate change on aquaculture is presented, before the relationship between climate change and the impact of emerging diseases on the industry is examined. Climate change has been shown to affect salmon both directly, through abiotic factors, and indirectly, through pathogens. The abiotic factors are expected to change in a direction unfavorable to salmon, causing them to experience more stress. Pathogens, on the other hand, tend to thrive in the changing environment, according to the studies conducted. Several studies have examined various emerging diseases, and all agree that infectious diseases will be a greater problem in the future. It is expected that some of the pathogens present in the Norwegian industry today will emerge either in the form of incidence/virulence or geographically. Wild salmon have been shown to be carriers for many pathogens, making disease reoccurrence easier and disease outbreaks difficult to control. Vaccinations are used in the farming industry to control some diseases, such as Furunculosis. Diseases that are expected to continue to impact the farmed salmon industry and become more prevalent as a result of climate change include salmon louse, heart and skeletal muscle inflammation, cardiomyopathy syndrome, amoebic gill disease and proliferative kidney disease.

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1. Introduction

1.1 An important subject

The impact of climate change on the Norwegian salmon industry in the coming years is a topic on which there is a lack of information, and further research is needed. The Norwegian salmon industry is growing rapidly, and Norway is now the country that exports the most salmon (Olsen & Osmundsen, 2017; Stien et al., 2020). The farmed salmon industry in Norway has developed rapidly since 1970, and must continue to grow to meet future food needs (Liu et al., 2011). Given the importance farmed salmon has today and will have in the future, it is important to research and predict the potential challenges the industry will face in the coming years. By staying ahead of the potential challenges, it is possible to prevent and stop the potentially harmful outbreaks.

Pathogens have always been a treat for the industry, and for some time it has been reported that disease incident is approaching the poles (Bramwell et al., 2021). New pathogens are a threat to salmon health and also to the rapidly growing industry. Therefore, predicting the occurrence of pathogens is of interest. Climate change has been looked at as a factor influencing the shift of pathogens toward the poles.

1.2 Composition

First, the basics, the structure of salmon farming and the development of the industry in Norway are presented. It is important to understand how farmed salmon function in order to address the potential threats that farmed salmon face from climate change. An introduction to the salmon life cycle and its optimal conditions will be given to understand how the industry can propagate salmon faster. The issue is climate changes that can directly and indirectly affect farmed salmon. Abiotic changes are the direct effects, i.e., temperature, pH, salinity, and dissolved oxygen. Pathogens are the one indirect factor we will focus on.

Pathogens adapt to changes in the environment in different ways, and the different adaptations are explored in this text. One is the emergence of diseases that increases in incident, and the other is emergence in geographic space. At the end, there is a discussion that brings the different parts together before summarizing the results.

2. Facts and theory

2.1 The salmon industry in Norway

The salmon industry makes an important contribution to Norwegian society and brings social, economic and cultural benefits to Norway (Liu et al., 2011). The salmon industry in Norway was dominated by sea and river fishing for wild salmon before the farming industry developed around 1970 (Liu et al., 2011). The wild fishery declined, and as a result, the farming industry developed (Liu et al., 2011). Initially, salmon were farmed on a small scale in family-run fish farms (Stien et al., 2020). They aimed to restore livelihoods to rural fishing communities (Liu et al., 2011). The small industry expanded, and in the last 40 years the farming industry has grown significantly (GLOBAL SALMON INITIATIVE, 2017; Stien et al., 2020). Farmed salmon is now the most important sector of the salmon industry in Norway, and has replaced sea and river fishing, which used to be the most important sector (Liu et al., 2011). Farmed salmon now accounts for 60 % of total salmon production, and aquaculture is Norway's second largest export industry (GLOBAL SALMON INITIATIVE, 2017; Olsen & Osmundsen, 2017).

Norway is one of the few countries in the world who has developed a farmed salmon industry (GLOBAL SALMON INITIATIVE, 2017). The success of aquaculture depends largely on the complex ecology of the aquatic environment (Callaway et al., 2012). This complex ecology includes water temperatures between 8°C and 14°C, a sheltered coastline, and other biological conditions (GLOBAL SALMON INITIATIVE, 2017). These particular natural conditions exclude countries where farmed salmon can be raised. 95.6 % of farmed salmon was produced by five countries in 2015: Norway, Chile, Scotland, Canada and the Faroe Islands (Iversen et al., 2020). The last 4.4% was produced by eight different countries that do not have the required complex ecology (Iversen et al., 2020). Norway has the optimal conditions: the second longest coastline in the world, deep fjords, favorable temperatures, and oxygen-rich waters (Regjeringen, 2021). These conditions contribute to the fact that Norway is the largest producer of farmed salmon, figure 1 (Olsen & Osmundsen, 2017; Stien et al., 2020).

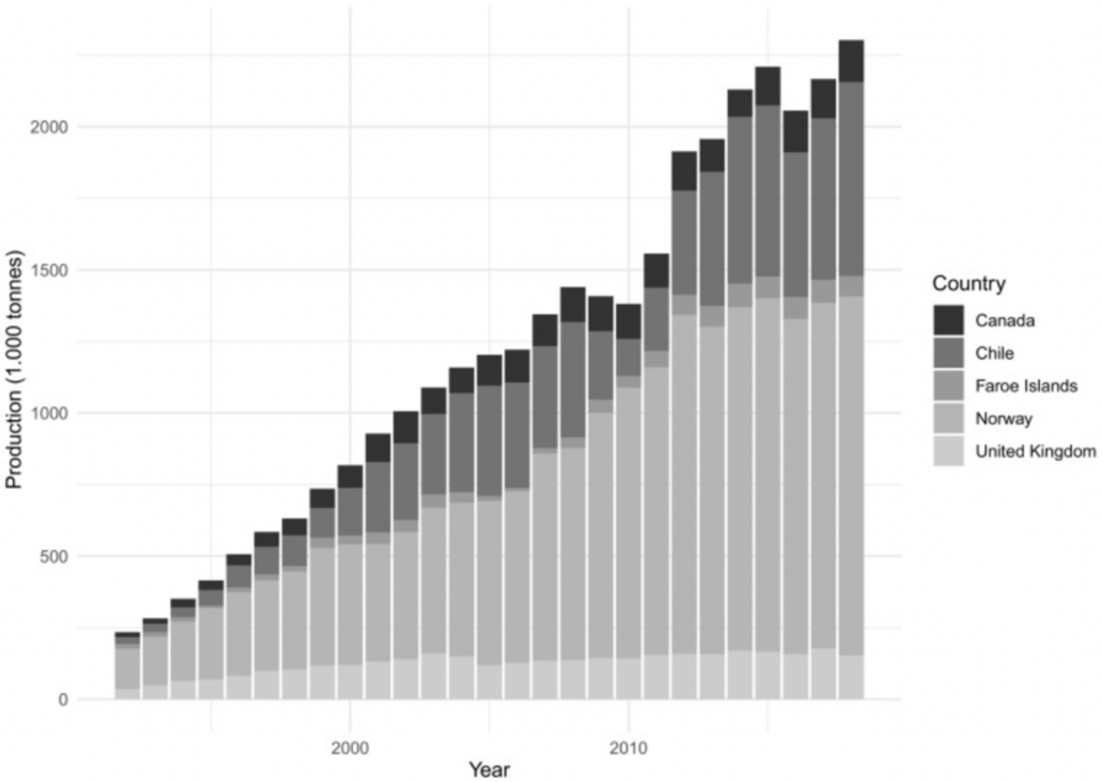

Figure 1 The amount of salmon produced for the five countries that account for the largest share of production (Iversen et al., 2020).

2.2 Atlantic salmon in natural conditions

Atlantic salmon (*Salmo salar*) is the species making success for farmed salmon industry in Norway. The Atlantic salmon has its natural habitat in the subarctic regions of the North Atlantic, the Barents Sea and the Baltic Sea (Thorstad et al., 2021). The production growth of Atlantic salmon is higher than that of aquaculture in general, possibly due to the fact that this species is the most studied species in the Northern Hemisphere (Iversen et al., 2020; Thorstad et al., 2021). Like salmon in general, Atlantic salmon are anadromous fish (Thorstad et al., 2021). Their natural life cycle consists of a juvenile phase in freshwater before migrating to the ocean to grow for one to several years and then returning to freshwater to spawn (Thorstad et al., 2021). The six different phases of the Atlantic salmon natural life cycle are described in more detail below.

1. Eggs and Alevins

The life of an Atlantic salmon begins in freshwater, where the eggs are buried in redd for protection from predators, light, low temperatures, and leaching (Centre for Environment Fisheries and Aquaculture science). Spawning of the eggs occurs from September to February, and the embryos develop during this time (Thorstad et al., 2021). In the spring, the eggs hatch and the embryo, an alevin, emerges (Thorstad et al., 2021). During the first period, the alevin takes food from a yolk sac it carries on its abdomen (Centre for Environment Fisheries and Aquaculture science). The alevin remains near the redd for several months while it grows (Centre for Environment Fisheries and Aquaculture science). After some time, when the alevin is no longer dependent on the yolk sac, it leaves the area and becomes a juvenile fish (National Park Service, 2019).

2. Fry

When it becomes a fry, it swims to the surface to fill the swim bladders with oxygen and then begins to feed (National Park Service, 2019). The length of the frying period varies from one year to more (National Park Service, 2019; Thorstad et al., 2021).

3. Seaward Migration

Seaward Migration is the largest stage in which the fish is modified for life in the oceans and passes into the smolt stage. Body shape and color, behavior, and physiology change (Centre for Environment Fisheries and Aquaculture science). Migration to seawater is triggered by environmental stimuli, but also by the fact that fish are not adapted to freshwater because they have been modified for seawater (Centre for Environment Fisheries and Aquaculture science; National Park Service, 2019). Once it reaches the sea, it heads to feeding grounds to feed heavily and try to survive in the sea (National Park Service, 2019).

4. Ocean life

Marine life varies greatly among salmon species. Atlantic salmon spreads over large areas, with most being present near the Faroe Islands and West Greenland. The migration route and feeding areas vary depending on the region where the salmon lives. The time it spends in the sea water varies from one to several years (INSTITUTE OF MARINE RESEARCH, 2020; National Park Service, 2019).

5. Spawning Migration

After a life in sea water, the fish migrates back to the river where it grew up (Centre for Environment Fisheries and Aquaculture science). It is believed that the fish finds the place with the help of its sense of smell, its magnetic field and the sun (Centre for Environment Fisheries and Aquaculture science; Dixon, 2018; National Park Service, 2019). When it returns to the river, it begins to prepare for spawning, and when it reaches the river, it stops feeding (National Park Service, 2019).

6. Spawning and Death

Upon their return, female salmon begin building rods in the river by turning on their sides and moving stones with their tails (Centre for Environment Fisheries and Aquaculture science). The dominant male courts the female, and after spawning, eggs are released into the redd (National Park Service, 2019). The female salmon covers the redd with stones before moving upstream to repeat (National Park Service, 2019). After spawning, both the female and male salmon die and provide nutrients to the river (National Park Service, 2019).

2.3 Farmed Atlantic salmon

The farmed salmon industry is based on the natural life cycle just presented, but optimal conditions are created to increase the speed of farming. The life cycle of a farmed salmon usually lasts three years and includes two main phases (Glover et al., 2017). The first phase is spent in controlled freshwater before the farmed salmon are transported to seawater cages, where they remain until they reach the wanted size, and are then prepared for sale (GLOBAL SALMON INITIATIVE, 2017; Glover et al., 2017). A more detailed description of the phases is presented.

1. Controlled freshwater

The life of a farmed salmon begins in an incubator where eggs are laid by female salmon and fertilization occurs (SEAFOOD FROM NORWAY). Fertilization takes place in fresh water at a constant temperature and after about 80 days the egg hatches (SEAFOOD FROM NORWAY). Like the wild salmon, the farmed salmon initially feeds on the yolk sac (SEAFOOD FROM NORWAY). When this is empty, they are fed with pellets (SEAFOOD FROM NORWAY). As the salmon grow, they are moved to larger tubes in the industry (SEAFOOD FROM NORWAY). At the end of their life in fresh water, they begin to change for a life in seawater.

2. Seawater cages

After 10-16 months in freshwater, they are transferred to seawater cages (SEAFOOD FROM NORWAY). In the seawater cages they grow until they reach a certain size, as they are fed with pellets (SEAFOOD FROM NORWAY). Usually they stay in the sea for 12-18 months until they reach a size of 2-5 kg. When the salmon reaches the wanted size, it is transferred to a facility (SEAFOOD FROM NORWAY).

2.4 Optimal conditions

As mentioned above, the facilitation of optimal conditions in the farming industry is carried out to increase the speed of growing farmed salmon. In order to achieve an optimal life cycle and fast growing salmon, some conditions must be optimal at different stages of the life cycle. If these conditions are not present, the resilience of the salmon may decline (Thorstad et al., 2021). The likelihood that pathogens, climate changes, and other ecosystem changes will cause stress to salmon increases when conditions are not optimal (Thorstad et al., 2021). Salmon depend primarily on three factors: Temperature, food and oxygen. All these factors are controlled in the farming industry, Figure 2. The factors will be presented below.

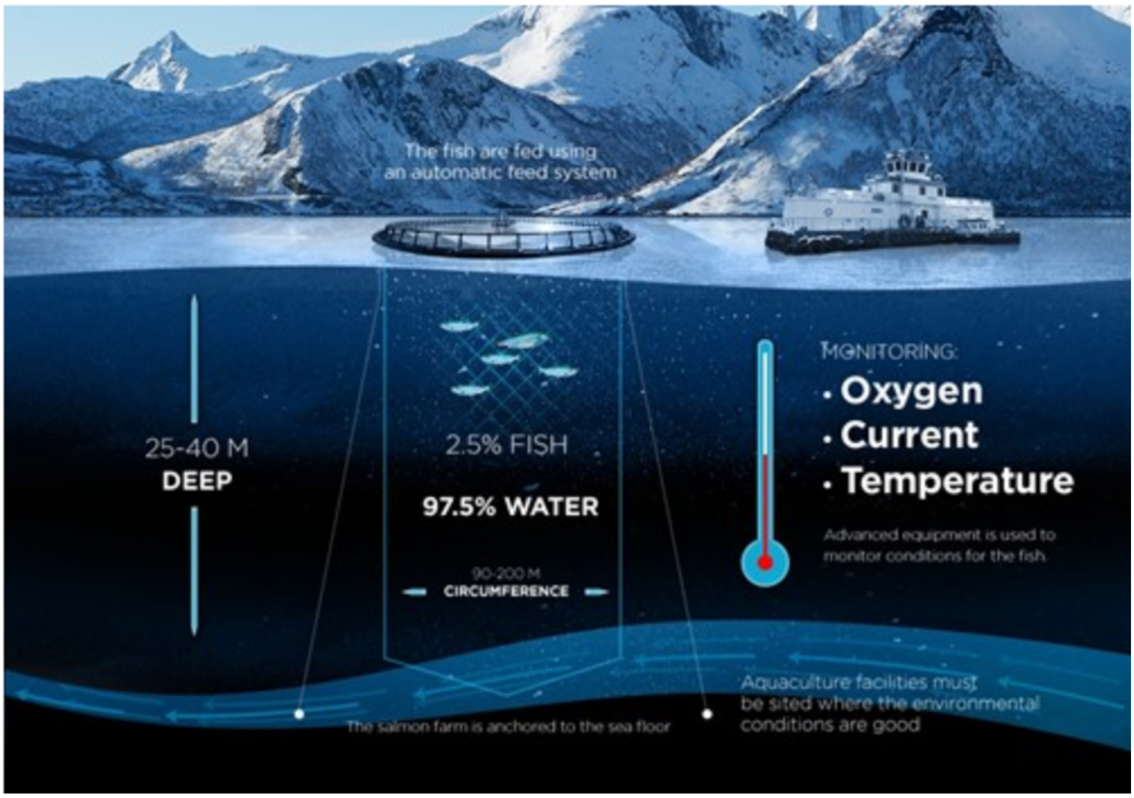

Figure 2 The hatchery in the sea. It shows that oxygen and temperature are monitored and food is supplied through an automatic feed system (SEAFOOD FROM NORWAY).

Temperature

Optimal temperature is critical and plays an important role in all stages of the salmon's life cycle because salmon are poikilothermic, meaning they are cold-blooded and cannot control their own body temperature (Marcos-López et al., 2010). The body temperature of Atlantic salmon changes therefore with changing environmental temperatures (ClimeFish, 2019a; Marcos-López et al., 2010).

Temperature is even important before the salmon is hatched because it is the factor that determines when the egg hatches. In nature it is important that hatching occurs at the right time, otherwise there may be a mismatch between hatching and the presence of the right environmental conditions (Centre for Environment Fisheries and Aquaculture science). In the farming industry, the goal is to have fish hatch as quickly as possible when they are ready. Atlantic salmon has an optimum temperature of about 16-19 °C, which can be discussed, and the growth rate increases up to this optimum temperature. (Centre for Environment Fisheries and Aquaculture science). So the temperature of the fresh and sea water helps regulate the growth rate of the salmon. Salmon are most sensitive when they are in the smolt phase, the phase when they move from freshwater to seawater. Optimal conditions at this stage prevent a high mortality rate (Persson et al., 2022). The farming industry can only control temperature during the first phase when salmon are in an incubator tray (Boyd, 2018b). When the salmon are moved to seawater to hatch, the temperature can no longer be changed by the industry, the temperatures are natural.

Food

Food availability is another factor that can easily influence salmon growth. Access to food is important at most stages when salmon begin to feed (Centre for Environment Fisheries and Aquaculture science). As with optimal temperature, access to food is especially important at the smolt stage to minimize fish mortality (Centre for Environment Fisheries and Aquaculture science). Access to food is one factor that is facilitated for salmon in the farming industry. They are fed dry pellets consisting of 70% vegetables and 30% marine raw materials such as fish and fish oil (SALMON FACTS, 2016). The pellets also contain various vitamins, minerals, pigments and amino acids (SALMON FACTS, 2016). The antioxidant astaxanthin is also included in the pellets to strengthen the immune system and protect fish tissue (SALMON FACTS, 2016). This contributes significantly to the faster and less stressful growth of salmon compared to wild salmon.

Dissolved oxygen

Dissolved oxygen is also a factor that salmon need, a certain level must be present. Atlantic salmon are a cold water species and require dissolved oxygen levels of 6 mg/L or greater to avoid stress (Boyd, 2018a; Mallya, 2007). Too low a level will result in lower survival and production (Boyd, 2018a; Mallya, 2007). In the floating systems used in farming, there is a complete oxygen supply system to ensure that these conditions are optimal (Noal Farm, 2020).

2.5 Pathogens in the Norwegian industry

As mentioned earlier, Norwegian industry has grown considerably since its beginnings, but like most industries, it has had to contend with various challenges. From the beginning, the biggest challenge has been disease outbreaks. As salmon are the host for many pathogens, it is natural that pathogens have affected the salmon industry, causing disease outbreaks and mortality. Today, the Norwegian coast is divided into 13 production areas. (Jensen & Sommerset, 2021; Kristoffersen et al., 2018). The 13 production areas that exist today were first established in October 2017, when "Production area legislation" came into force. An illustration showing how the coastline is divided today can be found in Figure 3 (Jensen & Sommerset, 2021).

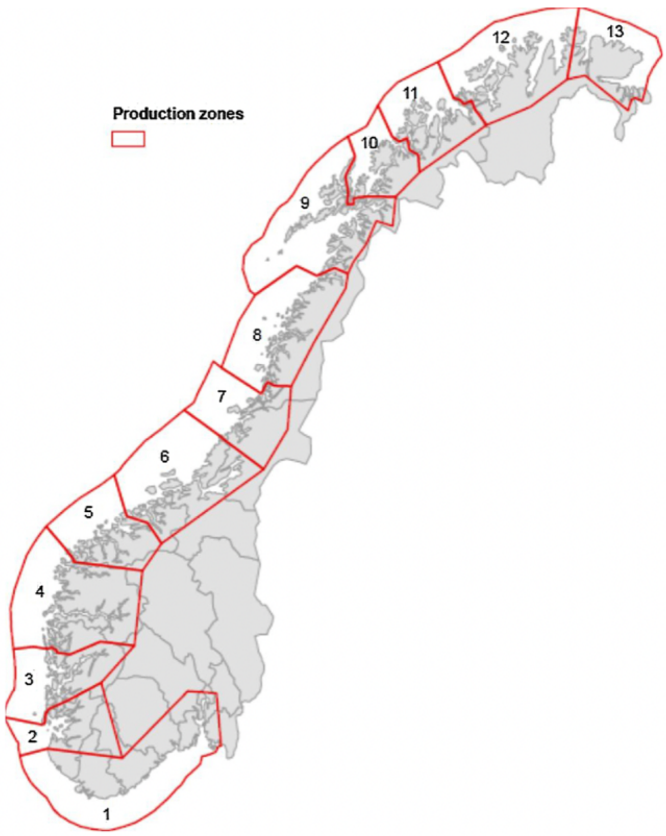

Figure 3 The 13 production areas the Norwegian costline is devided into (Kristoffersen et al., 2018).

The Norwegian Veterinary Institute publishes a report every year that it written to summarize the health situation in Norwegian aquaculture. Some diseases are reportable if an incident occurs, these are the notifiable diseases (Jensen & Sommerset, 2021). Others do not have to be reported because they are non-notifiable diseases. However, with the help of farms and private diagnostic laboratories, the Norwegian Veterinary Institute has been able to compile diagnostic statistics for these diseases aswell (Jensen & Sommerset, 2021).

2.5.1 NOTIFIABLE DISEASES

The notifiable diseases with the most incidents and increasing trends in the Norwegian farmed salmon industry from the Norwegian Aquaculture Report 2020 are Infectious Salmon Anemia (ISA), Pancreatic Disease (PD) and Furunculosis (Sommerset, 2021b). The diseases set in differently and cause different health problems, but they all have a negative impact on salmon.

Infectious Salmon Anemia (ISA)

Infectious salmon anemia (ISA) is caused by infectious salmon anemia virus. This disease is restricted to farmed salmon, as natural infection has not been demonstrated in wild salmon (Kibenge, 2016). The virus forms colonies on the surface of organs, gills, and skin before invading and settling in the bloodstream (Jansen et al., 2021). This invasion causes a deficiency of red blood cells in the gills, severe anemia, various circulatory disorders, damage to blood vessels, edema, necrosis, and hemorrhage in the eyes, skin, and internal organs (Jansen et al., 2021). There is a non-virulent variant called ISAV HPR0 and a virulent one called ISAV HPR -del (Vike et al., 2014). A difference in the amino acid sequence within the hypervariable region encoding the hemagglutinin esterase protein separates them (Jansen et al., 2021). The non-virulent form is the most common, the virulent strain comes from a mutation of the non-virulent form (Jansen et al., 2021). Most outbreaks of ISA in Norway occur in spring to fall at temperatures between 10 to 15 °C (Vike et al., 2014). The outbreaks are difficult to detect at an early stage, as the disease is often not seen on the salmon until the outbreak has already begun (Jansen et al., 2021).

Pancreas disease (PD)

Salmonoid alphavirus (SAV) is the virus that causes pancreatic disease (Sindre et al., 2021). The virus mainly affects farmed salmonids in the North Atlantic (Bang Jensen et al., 2021). These viruses cause pathological changes in the pancreas, decrease the production of digestive enzymes, and causing damage and inflammation in the heart and skeletal muscles (Bang Jensen et al., 2021; Sindre et al., 2021; Stien et al., 2020). As with ISA, there are several types of SAV. The types found in Norway are SAV2 and SAV3 (Sindre et al., 2021). SAV3 was the first genotype found and is also the one with the highest mortality rate compared to SAV2 (Sindre et al., 2021). Today, the different genotypes are restricted to different geographical areas in Norway (Bang Jensen et al., 2021). In the western part of Norway, PD is classified as an endemic disease, but from the middle of Norway to the northern part, the disease is considered an emerging disease, as it is not normally found in these areas (Pettersen et al., 2015; Sindre et al., 2021). PD has become a threat to the fast growing salmon production in Norway during the last decade, with increasing cases and high mortality (Kibenge et al., 2012). Table 1 shows that the number of registered cases of PD in 2020 was 158 and that the number of incidents has increased, as there were 100 cases in 2013 (Sindre et al., 2021).

Furunculosis disease

Furunculosis disease is caused by *Aeromonas salmonicida* subspecies *salmonicida* (Colquhoun, 2021). The infection is caused by a bacterium and not viruses like ISA and PD. The disease causes a high mortality rate in both fresh and marine water, but most cases of the disease are recorded in the marine phase (Colquhoun, 2021). The disease is thought to be transmitted horizontally, vertical transmission has not yet been demonstrated (Colquhoun, 2021). Horizontal and vertical transmission are the two possible modes of disease transmission. In horizontal transmission, an infected salmon transmits the pathogen to a salmon of the same generation. In vertical transmission, transmission occurs from the mother to her offspring (Chen et al., 2006). Like the other notifiable diseases, there is some variety within the pathogen. The Norwegian Veterinary Institute has found twenty-three variations of proteins on the surface of Aeromonas spp. (Colquhoun, 2021).

Table 1 Number of incidents for the different notifiable diseases (Sommerset, 2021b)

	List	2013	2014	2015	2016	2017	2018	2019	2020
Farmed fish: salmonids									
ISA	2	10	10	15	12	14	13	10	23
VHS	2	0	0	0	0	0	0	0	0
PD	3	100	142	137	138	176	163	152	158
Furunculosis	3	0	1	0	0	0	0	0	5
BKD	3	1	0	0	1	1	0	1	1
Systemic *F. psychrophilum* in rainbow trout	3	3	2	3	4	1	4	4	2
Farmed fish: Marine species									
Francisellosis (cod)	3	1	1	0	0	0	0	0	0
VNN, nodavirus	3	1	0	0	0	0	0	0	0
Furunculosis (lumpfish)	3	0	0	1	4	0	0	0	3
Wild salmonids (fresh water)									
Gyrodactylus salaris	3	1	1	0	0	0	0	1	0
Furunculosis	3	0	0	2	1	2	0	2	0

2.5.2 NON-NOTIFIABLE DISEASES

In addition to the notifiable diseases that pose a threat to farmed salmon, the non-notifiable diseases are also a major threat to salmon and the industry. The diseases that do the most damage and cause the most cases of non-notifiable viral diseases are heart and skeletal muscle inflammation (HSMI) and cardiomyopathy syndrome (CMS) (Sommerset, 2021b). As mentioned earlier, farms and private diagnostic laboratories have made it possible to investigate the situation of these non-notifiable diseases by sending in their data (Jensen & Sommerset, 2021). A summary of the incidents of these diseases can be found in Table 2.

Table 2 Incidents of the viral diseases, showing three non-notifiable diseases at the bottom (Sommerset, 2021a).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
ISA	7	1	2	10	10	15	12	14	13	10	23
PD	88	89	137	99	142	137	138	176	163	152	158
CMS	49	74	89	100	107	105	90	100	101	82	154*
HSMI	131	162	142	134	181	135	101	93	104	79	161*
IPN	198	154	119	56	48	30	27	23	19	23	22*

Heart and Skeletal Muscle Inflammation (HSMI)

Piscine orthoreovirus (PRV) is a double-stranded RNA virus that causes cardiac and skeletal muscle inflammation (Lund et al., 2017). The virus causes subsequent infection of myocytes and inflammation of the heart and red skeletal muscle (Dhamotharan et al., 2019). Infection usually occurs in the first year in seawater, but can also occur in hatcheries (Dahle & Olsen, 2021). The first outbreak was reported in 1999 and occurred at a farmed salmon production facility in mid- Norway (Dhamotharan et al., 2019; Pettersen et al., 2015). Since then, the disease has recurred, and in 2017 it was reported as the most important infectious disease from mid- Norway to the north (Dhamotharan et al., 2019). There are three types of PRV, but in Atlantic salmon it is PRV1, which has been found in both farmed and wild salmon along the entire coast (Dahle & Olsen, 2021; Dhamotharan et al., 2019). Different PRV1 strands have been found, some of which are more pathogenic than others (Dhamotharan et al., 2019). Even when salmon are infected with PRV, they do not necessarily develop HSMI because the pathogenicity of the strains is low (Dahle & Olsen, 2021; Dhamotharan et al., 2019). The mortality rate in infected Atlantic salmon is only 20 % (Dhamotharan et al., 2019).

Cardiomyopathy syndrome (CMS)

Cardiomyopathy syndrome is caused by the virus Piscine Myocarditis, a double stranded RNA non-enveloped virus (Fritsvold & Jensen, 2021). The virus affects the heart, causing inflammatory changes in the inner, spongy parts of the atrium and ventricles. In extreme cases, the heart wall may burst (Fritsvold & Jensen, 2021). The infectious disease usually affects salmon in their second year in the sea, but incidents shortly after sea transfer have been found (Bang Jensen et al., 2020; Garseth et al., 2018). The disease has a significant impact on salmon production as it affects approximately 100 farms each year (Table 2) (Fritsvold & Jensen, 2021). CMS is seen in all production areas along the coastline, from south to north, but most cases are reported from central Norway (Garseth et al., 2018). The first incident happened in 1985 in Norway. It was first a diseases thought not to spread, but in recent years it has been seen in other countries as well and it seems like the virus is more widespread, but is mainly in the north-eastern Atlantic Ocean (Bang Jensen et al., 2020; Garseth et al., 2018). The Norwegian Veterinary Institute concludes that the horizontal transmission route is the only one known for CMS (Fritsvold & Jensen, 2021). A project to summarize current knowledge about CMS and transmission states that several studies have shown that vertical transmission can also occur (Garseth et al., 2018). This study did look at risk factors for development of CMS. Fish affected by PD or HSMI could be more exposed to CMS, as the diseases also affects the heart. The reduction of PD and HSMI could mean that the mortality of CMS will decrease (Bang Jensen et al., 2020).

2.6 Climate change

Climate change is another challenge for farmed salmon and became a challenge for farmed salmon some time ago. Climate change has been on the agenda for a long time, especially concerns about human-induced changes. Carbon dioxide produced by human activities is the largest contributor to climate change. The burning of fossil fuels has increased extremely, and the amounts of carbon dioxide released are enormous. Deforestation does not contribute because more carbon dioxide is released when trees are cut down (European Commission). Anthropogenic emissions will have both direct and indirect effects on aquatic habitats, such as physiology, growth performance, reproduction, and infectious disease incidence. The changes that occur may result in both favorable and unfavorable changes for farmed salmon in the short and long term (Cubillo et al., 2021).

2.6.1 INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

The United Nations established The Intergovernmental Panel on Climate Change (IPCC) in 1988 to conduct a scientific assessment of current climate change (IPCC, 2022b). A total of five assessment reports were produced between 1990 and 2014, and a sixth assessment report is currently underway (IPCC, 2022b). In addition to the assessment reports, a number of special reports are also produced from time to time (IPCC, 2022b). In addition to work on the sixth report, three special reports have also been prepared. Two of these are of interest to the climate changes affecting salmon: "Global Warming of 1.5 °C " and "The Ocean and Cryosphere in a Changing Climate."(IPCC, 2022b). It is of great interest to look at these reports as they summarize what science knows about climate change (IPCC, 2022a).

Global Warming of 1,5 °C

This report considers different areas that are affected by an increase in temperature by 1.5 °C above pre-industrial levels. The information of interest from the report is the one considering aquaculture and salmon, and this will be presented here.

The report notes that temperature rise has already led to environmental changes such as more droughts, flooding, sea level rise, and loss of biodiversity (Allen et al., 2018, p. 69). Vulnerable populations are affected by these changes, and this will cause even greater problems for these populations (Roy et al., 2018) The ecosystem in the Arctic environment is already vulnerable and will be particularly threatened by estimated temperature increases (Roy et al., 2018). Atlantic salmon in Norway are part of this ecosystem, and therefore there are concerns for salmon in the future. The report states that as temperatures rise, many marine species will migrate to higher latitudes, increasing pressure on the Arctic ecosystem (IPCC, 2018). This could lead to increased competition for species and the introduction of new infectious diseases. At low latitudes, demand could increase, leading to lower productivity in fisheries and aquaculture (IPCC, 2018).

Physically, temperature increases will affect the growth, development, calcification, survival, and thus abundance of a wide range of species, from algae to fish (IPCC, 2018). For fish such as Atlantic salmon, it will affect physiology, survival, habitat, reproduction, disease incidence, and risk of invasive species (IPCC, 2018).

The industry will most likely notice a decrease of production in aquaculture. A model has shown that for a 1.5 °C increase, the estimated decrease in catch for marine fisheries would be 1.5 million tons, while for a 2.0 °C increase, the decrease in catch would be 3 million tons (IPCC, 2018). This shows that a 2.0 °C increase is much worse than a 1.5 °C increase, and this trend of large consequences for a “small” temperature increase is shown in most changes that are predicted to happened.

Ocean and Cryosphere in a Changing Climate

The Ocean and Cryosphere in Climate Change Special Report presents the evidence and studies on how the ocean and cryosphere will be affected by climate change. The report shows that the cryosphere has shrunk over time, due to physical changes in the ocean and cryosphere. This has led to a decreasing snowpack, a decrease in Arctic sea ice, and an increase in permafrost temperatures (IPCC, 2019). Most of these changes are caused by rising temperatures. The report notes that ocean warming has more than doubled since 1993 (IPCC, 2019). The same is for heat waves, which have doubled in frequency since 1982 (IPCC, 2019). As with Global Warming of 1,5 °C, this report refers to ocean species moving from the equator to the poles. This report assumes that the speed and direction of movement in coming years will be determined by local temperatures, oxygen levels, and ocean currents (IPCC, 2019).

2.7 Consequences of climate change

A closer look at how climate change is affecting salmon is needed. Climate change affects the salmon industry in two ways, both directly and indirectly (Bramwell et al., 2021). The changes that directly affect salmon are changes in water temperatures, salinity, pH, and dissolved oxygen levels (Callaway et al., 2012). As climate changes, there will also be cascading impacts; infectious disease is one of these indirect impacts that could have a greater impact on salmon in the future based on the environmental changes affecting the salmon (Bramwell et al., 2021; Cubillo et al., 2021). The success of aquaculture production is closely linked to environmental conditions (Callaway et al., 2012). Farmed salmon are less adapted to the natural environment compared to wild salmon and can be more easily stressed in a rapidly changing environment (Thorstad et al., 2021). In addition, salmon farm sites are often located in areas subject to the greatest climatic changes: coasts and estuaries are susceptible to changes in water temperature, storm intensity or frequency and sea level changes (Callaway et al., 2012).

2.7.1 DIRECT IMPACTS

Shifting temperatures

Temperature variation is the factor that most affects salmon. Two references agree that salmon have an optimal temperature of 8-14 °C and that fish mortality can occur at temperatures above 23 °C (GLOBAL SALMON INITIATIVE, 2017; The Fish Site, 2019). Some other scientific experts argue that the optimal temperature for salmon is between 16-19 °C (Centre for Environment Fisheries and Aquaculture science). Even though most studies show that the limit of fish mortality is 23° C, some salmon have been found dead even at temperatures as low as 20 °C (The Fish Site, 2019). The different results of the studies conducted may indicate that there are differences within the salmon species (The Fish Site, 2019).

Water temperatures have risen 1 degree since 1980 alone and are expected to continue to rise in the coming years (The Fish Site, 2019). One project has estimated a temperature increase of 0.4 °C to 0.6 °C at 50 m depth by 2050 (ClimeFish, 2019a). The projected temperature increase is expected to have severe impacts on salmon because they are a poikilothermic, cold-blooded species that cannot control their body temperature (The Fish Site, 2019). One study has shown that temperatures above optimal levels lead to a reduction in apatite, which impairs growth, increases mortality and makes salmon more susceptible to disease (The Fish Site, 2019). Temperature is a critical factor because it directly affects growth and survival (Boyd, 2018b). Increasing temperatures have been shown to affect salmon in southern areas first. Northern populations have more room to adapt because temperatures there are lower and not yet at the limit of salmon's thermal tolerance as in southern areas (Thorstad et al., 2021).

Acidification / pH

Ocean acidity is a threat to the marine ecosystem (Callaway et al., 2012). The pH correlates with warming, an increase in temperature causes the equilibrium of the chemical reaction to lower the temperature by absorbing additional heat. The absorbance of heat cause the water to become more acidic because more hydrogen and hydroxide ions are created (Baag & Mandal, 2022; Gillespie, 2018). Since pre-industrial times, water has become more acidic, with a 0.1 unit decrease in pH (Baag & Mandal, 2022). The oceans act as a sink, absorbing C02. Increasing anthropogenic carbon emissions have resulted in more CO_2 being absorbed by the ocean (Baag & Mandal, 2022). This changes water chemistry by increasing hydrogen and bicarbonate ions and decreasing carbonate ions, making the oceans more acidic (Baag & Mandal, 2022). One study has predicted a decrease in pH of 0.13 to 0.42 units by the year 2100 (Baag & Mandal, 2022). Studies have shown that individual species respond differently to acidification levels (Callaway et al., 2012). The most vulnerable group is the calcifying marine species, as problems with calcium carbonate production increase with ocean acidity (Callaway et al., 2012). The finfish group, including Atlantic salmon, is thought to cope better because they are already adapted to some of the stresses associated with acidification, having experienced the high concentrations found at deep-sea sources and the elevational changes of the intertidal zone. These adaptive responses may have made salmon less sensitive to the changes caused by anthropogenic emissions (Pörtner, 2008).

Most studies that have examined how acidification affects finfish have found no direct adverse effects on growth, egg survival, or swimming performance. Thus, it appears that acidification is not yet a problem for salmonids due to the predicted pH changes in the further, but more research is needed to be certain (Callaway et al., 2012). I If environmental predictions change and pH and temperature change more than anticipated, this could potentially affect salmon much more severely. The processes in fish metabolism that could then potentially be affected are shown in Figure 4 (Baag & Mandal, 2022).

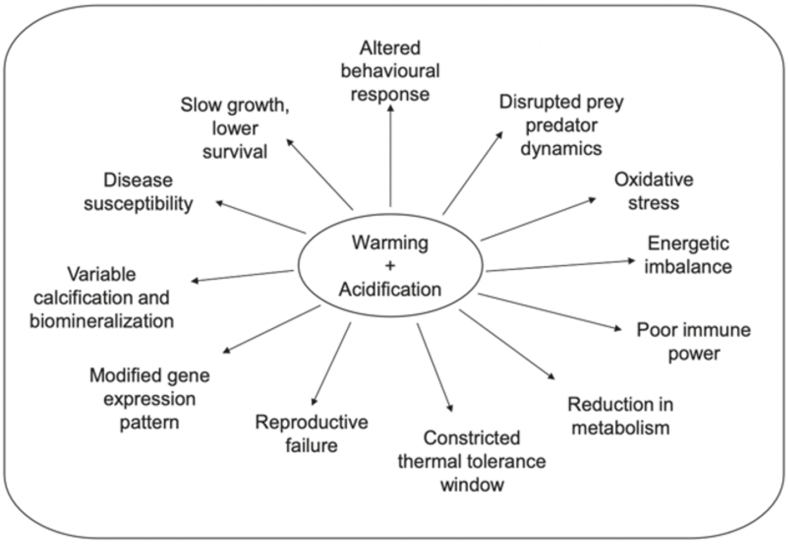

Figure 4 Different effects changing temperature and pH can have on the salmon (Baag & Mandal, 2022)

Salinity

Atlantic salmon are highly dependent on environmental salinity conditions. Changes in salinity affect the fish's cellular processes, such as osmotic regulation and respiration (Lawlor & Arellano, 2020). The fish experiences problems with survival, growth, development, metabolism, osmotic capacity, and reproduction as these are controlled by osmotic regulation and respiration (Duan et al., 2021). As mentioned earlier, the salmon is sensitive in the smolt phase and salinity is important in this phase because the salmon adjusts its osmotic pressure and improves its salt tolerance at this stage in the life cycle (Duan et al., 2021; Lawlor & Arellano, 2020).

Dissolved oxygen

Dissolved oxygen is one of the most important factors affecting the metabolism, welfare and growth of fish (Burke et al., 2021). As temperatures rise, the concentration of dissolved oxygen decreases because warmer water holds less dissolved oxygen and the solubility of oxygen decreases as temperature increases (Boyd, 2018b). The dissolved oxygen problem arises because dissolved oxygen decreases and the respiration rate of fish increases as temperature increases (Boyd, 2018b). Atlantic salmon are aerobic organisms that depend on sufficient dissolved oxygen because it is the primary limiting factor for aerobic metabolism (Boyd, 2018b; Solstorm et al., 2018). The amount of oxygen required to maintain aerobic metabolism and not switch to anaerobic metabolism increases with increasing temperature. One study has shown that at 6 °C oxygen saturation of at least 30 % is required, and at 19 °C, oxygen saturation of at least 55 % is required (Solstorm et al., 2018). At oxygen concentrations outside the optimal level, hypoxia occurs and can lead to fish mortality (Burke et al., 2021).

Variations of dissolved oxygen has been observed in marine cages used in farmed salmon, both within a cage and variation through the year (Solstorm et al., 2018). It has been observed that the condition in a marine cage varies in the vertical direction. It is expected to vary in the horizontal direction as well, but there are no clear results from studies conducted. A study that examined the variations in a cage, up to 20 % vertical variation was observed between the surface and the cage bottom (Johansson et al., 2006). The study also showed that the saturation of individual fish in such cages varied from 30 % to 90 % (Solstorm et al., 2018).

One study examined how dissolved oxygen in a commercial fish farm changed throughout the year. The study showed an increase in dissolved oxygen starting in mid-October, as temperatures were also dropping at that time (Burke et al., 2021). This shows the correlation between temperature and dissolved oxygen. When the temperature decreases, the water receives a higher potential of dissolved oxygen and the water exchange at the air- sea interface increases. Also, the salmon breathing rate decreases when the temperature is lower, which means that the salmon consume less oxygen. So overall, dissolved oxygen levels are highest when the temperature is low, and salmon thrive better because more oxygen is available (Burke et al., 2021).

2.7.2 INDIRECT IMPACTS

The factors just considered individually: rising water temperature, change in salinity, pH, and dissolved oxygen, must also be considered together. One study has shown that the climate change stressors are unlikely to occur alone. It is more logical to look at them together to see the consequences (Baag & Mandal, 2022). Infectious disease is one of the consequences that climate change will have indirectly on salmon (Cubillo et al., 2021). Environmental conditions are expected to increasingly fall outside the optimal range for salmon. Conditions outside the salmon's optimal range cause stress and make the salmon more vulnerable. It will then be easier for Atlantic salmon, the host, to become infected with a pathogen.

Atlantic salmon thrive best when environmental conditions are within the optimal range, and their susceptibility is particularly dependent on temperature. At an optimal temperature, Atlantic salmon is strongest and can resist the best diseases. The pathogen has this in common with salmon. The pathogen also has an optimal temperature at which it works best and at which it can multiply the fastest (Marcos-López et al., 2010). So we know that the immune response of the salmon and the replication of the pathogen are dependent on temperature. The likelihood of causing disease depends on the interaction between the host, the pathogen and the environment (Marcos-López et al., 2010). Temperature is a factor that affects all three elements and determines whether an infection will result in mortality or recovery (Marcos-López et al., 2010).

2.8 Pathogens in the future

Earlier I introduced you to the pathogens that are causing most of the outbreaks in the farming industry today, but below we will take a look at the pathogens that are trending to change with climate change. Pathogens are the biggest threat to Norwegian agriculture, causing high mortality rates and resulting economic losses (Silva De Oliveira et al., 2021). As mentioned earlier, pathogens are also affected by temperature, so it is expected that the group of pathogens will change with climate change. Emergence of infectious diseases in marine or freshwater environments has been reported (Callaway et al., 2012). An emerging disease is one whose incidence/impact or geographic distribution has recently increased (Kibenge, 2016). An emerging disease is one whose incidence/impact or geographic distribution has recently increased. Several factors are responsible for the occurrence of viral diseases, and the interaction of these factors determines the outcome. The factors are: Virus, Host, and Environment, see Figure 5 (Kibenge, 2016). Studies have shown that climate change appears to contribute to disease occurrence by increasing the number of incidents and expanding geographic distribution (Kibenge, 2016).

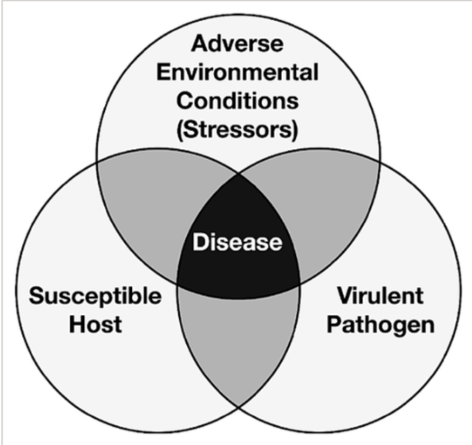

Figure 5 The attributes for emergence diseases presented in a Venn diagram (Callaway et al., 2012)

2.8.1 EMERGENCE OF DISEASES BASED ON AN INCREASE IN INCIDENT

Some diseases are emerging diseases or are predicted to become emerging infectious diseases as the number of cases increases due to their virulence (Kibenge, 2016). Virulence of non-native parasites and pathogens to native species may increase due to rising temperatures predicted for the coming years (Callaway et al., 2012). As temperatures rise, some pathogens gain more optimal conditions that allow them to complete their life cycles more quickly (Marcos-López et al., 2010; Rahel & Olden, 2008). Some pathogens present in Norwegian farmed industry today show a tendency to thrive in the changing climate.

Furunculosis

A study was conducted to investigate how *Aeromonas* responds to various abiotic factors. Laboratory simulations with microcosm tests were performed for this purpose (Grilo et al., 2021). The study showed a biphasic effect for *Aeromonas* at different temperatures. As temperature increased, both growth and metabolic activity increased, up to a certain level where growth decreased. *Aeromonas* also benefited from a low pH in which it grew better compared to an alkaline environment (Grilo et al., 2021). Other studies however did not see any effect of acidic versus alkaline environment (Sautour et al., 2003). It can indicate that *Aeromonas* may evolve in different directions, some tolerating alkaline environment and some not (Grilo et al., 2021). The Norwegian Veterinary Institute found twenty-three variations of the protein on the surface of *Aeromonas spp*.(Colquhoun, 2021).

Pancreas disease (PD)

In the western part of Norway, PD is classified as an endemic disease, but from central Norway to the northern part, the disease is considered an emergency disease because the disease is not normal in these areas (Pettersen et al., 2015; Sindre et al., 2021). The limited number of cases registered at PD in the northern part may be related to the lower density of sites in the north compared to western Norway. PD has become a threat to the fast-growing salmon production in Norway in the last decade as more cases occur and mortality is high (Kibenge et al., 2012). One study reported that subclinical infections have occurred in Atlantic salmon in Scotland. Based on the results, it is thought that environmental factors and host/pathogens may influence the severity of an outbreak of PD (Kibenge et al., 2012). Another study examined the correlation between temperature and outbreaks in different seasons and found that temperature is a factor influencing outbreaks of PD. The optimal temperature for this virus in ocean temperatures was reported to be about 6-10 °C (Stene et al., 2014).

Infectious salmon anemia (ISA)

One study has shown that ISA virus can reappear in the environment, making the disease a constant threat to industry (Pettersen et al., 2015). Studies have also been conducted to determine the optimal temperature for this pathogen. One study has shown that most outbreaks of ISA occur in the spring to fall in Norway when temperatures are between 10-15 °C (Vike et al., 2014).

Proliferative kidney disease (PKD)

Several studies have also been conducted for Proliferative kidney disease (PKD). One study has shown that PKD is an infectious disease that can become more virulent with increasing temperatures. The disease is temperature dependent and infections with PKD do not occur until temperatures reach 15 °C or higher (Anders Gravbrøt Finstad (red.), 2005). Other studies support these findings, and in both Switzerland and Norway there is evidence that PKD becomes contagious with increasing temperature (Marcos-López et al., 2010).

2.8.2 EMERGENCE OF DISEASES BASED ON GEOGRAPHICAL RANGE

Stressors experienced by salmon due to climate change have been shown to force organisms and pathogens to adapt to environmental changes or move to other areas with more optimal temperatures. This can lead to additional competition and new viruses, bacteria, protozoa, and multicellular parasites introduced by new invasive species (Thorstad et al., 2021). The species moves to find more favorable environmental conditions. Pathogens are therefore of particular concern because they can become more virulent in a more optimal environment (Kibenge, 2016). One study has shown that organisms in general, including pathogens, move to the poles when temperatures rise (Bramwell et al., 2021). There is a lack of studies looking at specific species, and pathogens in particular, in relation to salmon and aquaculture in Norway. One study has shown that about 400 species and infectious diseases are moving toward the poles at rates ranging from 14.4+-8.7 km to 72.0+-13.5 km per decade (Bramwell et al., 2021). Another study examined the last 50 years and found an average shift of 1.4 to 28 km/decade for marine communities (Rahel & Olden, 2008). Environmental impacts are expected to vary globally as environments change differently, but organisms are expected to respond by migrating to maintain their thermal niches regardless of these differences (Rahel & Olden, 2008).

Salmon louse and amoebic gill disease

A study conducted in Ireland showed that salmon louse (*Lepeophtheirus salmonis*) and amoebic gill disease (AGD) are diseases of concern to the Atlantic salmon industry there (Mc Dermott et al., 2021). Another study that presents the treats for the Norwegian industry writes about *Lepeophtheirus salmonis* (Forseth et al., 2017). *Lepeophtheirus salmonis* has been present in the Norwegian salmon industry since late 1980 (Forseth et al., 2017). It is predicted that salmon lice may reduce salmon survival in farmed areas, especially in the southwest and central areas, but northern Norway may also be affected. The expansion to the northern part is a result of increasing water temperature. The risk assessments conducted in the study showed an increase in salmon lice from 2010 to 2015 (Forseth et al., 2017). The amoebic gill disease is also present in Norway and causes most cases in the warmer seasons when the water is warmer and has high salinity (Lillehammer et al., 2019). These results suggest that there may be more cases of the disease when temperatures rise and amoebic gill disease will then be more common in Norwegian aquaculture. Several studies support the trend, the studies has shown that increasing water temperature and high salinity levels contributes to outbreaks of amoebic gill disease (Flores-Kossack et al., 2020).

Proliferative kidney disease (PKD)

PKD is also expected to spread geographically. One study has shown the occurrence of PKD in northern regions (Gorgoglione et al., 2020). It has been reported that the causes of PKD are appearing in new areas around the world and that northward spread is being observed (Gorgoglione et al., 2020). The life cycle of PKD is favoured by warmer water temperatures (Gorgoglione et al., 2020). Increasing temperatures caused by climate change have been shown to be a factor influencing the occurrence of the disease in northern areas. Both Europe and North America have been more affected by PKD outbreaks in recent years due to rising temperatures. These areas tended to be cold in the past, which prevented outbreaks, but as temperatures rise, the disease is beginning to thrive in these new regions (Gorgoglione et al., 2020). Another study that looked at PKD concluded that PKD is considered an emerging disease due to anthropogenic changes and that the geographic range will expand as temperatures rise (Bruneaux et al., 2017).

2.9 Correlation between wild and farmed salmon pathogens

Wild and farmed fish share the same water, providing many opportunities for interactions between the pathogen flora of wild and farmed fish (Tengs & Rimstad, 2017). Therefore, it is of interest to study pathogens in the wild, because they can often introduce new pathogens into the farming industry and also spread diseases they got from farmed salmon (Tengs & Rimstad, 2017). Most of the viral diseases that cause problems in the industry are enzootic, meaning they originate from wild fish (Kibenge, 2016).

While many of the diseases are unique to the farming industry, it has been shown that the pathogen causing the diseases is often present in the wild population. ISA, PD and HSMI are three diseases that are unique to farmed fish, but carriers of these diseases are found in wild salmon (Kibenge, 2016). SAV has been observed in other species where it replicates, these species serve as carriers and reservoirs for the pathogen. The same has been observed in PD (Kibenge, 2016). The pathogen SAV has been found in wild populations, but no disease outbreak from PD in the wild, only in farmed salmon. HSMI is also only registered and has been found in the farmed industry, but the pathogen *Piscine orthoreovirus* has been found in wild organisms (Kibenge, 2016).

However, this correlation between wild and farmed salmon shows that wild salmon are more affected than farmed salmon. When farmed salmon escape into the wild, pathogens are transmitted to the wild population, and escapes also affect wild salmon through competition (Liu et al., 2011; Thorstad et al., 2021). Sea lice are the disease that most affects wild salmon populations when farmed salmon escape (Thorstad et al., 2021). Sea lice can reduce wild salmon population size and cause more mortalities, making the population more vulnerable to climate change (Thorstad et al., 2021).

On the other hand, interbreeding is also a problem when farmed salmon escape, and it has become a major problem. In one study, it was estimated that 14-36 % of the spawning population in Norwegian rivers consists of farmed salmon (Liu et al., 2011). The consequences of this number of escaped farmed salmon are changes in genotype and loss of genetic variation and local adaptation in the wild population, possibly leading to the disappearance of threatened wild salmon populations (Liu et al., 2011). The problem may also pose problems for farmed salmon in the long term because the farmed animals come from different wild populations (Liu et al., 2011).

Figure 6 A prototype of a closed caging system (Olsen, 2020)

Several studies have looked at closed containment technologies as a possible solution to end the negative consequences of escape of farmed salmon.
The sea catches used mainly today are open net catches. The solution to use more closed caging systems will separate farmed salmon from wild salmon and thus solve the correlation problem. There are some challenges to progress, however, as it requires a lot of space, which can lead to conflicts with other users of these areas (Thorstad et al., 2021). But the technology is already in operation in small production areas in Canada (Thorstad et al., 2021). A prototype has also been built on the west coast of Norway, figure 6 (Olsen, 2020). The salmon farmed in this facility were bigger and better, probably due to even more controlled conditions (Olsen, 2020).

2.10 The use of vaccines and antibiotics

Vaccines have been a part of the farming industry since 1990 when the use of vaccines in fish farming became popular (Kibenge et al., 2012). It is well known that sustainable and successful aquaculture depends on the use of vaccines (Kibenge et al., 2012). The use of vaccines facilitates the prediction of future disease situations and the management of diseases in intensive production (Brudeseth et al., 2013). The use of vaccines facilitates the prediction of future disease situations and the management of diseases in intensive production. Vaccines against bacteria have performed well, and furunculosis is one of the bacterial diseases that is well controlled thanks to vaccination (Colquhoun, 2021). Vaccines against viral diseases are more difficult to develop, and there are relatively few effective and officially licensed viral vaccines. Little research has been done on fish vaccination, and antiviral drugs are not yet used in aquaculture (Kibenge et al., 2012).

Farmed salmon are now routinely vaccinated against several potential pathogens. Vaccines can be either water- or oil-based and are administered either orally through the feed, by immersion in dilute vaccine suspensions, or by injection through the intraperitoneal or intramuscular route. Vaccination is usually given when the salmon weighs 30-40 g before reaching the smolt stage (Kibenge et al., 2012). In Europe, salmon are vaccinated with a single injection of a multivalent vaccine, a vaccine designed to protect against multiple bacterial viruses such as furunculosis and vibriosis and viral diseases such as IPN, ISA and PD (Kibenge et al., 2012). The Norwegian Veterinary Institute states that intraperitoneal injection of multivalent oil-based vaccines is used in Norway. In addition, it is common to use single component vaccines for some diseases. Farmed salmon in Norway are usually vaccinated against furunculosis, vibriosis, cold water vibriosis, winter ulcer and IPN. PD Vaccines should now be used for salmon between Taksneset (Fræna) in the south and Langøya near Kvaløya (Sømna) in the north (Nielsen et al., 2021). Although they have been vaccinated, there are cases of multiple disease. The vaccines have reduced the number of disease cases and the need for antibiotics, thus improving the welfare of the fish (Brudeseth et al., 2013; Nielsen et al., 2021). Outbreaks of PD have decreased since the vaccines were used. Vaccination has also led to a decrease in viral shedding from infected fish. A new DNA-based vaccine has been introduced that has reportedly shortened the duration and impact of the disease and resulted in fewer fish dying after outbreaks. The number and prevalence of furunculosis decreased when effective vaccines were introduced. There is a vaccine against ISA, but it is not yet widely used. The Norwegian Veterinary Institute reports that interest in the vaccine seems to be increasing. Vaccines have not yet been developed for all diseases. There are no vaccines yet for the non-notifiable diseases HSMI and CMS, but vaccines are being worked on (Dahle & Olsen, 2021; Fritsvold & Jensen, 2021).

Although vaccines have improved fish welfare, side effects are also reported. The most normal side effects in Norway are growth of connective tissue between internal organs and between internal organs and peritoneal walls, melanin deposition, decreased appetite, and decreased growth (Kibenge et al., 2012; Nielsen et al., 2021). Since vaccines against cold water vibrosis and furunculosis have become available, the need for antibiotics in the Norwegian industry has been low and is only used in a few cases when disease outbreaks become too large. The Norwegian Veterinary Institute has concluded that the incidence of antibiotic resistance in fish pathogens is very low (Colquhoun & Nilsen, 2021).

2.11 Local differences in climate change

The climate along the Norwegian coast varies enormously. Environmental conditions vary because the latitude spans 13° latitude from 58°N to 71°N (Falconer et al., 2020). Risks to industry can therefore be difficult to determine, as risks are likely to be both site and region-specific. Forecast models are therefore challenging (Smålas et al., 2020).

In some regions of Norway, the temperature has already exceeded the optimal temperature for salmon. These regions with already high temperatures will be particularly affected if temperatures continue to rise in the coming years (ClimeFish, 2019a). The southern parts of the country are most at risk from climate change, as physiological tolerance thresholds may already have been exceeded in these locations (Forseth et al., 2017). In one study, an individual-based mechanistic population model was used to determine climate changes for three climate regions in Norway. The model showed that there would be an increase in production in the western and northern parts of Norway. The reason for this positive development has to do with an expected increase in summer temperatures. (Forseth et al., 2017).

Another study has conducted a risk and opportunity assessment for the north and south of the Norwegian coast (Smålas et al., 2020). Based on the projected effects of climate change on salmon production, only the southern portion is at risk. Heat waves are the factor that poses a major risk to the fish. There is a large risk associated with the severity of pathogens that have a biological impact. There is also a risk associated with socioeconomics. This was a risk assessment for the decade 2030, and if you extend it to 2050, the risk increases and will get worse. The three factors are the spread of pathogens, the quality of fish, and the conflict between environment and space. For the decade to 2030, in northern regions, the greatest risks are associated with global fish feed markets and prices and consumer demand for salmon. For risk assessment through 2050, the main risks are associated with the spread and severity of pathogens, algae, jellyfish blooms, and fouling. Rising temperatures leading to faster fish growth and better feed conversion was an opportunity found in the north, but could be reduced by stressors such as increasing disease outbreaks. A model showed that pathogens could pose a higher risk compared to changes in water temperatures (Smålas et al., 2020)

One study showed how the 13 different zones into which the Norwegian coast is divided are affected by climate change. Since livestock cannot change locations, it is necessary to consider changes in conditions on the farm and in the surrounding area. In addition, this study provides more concrete information than the previously studied large-scale estimates (ClimeFish, 2019b). It is not easy to know which technology should be used to obtain the best results in predicting environmental changes in different parts of Norway. The study evaluated the use of a coarse-scale model. The study showed that in the southern part of Norway there were days with temperatures above 16 °C and even some above 20 °C. This resulted in a decrease in production. In the northern part, a temperature increase will also occur here, but it will cause a positive result with faster growth. Another side of the temperature increase in the north is the increase of infectious diseases. The different regions of the north may be affected differently due to their location and latitude variation, local hydrography and topography (Bang Jensen et al., 2020).

3. Discussion

This study was conducted to compile the knowledge on published research on Atlantic salmon and climate change to predict which pathogens can be expected in Norwegian farmed salmon in the coming years due to anthropogenic environmental changes.

3.1 Direct and indirect effects of climate change

Climate change is expected to affect several factors that are important to the salmon farming industry. Anticipated environmental changes are expected to affect salmon both directly and indirectly (Bramwell et al., 2021). Changes in temperature, pH, salinity, and dissolved oxygen are of concern to salmon because the species needs these conditions to be optimal, otherwise they may directly affect salmon physiology (Callaway et al., 2012). Some of these abiotic factors are of more concern than others, and they also vary along production areas because of the long coastline of different climates.

The salmon is dependent on the temperature as the specie is poikilothermic, meaning that their bodytemperature is shifting as the temperature does (Marcos-López et al., 2010). Temperature is expected to rise as CO2 emissions increase. Temperature outside the optimal is expected to affect survival, reproduction, habitat and disease incidents (IPCC, 2018). The increasing temperature is mostly a concern for the southern areas as they already have experienced temperatures reaching over the optimal temperature that is around 16-19 °C for the Atlantic salmon (Centre for Environment Fisheries and Aquaculture science; Smålas et al., 2020). If looking at the north part of Norway, the farming industry can benefit from the increasing temperature as the temperature then will reach a temperature that the salmon will most likely grow faster in. In the long term, however, rising temperatures are also expected to challenge the optimal temperature of salmon in these areas (ClimeFish, 2019b).

Ocean acidity (pH) is another factor that is expected to decrease in the coming years as temperatures rise and the balance in the water changes, creating more hydrogen and hydroxide ions. This leads to more acidic water. CO_2 is also taken up by the ocean, changing the water chemistry and making the water more acidic. Both factors contribute to a decrease in ocean acidity (Baag & Mandal, 2022). There are studies that show this will affect aquaculture, but for now it is mostly a threat for the calcifying marine animals (Callaway et al., 2012). Studies have shown that salmon are better able to adapt to changes in pH and that there are no direct physical effects (Callaway et al., 2012). However, there are not many studies in this field yet, so more studies are needed to rule out acidification as a threat.

Changes in salinity directly affect osmotic regulation and respiration (Lawlor & Arellano, 2020). If salinity changes in the future, problems are expected for salmon, but there is a lack of research for this factor aswell making it difficult to establish the risk.

Dissolved oxygen is the last direct factor considered in this study. This factor is closely related to temperature in terms of how it affects salmon. It is generally predicted that dissolved oxygen will decrease in coming years due to rising temperatures. Warmer water will hold less dissolved oxygen, and solubility will decrease. Atlantic salmon need 6 mg/l or more to not normally experience stress (Boyd, 2018a). The relationship between temperature and dissolved oxygen is that salinity decreases as temperature increases (Boyd, 2018b). Salmon naturally need more oxygen as temperature increases, but with the expected decrease in dissolved oxygen, this will likely become a problem in the future. This will result in lower survival and production (Boyd, 2018a).

All these direct factors have shown tendency to maybe be a part of an increase of disease outbreaks, and can be expected to become worse as the changes in environment are going to increase. The different pathogens obviously react differently to the changes, but there is shown a emergence tendency of pathogens in general, either it is based on increase in incident/impact or pathogens entering new geographical areas (Kibenge, 2016). As with the salmon having its optimal range, the pathogens also have a optimal range (Marcos-López et al., 2010). These changes in the environment will therefor also affect the conditions to the pathogen. These changes have been seen to be favorable for some pathogens, and it is especially these pathogens that will be a threat for the farmed salmon industry.

3.2 The diseases of concern

Three major diseases, that today needs to be reported when an incident occur, shows tendency to keep on being a treat for the farmed salmon industry in the future.

Infectious salmon anemia is showing tendency to thrive when the temperature is highest at site. Studies has shown that it occurs mostly in spring to fall when temperature is between 10 to 15 °C (Vike et al., 2014). The disease is also thought to emerge in incidence as the pathogen is shown to reappear in the environment (Pettersen et al., 2015). Vaccines against

ISA has not yet been used much, so the vaccine can be of possible help to control the disease if their potentially should be an increase of incidents (Jansen et al., 2021). The second disease is pancreas disease, a disease that is stated as an endemic disease in western norway, but emerging in the middle part and to north (Pettersen et al., 2015; Sindre et al., 2021). A study has shown the optimal temperature for the virus to be at 6-10 °C (Stene et al., 2014). The favorable temperatures may be related to the occurrence of the disease at colder temperatures farther north. There have also been reported more incidents now compared to years ago, which has most likely resulted in the provision that all salmon from Taksneset (Fræna) in the south and Langøya near Kvaløya (Sømna) in the north should be vaccinated (Nielsen et al., 2021). Furunculosis disease is the last notifiable disease tought to emerge and predicted to be a treat for the following years and the only one caused by bacteria. Studies has shown that growth and metabolic activity increases as temperature increases up to a point, showing that the pathogen has a tendency for thriving in warmer temperature (Grilo et al., 2021). But on the other hand, all salmons are vaccinated again the disease, and the reported incidents has been quite stable over the last years (Nielsen et al., 2021).

Of the non-reportable diseases, the diseases of greatest concern are amoebic gill disease and proliferative kidney disease. From studies, proliferative kidney disease tends to emerge in the north, which is most likely due to temperatures in the north becoming warmer over the years, as the pathogen thrive when temperatures are warmer (Forseth et al., 2017; Gorgoglione et al., 2020). A study with amoebic disease has shown that the disease is more prevalent when temperatures increase (Lillehammer et al., 2019).

Based on the studies that have shown how pathogens respond to climate change, the cases of disease today, and the availability of vaccination against these diseases, reportable diseases do not appear to be a major problem. There are few cases of furunculosis, and vaccination against PD has begun. ISA may be a low threat, but vaccination is available if needed. However, salmon louse is a disease that is now causing a high mortality rate and is expected to be a threat as it increases and moves north.

The non-notifiable diseases, heart and skeletal muscle inflammation and cardiomyopathy syndrome, pose a greater threat as they thrive better with the predicted rising temperatures, plus vaccines are not yet available and the diseases are not being properly monitored. Amoebic gill disease is also a non-notifiable diseases that may become a concern in the coming years. The last disease that is a threat is Proliferative Kidney Disease. This disease is not mentioned in the 2020 report from the Norwegian Veterinary Institute, but studies have shown that the disease tends to spread in northern regions. So we can expect to see cases of Proliferative Kidney Disease.

3.3 Interaction between wild and farmed salmon is a problem

The farmed salmon industry is today mostly constructed with open net hatchery when the salmon grows in the sea. A result of this open net solution is the possibility of interactions between wild and farmed salmon, aswell as farmed salmon escaping (Liu et al., 2011; Tengs & Rimstad, 2017). This has led to problems both for the wild and farmed salmon as pathogens can easily transmit between. Sea lice causes problems for the wild salmon, and a study has shown that it will most likely cause more mortalities for the wild population, aswell as it will become more vulnerable (Thorstad et al., 2021). Many of the diseases in farmed salmon are not found naturally in wild salmon, but their pathogen has been found, making the wild salmon carrier for diseases like ISA, PD and HSMI (Kibenge, 2016). A potential solution that has been suggested and which is tested out is closed hatches. This solution require a lot of space, but can help with interaction problem (Thorstad et al., 2021). The diseases in farmed salmon can potentially be thought to decrease, as the pathogens are not transmitted to farmed salmon through the wild carriers. The problem caused for wild salmon, pathogens and interbreeding, will then also disappear as escapes is not possible.

3.4 More research needed

There are few studies on this topic. Especially, how different pathogens respond to different environmental changes. The basis for this study is based on the few studies that have been done on this topic. In addition, there are also few studies or models on how the climate will change in the coming years. The problem in predicting the climate in Norway is partly due to the different conditions because the coastline is so long, and partly due to the lack of a good, fine-scale model (ClimeFish, 2019b). To make a more accurate prediction, more studies are needed on how abiotic factors affect salmon and pathogens. Also, a good model for fine-scale environmental predictions needs to be developed. This will then provide a better basis for predictions. Once there is a good model and enough studies have been done, the results of the environmental model can be related to the results of the simulation experiments in the research.

Pathogens found in other countries could also become a treat for the Norwegian salmon industry, considering that it is moving toward the poles. Since we see a tendency for pathogens to move north within Norway, this tendency will also apply in general. Therefore, it might be useful to also study the pathogens in the countries south of Norway: Denmark and the Netherlands. There is no large farmed salmon industry in these countries, but the pathogens present in the wild may be of interest. However, since the industry in these countries is not very large, detailed information on the pathogens present is not available. When thinking about the major countries in the farmed salmon industry, the United Kingdom (UK) and Chile would be of interest because they are more southern than Norway. A study looking at emergence tendency of pathogens from the UK and Chile could potentially contribute to this thesis. A risk assessment based on treatments in our country as well as treatments from abroad would possibly give a more complete picture

4. Conclusion

The aim of this work was to predict which emerging diseases in Norway can be expected in the coming years due to climate change. The prediction was based on relevant scientific papers published on the subject. Based on this work, it was determined that climate change could potentially have an impact on salmon farming, both directly (changes in temperature, pH, salinity, and dissolved oxygen) and indirectly (pathogens). Predicted changes in direct, abiotic factors are expected to cause salmon to be more stressed and vulnerable. The more susceptible salmon will then become easier targets for pathogens. Many of the pathogens have shown a tendency to thrive better in the anticipated environmental changes and are expected to occur both in terms of incidence/virulence and geographically. The pathogen is therefore a major concern as it is expected to thrive better in future years and the host is expected to be more susceptible. Vaccines have already been used in Norway for many of the pathogens and have been shown to be effective, particularly against furunculosis. From the papers published today, we can conclude that the most dangerous diseases for Norway in the coming years among notifiable diseases are salmon disease and among non-notifiable diseases it is heart and skeletal muscle inflammation, cardiomyopathy syndrome, amoebic disease and proliferative kidney disease. The notifiable diseases are monitored and vaccinations are also available, so they are not a major problem. The non-notifiable is much more concerning and are expected to have a greater impact on salmon farming in the coming years, as most of them show a tendency to thrive in the changing climate and are also not monitored and not as easily controlled. In addition, there is no vaccination against them. We need more research on how pathogens change in different environments and a model to predict the expected climate in Norway to make a more accurate prediction based on published work. Including emergence tendency of pathogens from the UK and Chile would possibly give a more complete risk assessment.

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