Master's thesis

A First Assessment of Sea Lice Abundance in Arnarfjörður, Iceland

Sentinel Cage Sampling and Assessment of Hydrodynamic Modelling Feasibility

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Declaration

I hereby confirm that I am the sole author of this thesis and it is a product of my own academic research.

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Abstract

Two sea lice species are of significant concern for both aquaculture and wild salmonids in the North Atlantic, *C. elongatus* (von Nordmann 1832) and *L. salmonis* (Krøyer, 1837). Research has typically focused on the impacts from *L. salmonis*, as they are the most threatening for salmonid aquaculture causing epidemics in various countries such as Canada, Scotland and Norway. The focus of research has been to assess the abundance of sea lice to determine the threat of epidemics, need for treatment and management. This study used sentinel cages for sampling the abundance of sea lice in Arnarfjördur, Iceland in June, July and August. Results were used to provide a baseline data set; which is valuable for Iceland providing an idea of the lice abundance, before high levels of aquaculture production has developed. Sampling sea lice abundance and management is increasingly connected to hydrodynamic modelling, predicting the dispersal of sea lice in surface currents. This study also assessed the feasibility of hydrodynamic modelling in Arnarfjördur, in connection to the baseline sentinel cage and gill-netting data. Results from this study suggested two areas with significant lice abundance, representative of the sites closest to the aquaculture farms. This suggested an influence from aquaculture farms, but cannot be confirmed due to conflicting results from other sites. Hydrodynamic modelling feasibility is not restricted by the availability of data but by the cost of accessing it. Feasibility should increase with a increase in the threat of lice epidemics. In the future a comprehensive integrated management approach should be used.

Table of contents

List of figures

List of tables

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1 Introduction

1.1 Aquaculture in the global context

1.1.1 Global economic value of aquaculture

It is important to consider the role fisheries and aquaculture both play in the global food supply. Although the marine fisheries had expanded to a peak of 86.4 million tonnes in 1996, there has been a continual declining trend since then, with only 79.7 million tonnes caught in 2012 (FAO, 2014). The Food and Agriculture Organization of the United Nations states that in 2007 fish accounted for 15.7 percent of the world population intake of animal protein and 6.1 percent of all protein consumed (FAO, 2010). The Food and Agriculture Organization of the United Nations also states that aquaculture accounts for 45.7 percent of the fish food supply for human consumption in 2008. Although aquaculture is young, in terms of the age of an industry, it is a sector which has a high growth rate and is one of the only industries which has a growth rate higher than that of population growth (FAO, 2010).

Aquaculture is of considerable economic importance for the world fisheries, in 2012 production of aquaculture was valued at $144.4 billion US dollars (FAO, 2014). In regards to sea based aquaculture, FAO (2014) states “Although finfish species grown from mariculture represent only 12.6 percent of the total farmed finfish production by volume, their value (US$23.5 billion) represents 26.9 percent of the total value of all farmed finfish species”. Therefore mariculture represents a significant portion of the world's aquaculture economy. The economic value from aquaculture production is one aspect of importance, however another significant aspect of importance is the in-direct economic value from employment in the aquaculture industry. Employment in the aquaculture and capture fisheries industry was estimated to be 58.3 million people with 37 percent of the people in full-time employment (FAO, 2014).

1.1.2 Salmonid aquaculture in the sub-Arctic

Aquaculture is, in some regions of the Arctic, an important economic activity. Particular reference should be given to the production of salmonids in Norway, which accounts for 93 percent of the total value of aquaculture in the Arctic. In Norway in 2010 the value from salmonid aquaculture was roughly 2.5 billion US dollars with approximately 1.7 billion US dollars coming solely from the production of Atlantic salmon (Hermansen & Troell, 2012). Canada is another significant producer of Atlantic salmon, generating 88 percent of the value for the aquaculture industry (Hermansen & Troell, 2012). In Iceland in 2009 the value from salmonid aquaculture was roughly 18.5 million US dollars with approximately 3.5 million US dollars coming solely from the production of Atlantic salmon (Hermansen & Troell, 2012). In Sweden in 2010 the production of salmonid aquaculture was valued at 28 million US dollars, coming solely from the production of rainbow trout (Hermansen & Troell, 2012). In Finland in 2010, similar to Sweden, the production of salmonid aquaculture was solely from rainbow trout and was valued at only 1.3 million US dollars (Hermansen & Troell, 2012). In Russia in 2011 the value from salmonid aquaculture, based on Norwegian salmon prices, solely from salmon production was roughly 14.5 million US dollars (Hermansen & Troell, 2012). The data outlines the variation of salmonid aquaculture in the six main sub-arctic producing regions. In warmer sub-Arctic regions like Norway, Canada and Iceland Atlantic salmon have long been the dominant species or are increasing in production towards this trend. In colder regions like Sweden, Finland and Russia trout have been the dominant species, with a small proportion of Arctic charr also contributing to the salmonid production.

1.2 Aquaculture in Iceland

1.2.1 History

Aquaculture began in Iceland in 1884 by trying to fertilize and hatch salmonid ova, the purpose of which was to stock the rivers with the salmon fry (Kristinsson, 1992). The first production from a commercial aquaculture site in Iceland was a market rainbow trout fishery, established in 1951. It was at the time when the rearing of salmonids for a consumption market began, that a trigger for continual expansion towards salmonid fish farming was observed. The first open ocean trial aquaculture pen was opened in 1972 in Hvalfjörður located on the western coast of Iceland (Kristinsson, 1992). The first land aquaculture site was opened in 1978 near Grindavík on the south-western coast of Iceland (Kristinsson, 1992; Paisley et al., 2010). The aquaculture industry has maintained gradual expansion since the 1950s and has operated as a small scale industry since the 1980s, especially in the Westfjords region which is highly dependent upon fisheries as a socioeconomic driver. The aquaculture industry has been challenged by the economic crash of 2007/2008, when the production of all species which were used in aquaculture dropped by almost 50% (Rosten et al., 2013). The production of these species has remained relatively constant or showed an increasing trend for the past five to six years. As of the end of 2010, there were over 68 registered aquaculture farms with only 10 sea-cage farms the majority of which were producing cod *Gadus morhua* (Rosten et al., 2013).

1.2.2 Legislation

There have been very substantial increases in regulations and the use of environmental impact assessments following the enactment of the Icelandic Environmental Impact Assessment Act in June of 2000 (Paisley et al., 2010). This act made environmental impact assessments mandatory for any intensive aquaculture operation, defined as any sites which produce 200 or more tons of fish and any sites which produce 20 tons or more and the waste from the site is emptying into freshwater (Paisley et al., 2010). The environmental impact assessment is a comprehensive research and monitoring tool, encompassing pollution, various biological aspects such as infectious disease and genetic mixing. The key importance for the environmental impact assessment is the legality of it in the application process, an aquaculture license will not be issued before an assessment is done and the National Planning Agency responds with their opinions (Paisley et al., 2010).

Aquaculture licenses in Iceland are issued by the Ministry for the Environment and Natural Resources; however, there are also various institutions involved to represent the many stakeholders and their interests (Jonsson, 2000). Approval and licensing of aquaculture in Iceland is a complex system, authorities are divided depending on the size of the farm which is applying for a license and therefore, the various stakeholders must work independently and together to make the process function properly. The regulation of aquaculture in Iceland is covered under the Environmental and Food

Control Act No.7/1998 which outlines the regulatory framework for health, food control, pollution control, environmental monitoring, research and information (Jonsson, 2000). It is the Environmental Agency which acts as the supervising agency of this framework while the Local Health Inspection Authority is the main implementing body. The regulation of aquaculture in Iceland is also covered under the Environmental and Food Control Regulation No.48/1994 on Pollution Control which outlines areas of importance where pollution is not allowed (Jonsson, 2000). It is the Environmental Agency and the local planning authorities which designate these areas of importance and it is the local municipalities which are responsible for the implementation of this regulation. There are specific requirements in Iceland for the application and approval of aquaculture licenses and these can be outlined in three chapters. First, there is a set production volume which is allowed. Second, there is specific discharge and environmental standards which detail the requirements for pollution control and monitoring. Third, there are specific details for monitoring standards and sampling of the aquaculture sites to maintain environmental standards.

When focusing on the salmonid aquaculture industry there are additional requirements to be considered which are more specific towards marine cage farm applications. The farms must have a location outside common marine routes, the cages must be easily observed and marked well, current data and sedimentation data must be collected and analyzed and camera or a means of testing sediment deposition must be available upon a visit from a regulatory authority and finally each site must have a continual monitoring system of cages and sampling for analysis of environmental affects (Jonsson, 2000). Specific regulations are covered under The Salmonid Fisheries Act No. 76/1970, with later amendments primarily No. 63/1994, No. 24/1997 and No. 50/1988 (Jonsson, 2000). The purposes of these specific regulations are to ensure the sustainability of salmonid aquaculture while also protecting local wild populations. The regulations are quite extensive and approval of an application relies on the coordination and cooperation of various governing bodies, as an operating license will only be approved when all terms and conditions are met and the environmental authorities, veterinarian authorities and directorate of freshwater fisheries deem there to be minimal risk to local wild populations. Once this approval has been given then the salmonid farms are exempt from many protection regulations within the Salmonid Fisheries Act which are focused on the interaction with wild stocks (Jonsson, 2000).

1.2.3 Current concerns

Aquaculture of Atlantic salmon dominated until around 2006-2008, when a decrease of salmon production was observed as a result of the closure of two major sea-cage farms. The concerns at the time were foreign exchange, damage of cages from storms and the impact of jellyfish to the sea-cage farms (Paisley et al., 2010). Following the Icelandic economic crash of 2007/08 and the closure of the salmon farms, Arctic char and cod had increasingly become the dominant species (Paisley et al., 2010). One of these species, has now, in the mid 2010’s, reached a stage for which it is largely not economically viable. The farming of cod is associated with high feed costs, a long turn-over time and a return which is not sufficient for the effort and time put in. Therefore, aquaculture is now returning to focus on salmonid production as a more viable industry; with fast turnaround times, for a globally very marketable and high meat return fish. The increased popularity of salmonid aquaculture is now accompanied by new concerns, the main two being the impact to the environment and the exposure of farmed salmonids, especially Atlantic salmon, to sea lice parasites. The first concern, the impact to the environment includes sediment deposition, nutrient load increases and the impact to native salmonid species. The second concern and most paramount, sea lice parasites, includes two species of sea lice, *Caligus elongatus* (von Nordmann 1832) and *Lepeoptheirus salmonis* (Krøyer, 1837). Both sea lice species can cause devastating effects to both the aquaculture populations and the wild populations and have therefore become the most serious concern for both salmonid aquaculture production and the management of wild salmonids.

1.3 Research frame

1.3.1 Objectives

This study has two key objectives.

The first objective is to evaluate the prominence of sea lice in the surface current; as well as assess the life cycle distribution of sea lice in Arnarfjördur, located in the Westfjords of Iceland, **Figure 1.**

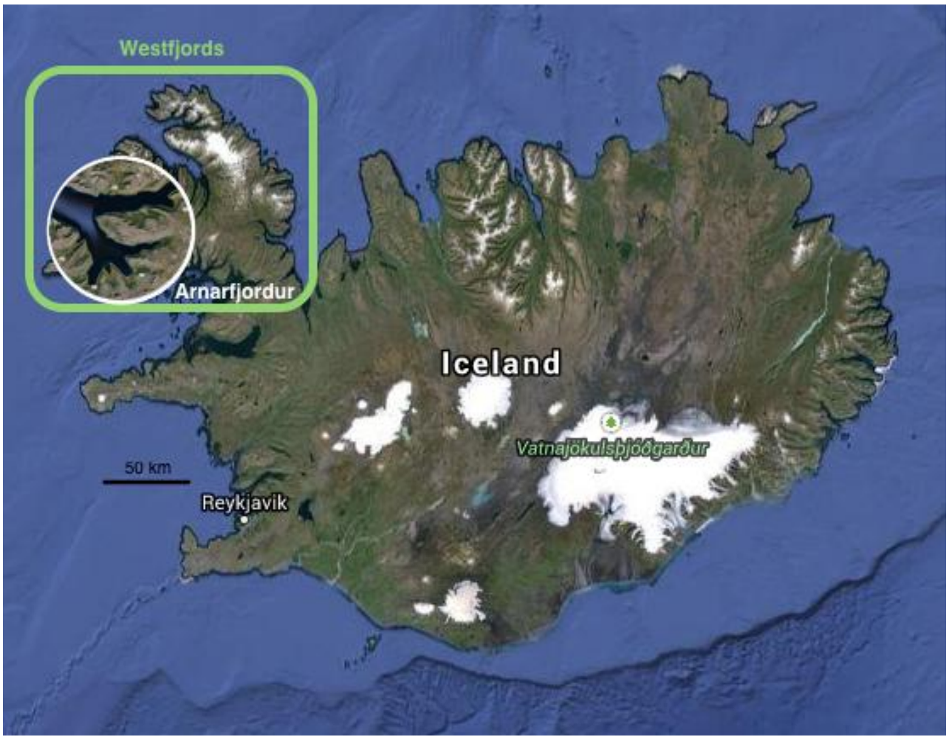

Figure 1: *Map of Iceland, with Westfjords region and Arnarfjörður study area highlighted (Created with Google Maps by Author)*

The second objective is to assess the feasibility of applying a hydrodynamic model to the movement of sea lice in Arnarfjördur, in the Westfjords of Iceland.

This study will contribute to the environmental assessment of salmon aquaculture in the Westfjords of Iceland, by attempting to suggest the potential sites or areas of increased risk. This study is also an important historical marker of the level of sea lice within Arnarfjördur; giving a view of the sea lice presence before salmonid aquaculture develops more significantly in this region.

Results from this study can also be linked to a second study which was conducted during the same time period by Niklas Karbowski. This second study will determine the natural sea lice load on wild salmonid populations in the area. The results from the second study can be combined with the results from this study to achieve an even more specific analysis of Arnarfjörður; regarding natural sea lice loads and high risk locations for new salmonid farms. Both studies will provide historical data on the numbers for sea lice present, before any significant salmonid aquaculture has been development. These numbers can also offer a source of information that can be used in other countries; such as Norway, which only began conducting research once salmonid aquaculture was already highly developed.

1.3.2 Aims

There are four main aims to this study. The first aim is to identify the data necessary for conducting hydrodynamic modelling; and the second aim is to evaluate the potential sources of this data. The third aim is to collect sea lice samples from sentinel caged salmonids for identification. The fourth and final aim, is to determine the species and life cycle stage of the sea lice collected.

1.3.3 Research questions

For the purpose of this study**,** three research questions need to be asked**.** These questions develop the basis for this study and will provide the means necessary to achieve the objectives and aims mentioned above.

1. How prominent are sea lice in the surface current of Arnarfjörður, Iceland?

2. How are life cycle stages of sea lice distributed among the sampling sites in Arnarfjörður, Iceland?

3. How feasible is it to use a hydrodynamic model to assess the movement of sea lice in Arnarfjörður, Iceland?

1.3.4 Data and methods

This study will rely on the sentinel cage data sampling methods conducted in other fjord regions such as Scotland and Norway (Bjørn et al., 2011; Jackson et al., 2012; Pert et al., 2014). This has however, been adjusted to suit Icelandic conditions. Assessing the prominence of sea lice in the surface current of Arnarfjörður, Iceland, will be done using sentinel cage data collection. Data collection will be conducted over three sampling periods. The life cycle stages of sea lice distributed among the sampling sites in Arnarfjörður, Iceland, will be done with the use of analysis of the Atlantic salmon sentinel cage smolts. Analysis will include identification and documentation of sea lice species and life cycle. Statistical analysis will also be done, with the use of statistical programs comparing multiple sites over the three sampling periods. The feasibility of using a hydrodynamic model to assess sea lice movement in Arnarfjörður, Iceland, will be done by assessing the data needed, collecting the data freely available and assessing the benefits of using a model against the potential challenges of accessing the data.

1.3.5 Research limitations

To the best of my knowledge this is the first time any form of sea lice research has been conducted in Iceland. As an initial study, there were several research limitations which presented themselves at various times throughout the study. The most consequential limitation for this study is the strong winds associated with Iceland; and therefore, the rough conditions in which the sentinel cage research had to be conducted. A secondary limitation was access to resources, as the need for certain materials was challenged by the remote nature of the study area; as well as the lack of availability of certain materials. Specific materials which were lacking in availability was access to a properly equipped boat; as well as a device to measure salinity and temperature, which was only received at the last month of the study.

2 Theoretical overview

2.1 Salmonids in Iceland

2.1.1 Introduction to salmonids

In Iceland three native salmonid species can be found, *Salmo salar* commonly referred to as Atlantic salmon, *Salmo trutta* the anadromous form of brown trout commonly referred to as sea trout and *Salvelinus alpinus* commonly referred to as Arctic charr. Throughout the rest of the paper they will be referred to by their common names Atlantic salmon, sea trout and Arctic charr respectively. These three species can be found in various locations throughout Iceland, although the majority of the populations originate from the southern coast near areas such as Thingvallavatn (Klemetsen et al., 2003). Relatively few populations of the three species exist in the Westfjords, the north western region of the country; however, small populations are still observed and are considered of particular importance for this study. Atlantic salmon, sea trout and Arctic charr share the same habitat as well as other important characteristics.

The three salmonid species are anadromous, which means they spend and can alternate part of their life cycle in freshwater and part of their life cycle in salt water (Klemetsen et al., 2003; Wagner, McKinley, Bjørn, & Finstad, 2004). The freshwater portion of the life cycle includes spawning in rivers; while the salt water portion of the life cycle includes migration to sea to feed (Kjartansdóttir, 2008). This characteristic was credited by observation and documentation in the mid-1970s in Newfoundland (Dempson, O'Connell, & Shears, 1996; Erkinaro & Gibson, 1997; O'Connell & Dempson, 1996). The importance and understanding of this received recognition and continued study throughout the world for several decades, in countries such as Iceland (Einarsson, Mills, & Johannsson, 1990), Norway (Halvorsen & Svenning, 2000), Finland (Jørgensen et al., 1999) and Ireland (Matthews, Poole, Dillane, & Whelan, 1997). This migration can occur multiple times throughout the life span of all three species. This aspect of the three salmonid species life cycle is highly important for this study and will be further discussed in a later section. Finally, it is important to note that although the three species of salmonids share a migration area, and make use of both fresh water and salt water habitat; they diverge considerably when timing of migration is considered (Bjørn, Finstad, Kristoffersen, McKinley, & Rikardsen, 2007; Carlsen, Berg, Finstad, & Heggberget, 2004). The life cycle, biology and fisheries of the three salmonid species is presented in further detail below, with particular emphasis and much more in-depth detail given to Atlantic salmon for the purpose of this study.

2.1.2 Atlantic salmon

The Atlantic salmon, *Salmo salar*, life cycle is outlined in **Figure 2.** The female chooses a site for spawning, once the female has made her choice she begins excavating a nest in the gravel substrate of the freshwater river. The female does not deposit all of her eggs in one location but several locations in close proximity to one another, these nests are called a redd (Kjartansdóttir, 2008). The female releases the eggs into the redd which is followed by the release of the male reproductive biological material, which is called milt (Kjartansdóttir, 2008). The female proceeds to cover the redd with gravel from the substrate once fertilization is complete (Jones, 1959). The fertilized eggs take approximately 70-160 days to fully develop; the range is largely attributed to variation in water temperature throughout their vast habitat (Mills, 1989). Once the eggs have hatched they are called alevins, which remain in the redd and carry a yolk sac for feeding (Mills, 1989). The yolk sac will become absorbed, the fish will exit the redd and are able to feed from the nutrients available in the river (Mills, 1989). The fry stage progresses to the parr stage by growing above roughly 7.0 cm; once the fish has developed into the parr stage, it will remain in the river for 2-8 years (Guðbergsson & Antonsson, 1996). The time which the parr stays in the river is highly dependent on the growth rate of the fish, as the next step in the life cycle stage is smoltification and migration to the sea (Guðbergsson & Antonsson, 1996).

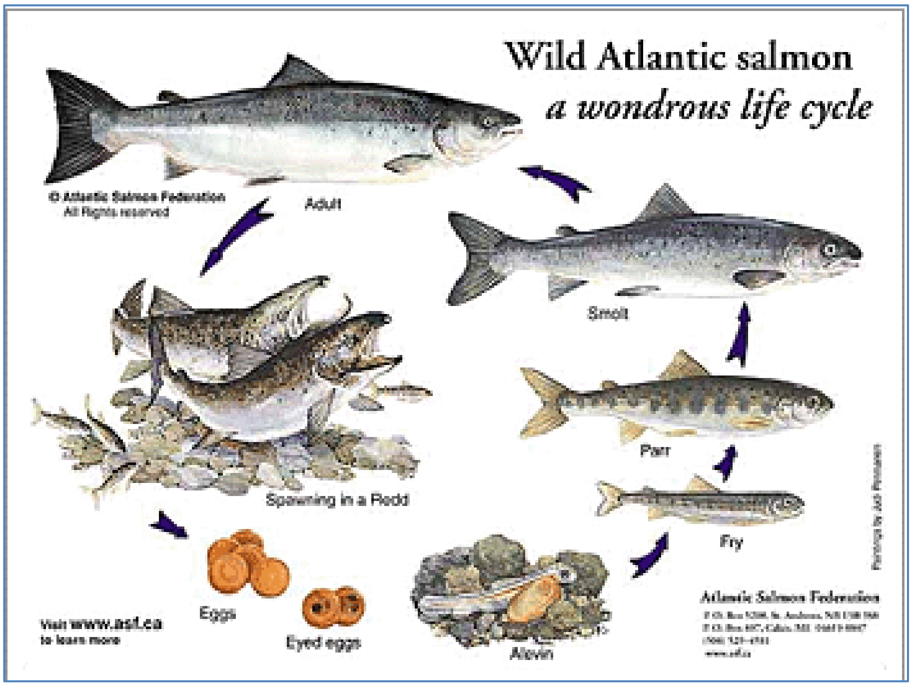

Figure 2: Life cycle of wild Atlantic salmon (Atlantic Salmon Federation, n.d.)

In Iceland, adults who are migrating back to their river of origin to spawn will typically begin the journey up the river anytime from the end of May to September; while July is the peak month for this rapid ascent (Guðjónsson, 1978; Jónsson, 1983). The spawning process takes place typically anytime from September to December (Guðjónsson, 1978) and hatching of the eggs from the redd can take between 6-8 months (Guðbergsson & Antonsson, 1996). Once the alevins have absorbed their yolk sac they will abandon the redd typically occurring in July and August (Jónsson, 1983). Smolts in Iceland typically stay within the river for 2-8 years (Guðbergsson & Antonsson, 1996) and when they have reached a length of around 10-12 cm long (Guðjónsson, 1978; Mills, 1989) they will begin the migration to sea. It is important to note that the development of the fish, and therefore time exhausted for each of the life cycle stage, is highly dependent on the growth rate of the fish. This can be strongly influenced by regional climate, weather and local geological conditions (Guðjónsson, 1978 & 1990).

The juvenile post-smolts, typically migrate from the river to the sea in the spring time around April and May; this aspect is of particular importance as “the timing of the migration has an important role in determining smolt survival in the marine environment“ (Thorstad et al., 2012). It is suggested that smolts have developed an adaptation which relies on the use of environmental cues while in the river; which are connected to opportune conditions at sea allowing them to signal and begin migration to sea (Thorstad et al., 2012). Once Icelandic post-smolts reach the sea it is quite difficult to identify where they go and exactly how they get there. However, tagging studies done in Iceland resulted in marked salmon being found near various rivers in areas of the Faroe Islands, Greenland, Norway and Scotland (Guðbergsson & Antonsson, 1996; Guðjónsson, 1978). It has also been suggested by (Hvidsten, Johnsen, & Levings, 1992 & 1995) through radio tracking, that the post-smolts migration to these areas is through quick movement away from their river and its coastal waters; grouping together following a path close to the surface (Moore, Lacroix, & Sturlaugsson, 2000; Thorstad et al., 2004). Post-smolt Atlantic salmon will stay at sea for typically 1-4 years. However, sea stays for up to 5 years have been observed (Dymond, 1963; Niemelä et al., 2006); this is again, largely dependent on the growth rate of the post-smolts as mentioned above. After staying at sea, the post-smolts will begin migration back to their parent river (Shearer, 1992; Tchernavin, 1939). This signifies the sexual maturation of the fish and ascent for spawning completing the life cycle. An important consideration, is that although salmon are characterized by high mortality following spawning, especially males (Mills, 1989); they are in fact iteroparous, which means that they have the ability to spawn repeatedly and it has been observed occurring up to 5 times (Ducharme, 1969).

Atlantic salmon fishery in Iceland is only allowed in freshwater rivers; fishing of Atlantic salmon at sea has been banned since 1932 (Kjartansdóttir, 2008). Rod and line fishery are the most prominent type of fishing allowed for Atlantic salmon in most Icelandic rivers, but there is also a net fishery in the largest glacial rivers where angling is not feasible due to the rough current and turbid water (Guðbergsson, 2014). The fishing season for Atlantic salmon takes place over a period of 105 days from the 20th of May to the 30th of September; for stocked rivers the period can be extended to 120 days leading into October (Guðbergsson, 2014). There is an exception to the 1932 ban on at sea fishing of Atlantic salmon, and that is that the use of gill-nets set from land for fishing was approved for landowners adjacent to certain rivers. The accessibility and use of these rivers is managed by the landowners who share rights to the same river and is limited to a certain number of fishermen and permits.

In the period of 1974-2013 in all of Iceland an average of 40861 fish were caught by rod every year, 36.689 were landed and 9,272 were caught and released (Guðbergsson, 2014). The catches have increased over the past 5-8 years in all three categories with a total of 68,042 Atlantic salmon caught in 2013, 23,133 of which were released resulting in a net catch of 44,909 Atlantic salmon landed for that year (Guðbergsson, 2014). This is remarkably less in the Westfjords region where 2,335 salmon were caught, 482 released therefore only 1,843 were landed by rod for the year of 2013 and a total of 17 fish were caught by net fishery (Guðbergsson, 2014).

2.1.3 Sea trout

Sea trout, *Salmo trutta* can spawn between five times and up to seven times (Euzenat, Fournel, & Richard, 2000). Ascent timing to their home river is suggested to depend on river size; therefore, it is highly variable between populations (Klemetsen et al., 2003). If spawning is taking place in a large river system, then sea trout may need to begin spawning migration potentially 6 months before spawning takes place (Campbell, 1977). However, if it is a small river or stream then ascent may begin only 1-2 months before spawning (Klemetsen et al., 2003). Therefore, spawning migration can begin anytime between 1-6 months before the typical spawning period of October to December. However, this is also largely dependent on local variations; as it is known that "the spawning period will be earlier the higher the latitude and altitude because of lower water temperature and longer egg incubation period" (Klemetsen et al., 2003). Female sea trout will dig a series of nests, a redd, on the river substrate (Brabrand, Koestler, & Borgstrøm, 2002); depositing her eggs in several batches which are located in close proximity to one another (Klemetsen et al., 2003). Although many males may compete for the ability to fertilize the eggs; it is the largest male which typically fertilizes the majority of the eggs (Largiader, Estoup, Lecerf, Champigneulle, & Guyomard, 2001), with the smaller males having the potential to contribute a small portion of biological material to the nests (Garcia-Vazquez et al., 2001).

The eggs will remain in the substrate typically between 1-8 months before they hatch (Klemetsen et al., 2003). The newly hatched larvae first feed off of a yolk sac reserve before reaching the alevin stage; the period of time over which this will occur depends on the temperature of the river with lower temperatures leading to a longer developmental time (Elliott & Hurley, 1998; Klemetsen et al., 2003). The amount of time spent in the river is typically between 1-8 years (Jonsson & L'Abee-Lund, 1993; L'Abee-Lund et al., 1989). However, this is largely varied between populations and dependent on local climate and geographical influence (Klemetsen et al., 2003). Sea trout migration to sea typically takes place from May to August and also from February to June (Gargan, Poole, & Forde, 2006; Jensen et al., 2012). Juvenile Sea trout will typically remain at sea for 2-3 years before smoltification is achieved (Jonsson & L'Abee-Lund, 1993). Following this maturation stage, sea trout will typically remain at sea for the majority of their life with exceptions occurring for spawning migrations (Järvi et al., 1996). After migration to sea has taken place sea trout prefer shallow coastal waters (Knutsen, Knutsen, Gjosaeter, & Jonsson, 2001). They typically remain in the upper 1-5m of the water column (Gjelland et al., 2014; Sturlaugsson & Johannsson, 1996); and are typically found within a 100 km range extending from the mouth of their home river (Klemetsen et al., 2003).

Catch statistics for Iceland have been monitored beginning in 1946, this information provides catch statistics for sea trout. The data however, combines both stationary and sea-run fish. Sea trout are caught in various rivers throughout the country and are for the majority caught by rod and line fishery; however, in some instances catches are a result of Atlantic salmon by-catch. In 2013, a total of 33.660 Sea trout were caught, 10.706 of which were released resulting in 22.954 fish landed (Guðbergsson, 2014). In the Westfjords region, a total of 34 sea trout were caught by rod and line in 2013 and no record of any net fishery (Guðbergsson, 2014).

2.1.4 Arctic charr

Arctic charr, *Salvelinus alpinus* are exceptionally diverse and complex with extensive variations between populations of the species. The migration is similarly complex with juvenile and adult fish participating in migration on a yearly basis (Klemetsen et al., 2003). Studies in Norway have observed that they begin seaward migration typically between May to the middle of June (Berg & Berg, 1989); with studies in Canada observing migration beginning in June (Johnson, 1989). In both cases the start of seaward migration took place as soon as the river opened, corresponding to the spring-time ice break (Klemetsen et al., 2003); and in both cases the largest fish were observed to migrate first. Studies were also conducted to determine the length of time spent at sea. In Canada, they returned to the river after 35-45 days (Klemetsen et al., 2003). However, they were also found to only return after 52-57 days (Dempson & Kristofferson A. H., 1987). In Svalbard, they returned to the river after 34 days (Gulseth & Nilssen, 2000). In mainland Norway, they returned after 48 days (Berg & Berg, 1989). Research into the spawning of Arctic charr was done in Canada, two studies observed that they will spawn every 2, 3 or even 4 years; however, the average spawning age was 13 years (Johnson, 1989) and spawning was observed to begin in October (Dempson & Green, 1985). They reside in coastal waters close to their home river; and in a study done in Norway, 74% of recaptured charr were located within 25 km. However, they did document one fish having travelled 940 km (Jensen & Berg, 1977).

The same catch statistics data for Iceland can be used for the fishery, it is again important to note that the data combines both stationary and sea-run fish. Similar to sea trout, Arctic charr are caught in various rivers throughout Iceland and are mostly caught by rod and line fishery. Arctic charr are also caught as a result of bycatch of Atlantic salmon fishing. In 2013, a total of 23.455 Arctic charr were caught, 5.149 of which were released resulting in 18.180 fish landed (Gudbergsson, 2014). In the Westfjords region, a total of 1.024 Arctic charr were caught by rod and line in 2013 and a total of 7 were caught by net fishery (Gudbergsson, 2014).

2.1.5 Summary

There are several similarities and differences between the three salmonid species; with sea trout and Arctic charr being more closely linked than either of them are to Atlantic salmon. The anadromous post-smolts of the three species are able to migrate between sea water and fresh water, having residence periods in both of these habitats (Wagner et al., 2004). This is made possible through several physiological adaptations, visible in all three species; such as secretion of minerals, e.g. sodium and chloride which is used to regulate the osmotic balance of the fishes (Høgåsen, 1998; Wendelaar Bonga, S E, 1997). Differences between species is more visible in the sea residence of the three species; with sea trout and Arctic charr having a similar coastal residence, compared to the extended sea ward migration and distant off-shore residence of Atlantic salmon

(Davidsen et al., 2008; Finstad, Okland, Thorstad, Bjørn, & McKinley, 2005; Thorstad et al., 2004). The difference in sea residence of the three species is especially important for this study; as the movements throughout the coastal waters will directly impact the exposure pressure each species will encounter (Davidsen et al., 2008; Finstad et al., 2005; Thorstad et al., 2004).

2.2 Sea lice in the north Atlantic

2.2.1 Background

Sea lice, is the common name referring to a large number of marine ectoparasitic copepod crustaceans from the family Caligidae; which are commonly found on salmonid species in the marine environment (Wagner, Fast, & Johnson, 2008). Sea lice are naturally occurring in the marine environment and are commonly found on wild salmonids; however, in relatively low numbers (Krkošek, Morton, Volpe, & Lewis, 2009; Tingley, 1997; Urquhart, Pert, Kilburn, Fryer, & Bricknell, 2008). Berland and Margolis (1983) found references to sea lice which date back to 1600 AD when the Danish-Norwegian bishop, Erik L. Pontoppidan (1698–1764), described

> "great schools of salmon moving from the sea into fresh water, partly to refresh themselves, and partly to rid themselves by rubbing and washing in the swift currents and waterfalls, of a kind of greenish vermin called 'Laxe-Luus,' attached between the fins, plaguing it in the heat of spring"

This suggests that historically, sea lice have been observed in the marine environment in considerable numbers; which was also observed by White (1940) when he described "fish…carried hundreds of lice … some of the grilse had an almost complete layer of lice extending from the posterior edge of the eyes to the caudal peduncle on the dorsal part of the body…". Both of these historical observations of sea lice are important, as they show the occurrence of sea lice over multiple centuries. They are also of considerable importance as today, sea lice are the most commonly found serious pathogens and most damaging parasites to wild salmonids and salmonid farming in the northern hemisphere (Costello, 2006; Costello, 1993; Pike & Wadsworth, 2000). Two species of sea lice have been the focus of research studies over the past few decades, *Lepeophtheirus salmonis* and *Caligus elongatus*. *L. salmonis* is referred to as the salmon louse (Kabata, 1979); as it is rarely found on non-salmonids (Finstad, Bjørn, Grimnes, & Hvidsten, 2000; Krkošek et al., 2013; Penston, Millar, Zuur, & Davies, 2008). *C. elongatus* on the other hand, is a generalist species; well known to be found on more than 80 fish species (Costello, 2009a; Oines, Simonsen, Knutsen, & Heuch, 2006; Penston et al., 2008).

2.2.2 Life cycle

For the two species this paper will focus on, *L. salmonis* and *C. elongatus*, the first part of their life cycle is planktonic and the second part of their life cycle is parasitic. *L. salmonis* has 5 phases to its life cycle; which are distinguishable from each other by a moult, whereby the sea lice will shed its outer cuticle and a new cuticle will become visible (Boxaspen, 2006; Hayward, Andrews, & Nowak, 2011). The first step towards beginning the life cycle is sexual reproduction. Pike & Wadsworth (2000) describe the process of sexual reproduction by which adult male sea lice, which grow at a faster rate and therefore co-occur with pre-adult I females, will mate with a female virgin. However, observation of adult males mating with pre-adult II females, when pre-adult I are unavailable is commonly observed. The mating process has been described "the male clasps the females genital segment and applies two external spermatophores on the females ventral surface" (Pike & Wadsworth, 2000). Following this process, females will produce egg strings which may carry between 100 to 1000 eggs (Costello, 1993). Several research studies have attempted to determine the number of pairs of egg strings a female sea lice may produce over their life span. Heuch, Nordhagen and Schram (2000) stated that results from an experimental study observed a female sea lice living for 191 days and producing up to 11 pairs of egg strings. This was similarly observed by Mustafa, Conboy, Burka, Hendry and McGladdery (2000) when they stated that they observed a female sea lice living for 210 days and producing up to 10 pairs of egg strings. As with all aspects of the sea lice life cycle, sexual reproduction is highly dependent on temperature. Heuch et al. (2000) observed that at a temperature of 7.1 °C females produced longer pairs of egg strings which contained a higher number of eggs which were also more viable, than those observed at a higher temperature of 12.2 °C.

Until recently it was thought that *L. salmonis* life cycle had ten stages of development; however, research by Hamre et al. (2013) has validated that only eight stages are observed as independent, **Figure 3.**

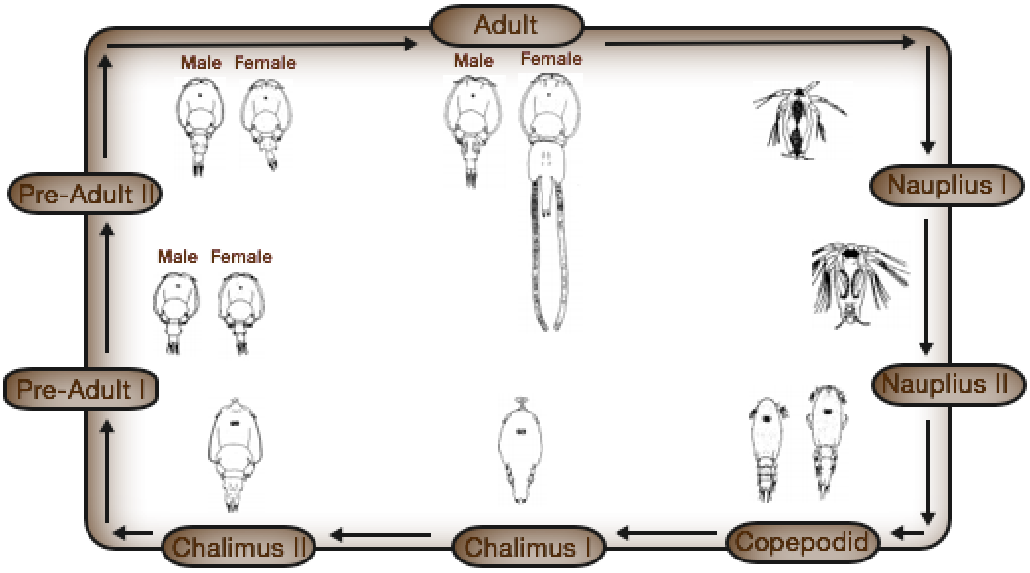

Figure 3*: Life cycle of Lepeophtheirus salmonis species of sea lice. All 5 phases and eight stages identified, with both male and female sexes presented, images not to scale (Source: Author; based on Revie, Dill, Finstad, & Todd, 2009)*

The first phase of the *L. salmonis* life cycle is nauplius, this phase has two stages nauplius I and nauplius II (Johnson & Albright, 1991b). These stages are planktonic larvae which rely on yolk reserves for survival (Gillibrand & Willis, 2007). Studies done by Johnson & Albright (1991a & 1991b) determined that in order to complete the development to the next phase, the nauplius I stage will take 52.0 hours at 5 °C, 30.5 hours at 10 °C and 9.2 hours at 15 °C and the nauplius II stage will take 170.3 hours at 5 °C, 56.9 hours at 10 °C and 36.6 hours at 15 °C. The nauplius will undergo the moltification process which signals the beginning of the second life cycle phase for the sea lice as a copepodid. The copepodid phase of the life cycle is only observed to have one stage (Costello, 2006). Following the moltification from nauplius the copepodid is still a non-feeding larvae which drifts throughout the current system, the larvae may drift until it finds a host or based on research studies done by Johnson & Albright (1991a) between 7 to 10 days at 10 °C before it will die from a lack of food (Penston et al., 2008). Following attachment the sea lice enters the second part of its life cycle and develops into a parasitic copepod. Once the copepodid has attached to the host it will feed off it for a period between 3-4 days at 10 °C (Wagner et al., 2008) before the moltification process will begin, signaling the third life cycle phase for the sea lice as a chalimus. The chalimus phase of the life cycle has previously been thought to have four stages (Costello, 2006; Finstad et al., 2011). However, research by Hamre et al., (2013) specifically examined the chalimus phase of the life cycle, and determined that there were no molts observed between chalimus I/II and chalimus III/ VI. The lack of observation of a molt determined that *L. salmonis* in fact only has 2 stages to its chalimus phase (Hamre et al., 2013). This is of high importance as research done prior to the Hamre et al. (2013) study was based on 4 stage assumptions, while research post Hamre et al. (2013) is based on the now accepted determination of 2 stages. Therefore, this must be considered when discussing data from both pre- and post- Hamre et al. (2013); however, for this research the updated 2 stage determination will be used. The moltification of the second chalimus stage signals the beginning of the fourth life cycle phase as pre-adult. The pre-adult phase of the life cycle has 2 stages, pre-adult I and pre-adult II (Pike & Wadsworth, 2000). These two stages are mobile and the sea lice are able to move around the surface of the host feeding off of its blood and tissue; the time of this phase is largely determined by sexual reproduction, once a mate is found the sea lice will moult signaling the beginning of the fifth and final phase, the adult (Johnson & Albright, 1991a, Pike &Wadsworth, 2000). The final phase of the life cycle is adult; only having one stage, the sea lice has reached sexual maturation. At this final stage, the males will begin sexual reproduction with the females; whereby, the females will continue to produce egg strings, while the males may reproduce with multiple females (Frazer, 2009; Heuch et al., 2000).

C. elongatus has four phases to its life cycle. These phases act in the same manner as those discussed above for *L. salmonis*; therefore, they will not be repeated here, only the differences and similarities in stages of each life cycle phase will be discussed. For the species *C. elongates* the four life cycle phases consist of nauplius, copepodid, chalimus and adult, differing from *L. salmonis*, as no pre-adult phase is observed **(Figure 4)**. The first phase, nauplius, is only observed to have one stage; differing from *L. salmonis*, which has two. The second phase, copepodid, is observed to have one stage; as also observed for *L. salmonis*. The third phase, chalimus, is observed to have four stages separated by moltification; this differs from the now accepted two stage *L. salmonis*. The fourth phase and final phase in the *C. elongatus* life cycle is adult; upon reaching sexual maturation, as similarly observed in *L. salmonis* (Costello, 2006; Johnson & Albright, 1991a).

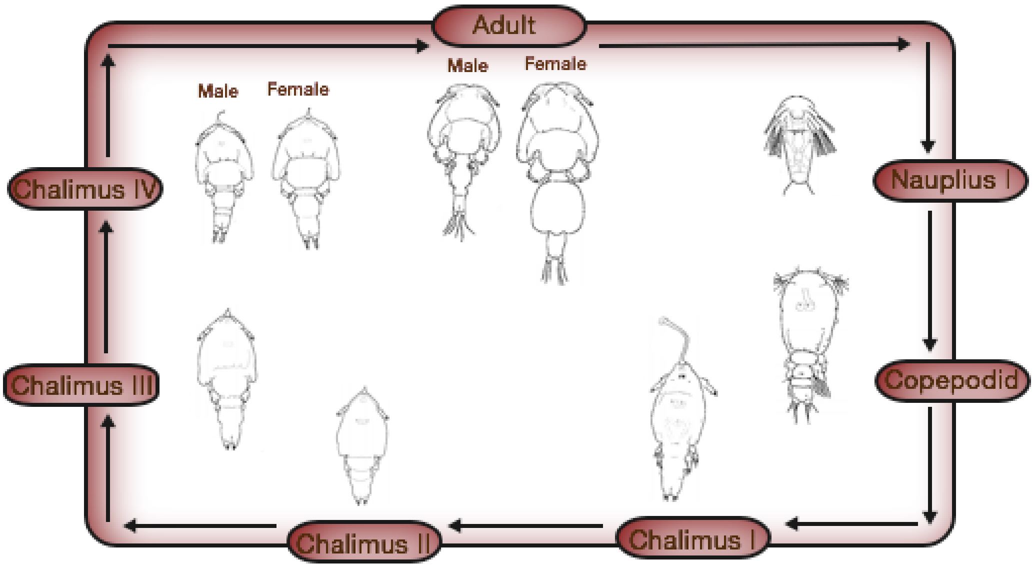

Figure 4*: Life cycle of Caligus elongatus species of sea lice. All four phases and seven stages with both male and female sexes presented, images not to scale (Source: Author; based on Piasecki, 1996)*

Sea lice growth is highly dependent on temperature and salinity (Costello, 2006). Johnson and Albright (1991a) determined that at a temperature of 10 °C the life cycle completion will take roughly 40 days for males and 52 days for females. Research studies have been conducted by laboratory experiments to determine the limits of salinity and temperature on sea lice development. These studies have shown that egg development cannot occur at a temperature below 12°C and a salinity of 10 practical salinity units (psu) or lower (Johnson & Albright, 1991a; Wootten, Smith, & Needham, 1982). Even though sea lice eggs are able to develop in water with a salinity below 15 psu, the eggs are unable to further develop into active nauplius. When exposed to salinity lower than 25 psu, sea lice larvae are unable to complete the moult from the nauplius stage to the copepodid stage (Johnson & Albright, 1991a). Successful life cycle development was only observed at salinity of 30 psu (Johnson & Albright, 1991a).

2.2.3 Movement and dispersal

It has been thought that sea lice acted as passive particles; their dispersal throughout the water to be driven by the circulation of surface currents and wind forcing. It is now understood that sea lice are able to move horizontally and actively move vertically, made possible through a swimming mechanism adapted to environmental cues

(Bricknell, Dalesman, O Shea, Pert, & Mordue Luntz, 2006; Costello, 2006). It is suggested that mechanisms for movement are adapted to tidal rhythms, sunlight, moonlight, salinity, water pressure and turbulence (Bricknell et al., 2006; Tully & Nolan, 2002). Sea lice have adapted to 'reverse' diurnal migrations, in which they swim upwards and concentrate in surface waters during the day and sink back down through the water column at night (Costello, 2006). This movement is important as it allows sea lice to concentrate in surface waters, which helps them to disperse greater distances due to typically strong surface-water currents (Penston et al., 2008). Sea lice have also been observed to express vertical migration, adapted to orient towards waters with the highest salinity and actively avoid salinities below 27 psu (Bricknell et al., 2006); typically being found in pycnoclines with salinities above 20 psu (Heuch, 1995). Sea lice have also been observed to express vertical migration in response to turbulent water, this is an attempt to locate themselves in turbulent areas typically associated with migration and feeding habitat for wild salmonids (Heuch, 1995; Heuch, Parsons, & Boxaspen, 1995). This has also been observed in several studies which have suggested that various environmental cues are an adaptation from sea lice to position themselves into areas of the water column which are most frequently used by wild salmonids (Costello, 1993 & 2006). Thorstad et al. (2007), Davidsen et al. (2008) and Hevrøy, Boxaspen, Oppedal, Taranger and Holm (2003) suggest that sea lice are positioning themselves in the surface water column, as it is the area most used by wild salmonids.

The horizontal and vertical movement of sea lice and the environmental cues which trigger them, is also an adaptation; increasing their chance of dispersion and ability to cover more distance and increasing the possibility of host encounter (Birkett, 2009; Johnsen, Fiksen, Sandvik, & Asplin, 2014). The dispersal of sea lice demonstrates large variation, depending on local factors; such as wind, weather, landscape and current speed (Amundrud & Murray, 2009). However, various research studies have observed that sea lice may disperse, on average, 30 km over 5-15 days (Costello, 2006; Siegel, Kinlan, Gaylord, & Gaines, 2003). This dispersal average is based on observations of sea lice dispersal reaching 12 km in low currents of 5 cm per second, and reaching 47 km in higher currents of 20 cm per second (Costello, 2006). These observations have been continually validated, with many research studies stating that most sea lice will concentrate within 30 km from their source; with a very small portion observed to disperse longer distance (e.g. Asplin, Boxaspen, & Sandvik, 2011; Middlemas, Fryer, Tulett, & Armstrong, 2013; Salama et al., 2013).

Dispersal of sea lice will typically lead to concentrations within certain areas; however, this is again highly dependent on local conditions. Several studies have suggested that sea lice dispersal will lead to a concentration of sea lice within shallow coastal waters near the mouth of an estuary (Costelloe, Costelloe, & Roche, 1995; McKibben & Hay, 2004; Penston, McKibben, Hay, & Gillibrand, 2004). Bjørn et al. (2007) state that the concentration of sea lice within shallow coastal waters is exacerbated, depending on locality; by the "turbulent current pattern and often distinct thermoclines and haloclines", which seem to be preferred by sea lice (Finstad et al., 2011; Heuch et al., 1995; McKibben & Hay, 2004). Sea lice rely on circulation systems, such as current, wind and tidal, to increase their ability to concentrate in favorable areas; and to avoid dispersal into unfavorable areas, with low survival potential (Miller & Morgan, 2013; Tapia & Pineda, 2007). Fiksen, Jørgensen, Kristiansen, Vikebø and Huse (2007) suggest that the most important mechanism sea lice use to secure this, is vertical movement and migration.

2.2.4 Attachment

Research done by Johnson & Albright (1991a) determined that sea lice attachment must occur between 7 to 10 days at 10 °C; otherwise it will die from a lack of food (Penston et al., 2008). The first aspect of sea lice attachment which needs to be addressed is the mechanism allowing them to find a host. Sea lice have multiple behavioral traits and modified senses which aid in their search to find a host in such vast environment; where, depending on the location, hosts may be sparsely available (Bailey et al., 2006; Mordue & Birkett, 2009; Torrissen et al., 2013). The first behavioral trait, is that sea lice can recognize light levels. Mordue and Birkett (2009) state that sea lice have "Perception of overall light levels and light related to the reflectance patterns of host fish". The second trait, is that sea lice are able to recognize the movement of a host via mechanosensors; which Heuch, Doall and Yen (2006) determined was possible from approximately 26 mm distance. This ability to sense a hosts movement has been suggested to be correlated to the current stream which is produced by a swimming fish (Mordue & Birkett, 2009). This has also been observed by Anderson, McGillis and Grosenbaugh (2001) who related the movement of a fish, and subsequent current to the creation of a boundary layer in close proximity to the surface of the host. Also observed by Genna, Mordue, Pike and Mordue (2005) who suggests the potential of low-frequency pressure waves to be created by the swimming of the host. The third trait, is the ability for sea lice to detect the host through olfactory cues; such as a hosts odour or chemicals (Bailey et al., 2006; Mordue & Birkett, 2009). The behavioral traits and modified senses discussed are aided by the general search strategy of a sea lice (Genna, 2002). Genna (2002) states that sea lice are able to move vertically throughout the water column; i.e exhibiting positive phototaxis, positive semiotaxis and positive rheotaxis, as well as chemotaxis within close proximity to a host (Bailey et al., 2006; Heuch, et al., 1995).

The next aspect of sea lice attachment which needs to be addressed is the attachment mechanisms used by the sea lice. Once in close proximity to a host, the sea lice as mentioned above, will increase their swimming speed propelling themselves towards the host (Costello, 2006; Genna et al., 2005; Mordue & Birkett, 2009). This propulsion is aided by the surface current generated by the hosts swimming (Costello, 2006). Once the sea lice reaches the surface of the host it will attach via its second pair of antennae and maxillipeds (Costello, 2006). The final mechanism used by sea lice for attachment occurs after the sea lice has landed on the host, when over a course of several hours the sea lice will taste the surface of the fish to determine if it is a suitable host (Costello, 2006). If the lice determines the host is unsuitable they will detach from the host in search of one which is more suitable; however, if they determine the host as suitable they will extrude their frontal filament and attachment will be complete (Costello, 2006; O'Shea, 2005).

The final aspect of sea lice attachment which needs to be addressed is the location of sea lice on the host following attachment and moltification into pre-adult. Movement of sea lice over the surface of the host is suggested by Connors, Krkošek and Dill (2008) to be in search of a mate, escape from predation and feeding. Todd et al. (2000) observed that adult male sea lice were typically located around the anterior dorsal region of the host, whereas females were typically located around the post-anal region. Costello (2006) on the other hand states that once sea lice are able to move along the surface of the host they tend to group around the head of the fish. Both of which are in contrast to Grimnes and Jakobsen (1996) and Bjørn and Finstad (1998) which observed sea lice preference for the fins of the host. These differing observation may be attributed to various factors; such as competition amongst individuals, the size of the host and the stage of development being observed (Jaworski & Holm, 1992; Pike & Wadsworth, 2000). Movement of sea lice on a hosts surface is also accompanied by the ability for pre-adult and adult sea lice to freely move between hosts (Costello, 2006); restricted solely by the availability of hosts.

2.2.5 Infection

Sea lice are considered to be parasitic for salmonids; this can be defined as placing constraints on the salmonids by using the fish as a host for nutrient access, i.e feeding and survival (Price, 1980). The two species of sea lice, *L. salmonis* and *C. elongates*, have been found to be pathogenic to salmonid species (Costello, 2009a). This has largely been linked to the development of sea-cage aquaculture, and the accompanying infection which has occurred on both farmed and wild salmonid populations (Costello, 2009a). In the Atlantic, the susceptibility of salmonids to infestation and infection by sea lice has been observed to vary between the three species (Bjørn & Finstad, 2002; Bjørn et al., 2007). Studies suggest that sea trout in the wild, are typically host to more sea lice than Atlantic salmon (Dawson, Pike, Houlihan, & McVicar, 1997). This increased occurrence of sea lice on wild sea trout is suggested to be due to a special immune response which Atlantic salmon possess. Sea trout are also exposed to more ideal sea lice habitat, in coastal waters where they reside throughout the majority of their time at sea; which is habitat that Atlantic salmon only use for quick transit to the open ocean (Bjørn et al., 2007; Costello, 2009a; MacKinnon, 1998). Although sea lice are naturally occurring they have not been regarded as a serious issue until the development and expansion of aquaculture. Research today has focused on the infestation of sea lice on salmonid farms and the interaction of sea lice between wild salmonids and farmed salmonids. The importance of this research is based on the complex interactions and transmission relationship occurring between farmed and wild salmonid populations. Today, the largest source of sea lice in the coastal ocean can be traced to areas with sea-cage aquaculture farms (Butler, Watt, & Mills, 2003); this is due to the continuous supply of hosts sustaining the sea lice population year round (Johnsen et al., 2014). It is however, important to note that it is typically the initial interaction with infected wild salmonids which will lead to the introduction of sea lice to the farmed populations (Bron, Sommerville, Wootten, & Rae, 1993). Once they have been introduced they will reproduce leading to continual re-infection unless intervention occurs (Jackson, Deady, Leahy, & Hassett, 1997; Tully, 1989).

For decades, research has been evaluating the effects of sea lice infection on salmonids, both wild and farmed. It is now well known that sea lice infections and associated attachment and feeding on the host can affect its growth, fecundity and survival (Boxaspen, 2006; Costello, 2006; Krkošek et al., 2013; Pike & Wadsworth, 2000; Skilbrei et al., 2013). Thorstad et al. (2014) placed the physiological responses to sea lice infection into three groups: primary, secondary and tertiary responses. The primary responses are characterized by changes to the hosts endocrine system, the secondary responses are characterized by changes in hydromineral balance, respiratory and immune functions and the tertiary responses are characterized by changes in growth, ability to resist disease, behaviour etc, (Bjørn & Finstad, 1998; Torrissen et al., 2013; Wells et al., 2007). These three groups are researched to great detail, however focus here will be on a few key impacts from sea lice infection.

The first impact, and one of the most observable effects of sea lice infection; is the damage to the hosts skin, causing severe erosion (Bjørn & Finstad, 1998; Jones, Sommerville, & Bron, 1990). This damage is largely linked to attachment and feeding and has been suggested to increase related to later life cycle stages of the sea lice (Bjørn & Finstad, 1998; Pike & Wadsworth, 2000). The potential severity of this is well described by Torrissen et al. (2013) stating “heavy infections lead to erosion of the epidermis with exposure of the dermis and, in severe cases, skeletal muscle”. The second impact, is the potentially severe increase in osmoregulatory stress. Boxaspen (2006) and Costello (2006) suggest that this increase will result in “changed levels of haematological parameters, reduced appetite, growth and food conversion efficiency” (Boxaspen, 2006). The third impact, which is exacerbated by the first and second, is that with prolonged sea lice infection the host will be forced into a state of morbidity, or disease; and this will likely be accompanied by death unless some manner of intervention occurs (Costello, 2006; Johnson, Blaylock, Elphick, & Hyatt, 1996; Wagner et al., 2004). The three impacts listed above are some of the most serious effects from sea life infection; however, it is important to note that there are several other sub-lethal impacts such as susceptibility to secondary infections and reduced swimming speed (Heuch et al., 2005; Wagner, McKinley, Bjørn, & Finstad, 2003).

When considering the above mentioned impacts from sea lice infection, it is important to discuss the studies which have attempted to evaluate the sea lice infection threshold a host can withstand. Various studies produce differing results on the critical level of sea lice infection. Kvenseth (1997) and Rae (1999) suggest that 0.05 to 0.1 mobile lice per gram will signal the need for treatment of smolt farms. This has been followed by Tully and Nolan (2002), as well as Johnson and Fast (2004), who determined that an infection level of less than 0.1 mobile lice per gram can trigger increased physiological response. And more recently, Costello (2006) and Wagner et al. (2007) determined that a lice infestation level greater than 0.5 to 0.75 mobile lice per gram can be pathogenic. An important consideration is that salmonids have a higher threshold for the non-motile chalimus life cycle stage of sea lice. This has been discussed by Bjørn, Finstad and Kristoffersen (2001), Gargan, Tully and Poole (2003) and Heuch et al. (2005) as they suggest that salmonids may withstand infection of chalimus stage sea lice; with observed numbers of up to 60 individuals per fish. They state that although these levels may irritate the host, it will not trigger a serious response; this will however, change quickly once the lice go through moltification, becoming motile and subsequently fatal (Bjørn & Finstad, 1997; Tully & Nolan, 2002).

2.2.6 Control on salmon farms

There are various control measures which can be used to treat the infection of lice on farmed salmonids as well as measures to lessen the spread of farmed sea lice infections to wild populations of salmonids. As suggested by Revie, Gettinby, Treasurer and Wallace (2003) the efforts which are exhausted to deal with the control of sea lice on farmed salmonids will increase, with the increasing abundance and frequency of sea lice on the fish. There are three main sea lice control measures which are typically used by salmonid farms, fallowing, chemical control and cleaner fish.

The first control measure, fallowing, is used as a mechanism to disrupt the life cycle of the sea lice (Costello, 2006). This is done by removing the host from the environment for a period of time, typically 4-6 weeks with 4 weeks being the minimal fallowing period needed to be effective (Costello, 2006; Jackson et al., 1997; Penston et al., 2008).

The second control measure, chemical control, can be applied in various manners and is used as both a mechanism for resistance and as a treatment mechanism (Costello, 2006). Chemical control can be implemented through in-feed parasiticides or an 'in-bath' method in which fish are grouped together, the cage is enclosed with plastic and the fish are coated with a chemical composition to rid the fish of sea lice (Costello, 2006; Grant, 2002; Torrissen et al., 2013). The third control measure, cleaner fish, is used as a continually occurring control once implemented. The cleaner fish are placed in the cages with the farmed fish and should theoretically feed on the sea lice (Costello, 2006; Treasurer, 2002). The cleaner fish control measure is the most recently researched method of sea lice control, and much is still to be tested as to the validity of using this practice in aquaculture cages in North America; as most species of cleaner fish are typically found in tropic climates. However, cleaner fish are the only real biological control available at this time; therefore, its use is highly suggested for continued research (Costello, 1993; Tucker, Sommerville, & Wootten, 2002). The implementation of these control measures has been an evolutionary process. In recent years, the coordination of control measures towards a more integrated management approach has become increasingly popular and has led to a more effective use and successful application of these measures (Salama et al., 2013; Torrissen et al., 2013).

In Iceland, sea-cage aquaculture farms have been under a national health control programme since 1985 and in 1993, Iceland began following the European Union (EU) disease control directives (MAST, 2013). Under the Disease control directives (MAST, 2013) diseases are organized into three main groups, divided by importance, A, B and C. Group A, is the most important, comprising transmissible diseases which have the ability for significant and rapid dispersal and are considered of high socio-economic importance. In the case of Group A, disease identification, "stamping out" management measures are taken immediately and reported to the EU. Stamping out measures are considered to be strict management controls such as cleaning, disinfection and fallowing of sea farms. Group B, is the second most important, comprising transmissible diseases which are considered of socio-economic and international trade importance. In the case of Group B, disease identification, management measures vary from "stamping out" to general vaccination. Group C, is the least important, comprising diseases identified once annually, no significant management measures are applied (MAST, 2013).

Sea lice infection falls within the second most important Group B of the disease organization, considered particularly important for its ability to spread and international trade importance. In general, Icelandic sea lice management is under various sea-cage aquaculture regulations such as *Regulation number 597/1989 on Disease Prevention and Health Inspection of Aquaculture Facilities* (Ísaksson, 2001). Sea lice management is also monitored and regulated by various governing bodies. The Veterinary Officer for Fish Diseases is responsible for the control of disease and medicine. The Veterinary Officer in cooperation with local veterinarians approve the use of medication. They also monitor the levels of medicine used and grant approval for when fish can be sold for consumption (Ísaksson, 2001). The Environmental and Food Agency of Iceland monitors and controls the approval and use of disinfectants. The Environmental Agency and communal Health inspection Authorities monitor and inspect the sea-cage aquaculture, with inspection occurring a minimum of two times a year (Ísaksson, 2001).

An operating license is granted by the Directorate of Freshwater Fisheries and regulates ecological, parasitological, disease and genetic interactions (Ísaksson, 2001). The operating license is only granted once consultation has taken place between the Fish Disease Committee, Freshwater Disease Veterinarian, Freshwater Fisheries Committee and the Institute of Freshwater Fisheries and an Environmental Impact Assessment is produced. Sea cage aquaculture farms are also required to keep records of all farm activity, such as health of fish, feeding, transfers, etc. These monitoring regimes are of particular importance for sea lice, as the sea cage aquaculture farms are required to monitor lice numbers, this is typically done once a month and is reported to the various regulating bodies. Up to this point, sea lice have not reached a level for which treatment has become a necessary management measure. Although it is important to note, that research is being done in Iceland into the use of Lump sucker fish as a cleaner fish for sea-cage aquaculture farms.

2.2.7 Consequences for wild salmonids

The sea lice species *L. salmonis* and *C. elongatus* are both threats to wild salmonids, this threat has historically been minimal with relatively little consequences for wild salmonids. However, the threat from sea lice to wild salmonids has increased with the increasing development of sea-cage aquaculture. Multiple research studies have determined that salmon lice has increased due to sea-cage aquaculture activity, evident in areas such as Norway, Scotland and Canada (Bjørn, Finstad, & Kristoffersen, 2001; Finstad et al., 2000; Heuch, Bjørn, Finstad, Asplin, & Holst, 2009). In some areas, research has observed that the sea-cage aquaculture source of sea lice can account for 95% of the sea lice present in the coastal waters (Butler, 2002; Tully & Whelan, 1993). An article by Serra-Llinares et al. (2014) outlines the role sea-cage aquaculture farms play in magnifying sea lice production; as sea-cage aquaculture provides an inordinately large amount of hosts for sea lice to infest and parasitize, and these hosts are to a certain extent non-depleting. Therefore, within areas which have intensive sea-cage aquaculture farming the result may be that sea lice larvae are produced at a rate several times higher than that which is observed in areas without sea-cage aquaculture farming (Jansen et al., 2012; Krkošek, Lewis, & Volpe, 2005). This information links the occurrence of sea-cage aquaculture farms with the increased abundance of sea lice in coastal systems; increasing the potential risk of infection and subsequent impacts to wild salmonid populations which occur within their vicinity, and rely on the same coastal areas as critical habitats.

When considering that sea lice today, are occurring in much higher densities in coastal systems which are extensively used by wild salmonids than pre- sea-cage aquaculture times; it is easier to understand the consequences sea lice have on wild salmonids. The most important consequence being the decline in wild salmonid populations over various regions of the north Atlantic (NASCO, 2011); and the associated changes and adaptations to these species. Both Krkošek et al. (2007) and Ford and Myers (2008) state that data is now able to suggest that wild populations may decline nearing extinction, directly related to sea lice infestations. Research done by Krkošek et al. (2013) also states that mortality of salmonids due to sea lice infestation may in the future be a significant factor; resulting in the closure of some fisheries. Frazer (2009) also states a similar view, that the fact that wild fish populations are declining in areas near sea-cage aquaculture farming are “unsurprising” and that local extinction is a significant possibility.

There are two significant behavioral alterations which can be considered important consequences to wild salmonids. First, the ‘premature return’ of wild salmonids (sea trout and Arctic charr) to the river to rid themselves of sea lice; and second, the ‘jumping’ of salmonids to rid themselves of sea lice and increased presence near the surface to avoid sea lice (Gjelland et al., 2014; Grimnes & Jakobsen, 1996). The first behavioural alteration, premature return, is done by salmonids as an attempt to rid themselves of sea lice; once sea lice are exposed to fresh water, the majority of them will fall off within 48 hours with a small number lasting up to 6 days (McLean, Smith, & Wilson, 1990). This behavioral alteration has been suggested to have both positive and negative consequences associated with it. The negative consequences of the alteration, is that premature return to the river will result in the reduced growth as well as reduced reproductive potential of the salmonid (Fjørtoft, Borgstrøm, & Skaala, 2013; Wells et al., 2007). Reduced growth is then linked to increased predation and reduced survival in the marine environment (Jonsson & Jonsson, 2009; Werner & Gilliam, 1984). However, the premature adaptation also has positive consequences, as it is effective in ridding the salmonid of sea lice; restoring osmotic and ionic balance and swimming speed (Bjørn et al., 2001; Wagner et al., 2004). The second behavioral alteration, jumping and positioning near-surface, is done by salmonids as an attempt to dislodge sea lice which have attached or to avoid or lessen the possibility of sea lice encounter. This behavioral alteration has both positive and negative consequences associated with it. The negative consequence is that salmonids are more easily visible to predators and the jumping motion may increase the likelihood of predation from numerous bird species (Ward & Hvidsten, 2010). The negative consequences of this alteration, are also presented in a study conducted by Gjelland et al. (2014) in which they determined that salmonids preferred less saline marine environments when sea lice infestation pressure was high; this however, in some cases resulted in salmonids remaining close to the river expending less energy on foraging and indirectly reducing their growth. This behavioral alteration of jumping and surface preference does however, have a positive consequences; as it in some cases allows for salmonids to remain foraging in coastal waters without need to return to the river directly and therefore, growth is maintained. It is only when the burden of lice infestation becomes too high that the first behavioral alteration will likely outweigh the second.

2.3 Collection of free-living planktonic sea lice larvae

2.3.1 Plankton tows

Plankton tows or plankton surveys are used as a method for collecting free-living planktonic sea lice larvae. This method of data collection is commonly used to assess the presence and abundance of sea lice in the water column. Plankton surveys are typically conducted in a similar manner; with differences observed in the frequency and amount of sites being surveyed, Penston et al. (2008) and Penston and Davies (2009). Surveys are typically conducted within the surface water column between 0 and 5m depth, surveys can be conducted at single or multiple locations depending on the need for the study (Penston et al., 2008). Typically, a conical net is used; it has a 0.5m mouth and typically is 1.5m long and has a 200 µ mesh size (Penston et al., 2008). The net is towed, at low speeds of approximately 0.5 m per second (Galbraith, 2005). Plankton tow duration varies dependent on desired distance to be covered; however, based on Penston et al. (2008) it will typically last 4 to 5 minutes with an average sample volume of 16 m^3. Following completion of towing, the plankton net is washed and sea water is filtered out; the plankton is then stored into a bottle or container with a roughly 4 percent formaldehyde solution (Penston et al., 2008). The plankton samples collected are then prepared for analysis, this involves washing the samples over a series of stacked sieves with the mesh size decreasing the lower in the stack; this allows for removal of larger material and reducing the size of the organisms in the sample to focus on sea lice plankton (Penston et al., 2008). The sample is then at a more manageable size for sorting and analysis to be done under a microscope (Galbraith, 2005; Penston et al., 2008). Another method for sample analysis, which can be used individually or to support microscopic analysis, has more recently been developed. A PCR Taqman®-MGB probe-based assay targeting the mitochondrial cytochrome oxidase I (mtCOI) gene, which allows for the identification of *L. salmonis* and *C. elongatus* from plankton tow samples (McBeath et al., 2006). This method has been proven successful in a study by McBeath et al. (2006), suggesting a new and more efficient method such as this can be applied to plankton tow samples. Although plankton sampling may vary in certain aspects, as mentioned above, the main purpose of this sampling method is to collect free-living planktonic sea lice larvae. Plankton surveys are one of the only direct observation methods used for this purpose, and have been successful in several countries such as Scotland and Norway (Penston et al., 2004). Plankton surveys have also been successfully used as validation for other sea lice collection methods such as sentinel cages.

2.3.2 Sentinel cages

Sentinel cages are used as a method for collecting free-living planktonic sea lice larvae. This method of data collection is most commonly used to assess the presence and abundance of sea lice larvae within the water column. The process involved in sentinel cage data collection is typically quite similar; however, cage structure, duration of exposure and amount of fish in the cages does vary between countries and also between studies. Jackson et al. (2012) discuss the three different cage designs which are used in Norway, Scotland and Ireland **(Figure 5).**

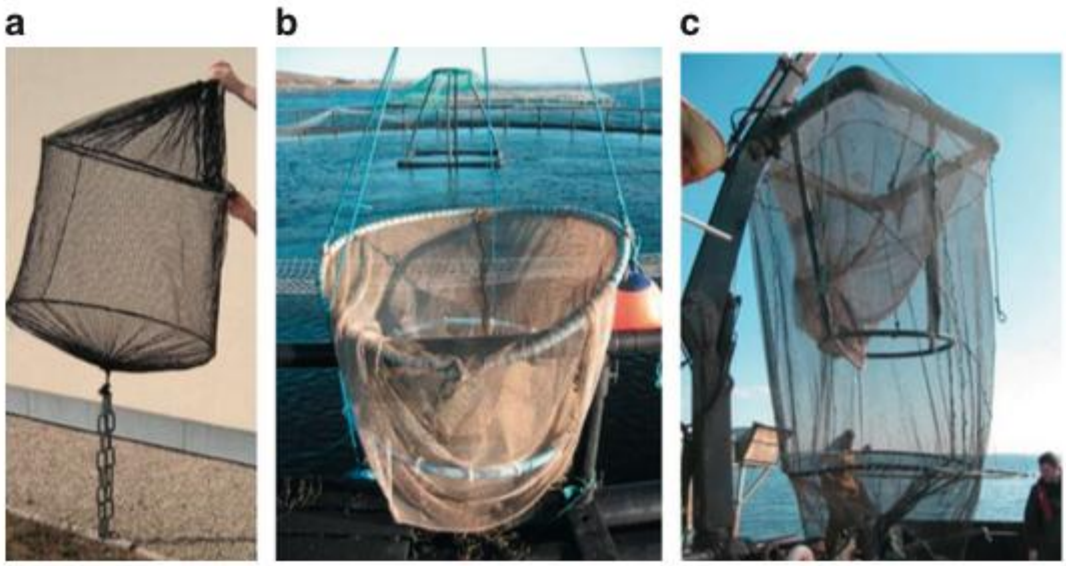

***Figure 5**: Image of three different designs for sentinel cages. a: Norway; b: Scotland; c: Ireland (Jackson et al. 2012)*

The Norwegian sentinel cage design is circular fiberglass construction, typically measuring 1m in diameter and 1m deep with 12 mm knotless mesh netting (Jackson et al., 2012). The Scottish sentinel cage design is a circular plastic construction, typically measuring 1.5 m in diameter and 2 m deep with 13 mm knotless mesh netting (Jackson et al., 2012). The Irish sentinel cage design is a square plastic construction, typically measuring 2 m by 2 m and 2.2 m deep with 16 mm knotless mesh netting (Jackson et al., 2012). The duration of exposure for the smolts in the sentinel cages may differ between studies. Salama et al. (2013) describe a 7 day exposure after which fish were removed and restocked. Bjørn et al. (2011) describe a 14 day exposure after which fish were removed and the cages restocked a week later. Jackson et al. (2012) described a 21 day exposure after which fish were removed and sentinel cages restocked. The number of smolts in each cage may also differ between studies. Pert et al. (2014) describes stocking each sentinel cage with 50 Atlantic salmon. While Bjørn et al. (2011) described stocking each sentinel cage with 25 Atlantic salmon. For all of the studies referenced above, the manner of collection is roughly the same; fish are taken out of the sentinel cages and placed in individual bags or containers, the fish are then taken to a laboratory and individually all contents from the bag are examined followed by the examination of the fish and subsequent identification of sea lice species and life cycle. The use of sentinel cages has become one of the most popular methods now used as an indirect method for assessing the free-living planktonic sea lice larvae (Jones & Beamish, 2011).

2.4 Implications for salmonid farms

2.4.1 Issues, costs and monitoring

In Norway, there are several hundred more farmed salmonids than there are salmonids in the wild (Heuch et al., 2005). This is also the case in areas such as Ireland and Scotland, where there are more salmonids being produced than can be found in coastal waters (Costello, 2006). The abundance of farmed salmonids, and the fact that they are present year-round, is also associated with there being 10 times more sea lice found on farmed salmonids than on wild salmonids (Heuch et al., 2005). This has also been suggested by Heuch et al. (2005) and Anon (2009), as there are more than 400 times the amount of hosts available now, in comparison to pre-farming times; which has resulted in a continuous availability of hosts in the environment and therefore, continuous production of sea lice is observed in areas with high farming production (Costello 1993 & 2009a). In many farms in these regions, the most problematic species is *L. salmonis*; while the species *C. elongatus* is also an observable problem, but to a smaller extent (Costello, 2006; Pike & Wadsworth, 1999).

Sea lice can cause serious issues for salmon farms; with initial infection being magnified by the number of available hosts, leading to large scale epidemics (MacKinnon, 1997; Krkošek, 2010). These epidemics will potentially result in a reduced appetite (Kvenseth, 1997; Rae, 1999; Boxaspen, 2006), significant levels of stress resulting in reduced swim performance, altered cardiac output and increased mortality (McKinley, Finstad, Bjørn, & Hunter, 2003). Therefore, the observable worst case scenario associated with sea lice is the mortality of farmed salmonids; this may results in mass deaths of the stock, if treatment is not used. The lesser issues such as increased stress are also potentially severe for salmonid farms as they will reduce efficiency of salmonids to grow and may reduce the quality of the product. It is important when considering these issues to then examine the costs.

There is also significant cost for the issues associated with sea lice on salmon farms. MacKinnon (1997) suggested that these costs may amount to 20 percent of the revenue in salmonid farming and many publications have referenced a figure of 100 million US dollars annually (Costello, 2009b; Johnson, Fast, Wiegertjes, & Flik, 2004; Rae, 2002). It is also suggested by Costello (2009b), that for the global production of Atlantic salmon in the year 2006 the cost associated with sea lice was roughly 350 million US dollars. The majority of the costs associated with sea lice on salmonid farms is prevention, treatment and losses from the fish experiencing reduced growth and reduced food conversion efficiency (Costello, 2009b). However, it is important to note that these costs could be four times higher, if prevention and treatment of sea lice would not be done (Mustafa, Rankaduwa, & Campbell, 2001).

As the issues and costs associated with sea lice can potentially be highly severe; salmonid farms rely on monitoring, as a tool for assessing the sea lice abundance on the farms. There are different monitoring methods which can be used; however, direct monitoring on the farms is the most practical method. In regions, which experience sea lice infestation on their salmonid farms such as Norway; sea lice counts are done on a weekly basis as a direct monitoring method (Salama et al., 2011). In Norway, weekly lice counts typically include a minimum of twenty-five fish per six cages (Salama et al., 2011). In Iceland, a region which has only recently developed salmonid sea-cage farming in comparison to regions such as Norway and Scotland; lice counting as a direct monitoring method is also used. In Iceland however, lice counts are only done on a once a month basis; in the region of Arnarfjördur, lice counts have only been done in roughly the last year; with only 2 months monitored for one farm and 4 months monitored for the other farm. Lice counts from the two farms located in Arnarfjördur are important for this study, and are therefore summarized in **Table 1** and **Table 2**. These lice counts are based on roughly twenty-five fish per six cages, similar to numbers done in Norway.

Table 1*: Summary of lice count data from Fjarðdalax aquaculture farm, located in Arnarfjördur, Iceland. Values are the number of lice found, on 20-30 fish analyzed monthly per 8 cage farm, during lice counts done in August and September of 2014. Distinction is made between Lepeophtheirus salmonis and Caligus elongatus species. (Source: Author)*

Date	*Lepeophtheirus salmonis* Adult Female with Eggs	*Lepeophtheirus salmonis* Adult Female without Eggs	*Lepeophtheirus salmonis* Pre-Adult Female	*Lepeophtheirus salmonis* Adult Male	*Lepeophtheirus salmonis* Pre-Adult Male	*Caligus elongatus* Male & Female
29/08/2014	0	0	0	0	0	8
18/09/2014	0	0	0	0	1	44

Table 2*: Summary of lice count data from Arnarlax aquaculture farm, located in Arnarfjördur, Iceland. Values are the number of lice found, on 20-30 fish analyzed monthly per 6 cage farm, during lice counts done in July, August, September and October of 2014. Distinction is made between Lepeophtheirus salmonis and Caligus. elongatus species. (Source: Author)*

Date	*Lepeophtheirus salmonis* Chalimus I-IV	*Lepeophtheirus salmonis* Pre-Adult I-II	*Lepeophtheirus salmonis* Adult Female	*Caligus elongatus*
23/7/2014	0	0	1	0
12/8/2014	1	0	0	0
03/9/2014	0	0	0	11
23/10/2014	1	0	0	29

2.5 Icelandic hydrographic conditions: Arnarfjördur

The hydrographic conditions for Iceland differ quite widely throughout the country; and there are various resources for acquiring data on these conditions. For the purpose of this study, it is important to outline the hydrographic condition within Arnarfjördur, in the Westfjords region of Iceland. This section will outline the various types of hydrographic data which are accessible, how they are accessed and the detailed data for Arnarfjördur will be discussed. There are various weather stations located throughout the country, collecting data on temperature, wind direction, wind speed, max wind speed and max gust. The weather stations record data every hour on the hour for everyday of the year. Numerous weather stations can be accessed online from the Icelandic website www.vegagerdin.is and the website www.vedur.is; which are both available in Icelandic and English, if the weather station data is not available online it can be requested directly from the Icelandic Meteorological office Veðurstofa Íslands. The most pertinent data was accessed from the Bíldudalur weather station number 2428 and is summarized in **Figures 6, 7 and 8.** This data is important for the scope of this study and is therefore included here as a summary of hydrographic conditions within Arnarfjördur.

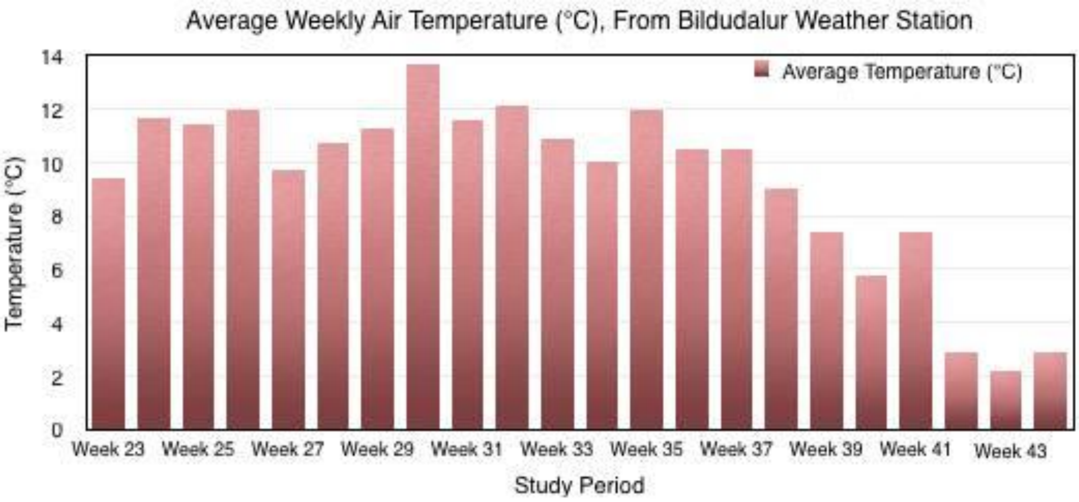

Figure 6*: Data summarized from Bíldudalur weather station number 2428. Summary of average weekly air tempurature (ºC) for the 22 week study period from the beginning of June to the end of October. Temperatures remained relatively high from week 24 throughout week 37, which was then followed by a rapid decline. (Source:Author)*

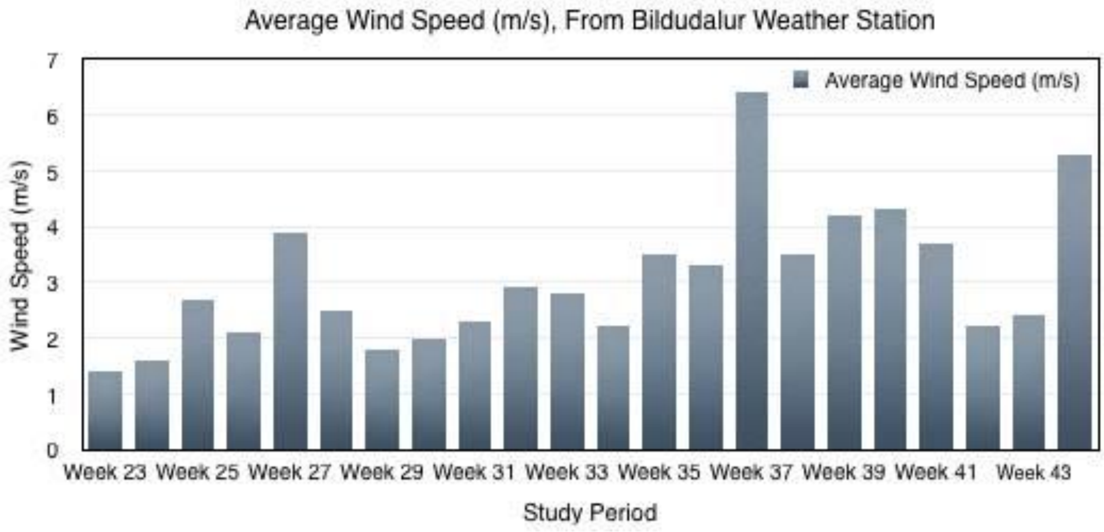

Figure 7*: Data summarized from Bíldudalur weather station number 2428. Summary of average weekly wind speed (m/s) for the 22 week study period from the beginning of June to the end of October. Wind remained consistently low for the first 12 weeks and then experienced higher wind speeds in general, if week 42 and 43 are excluded. (Source:Author)*

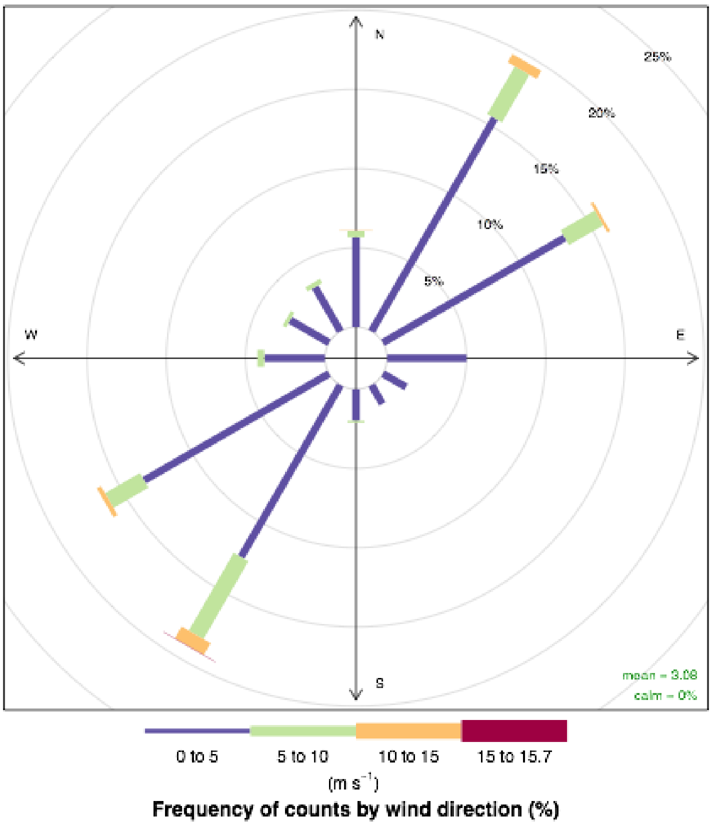

Figure 8*: Data summarized from Bíldudalur weather station number 2428. Summary of wind direction frequency for the 22 week study period from the beginning of June to the end of October. This wind rose illustrates the two dominant wind directions are North-East and South-West. (Source: Author)*

There are various wave buoys located along the coast throughout the country, collecting data on significant wave height, mean wave period, mean wave direction, air pressure, wind direction, mean wind speed, air temperature and sea temperature. The wave buoys record data every 6 hours at the hour for every day of the year. Numerous wave buoys can also be accessed online from the Icelandic website www.vegagerdin.is. There are also various tidal measurements for numerous areas throughout the country, collecting tides, current direction, current speed, surge and sea height. The tidal data is recorded every hour on the hour for every day of the year. Numerous tidal measurements can be accessed online also from the Icelandic website mentioned above. The tidal data was accessed from the Arnarfjördur tidal measurements, and is summarized in **Figure 9.**

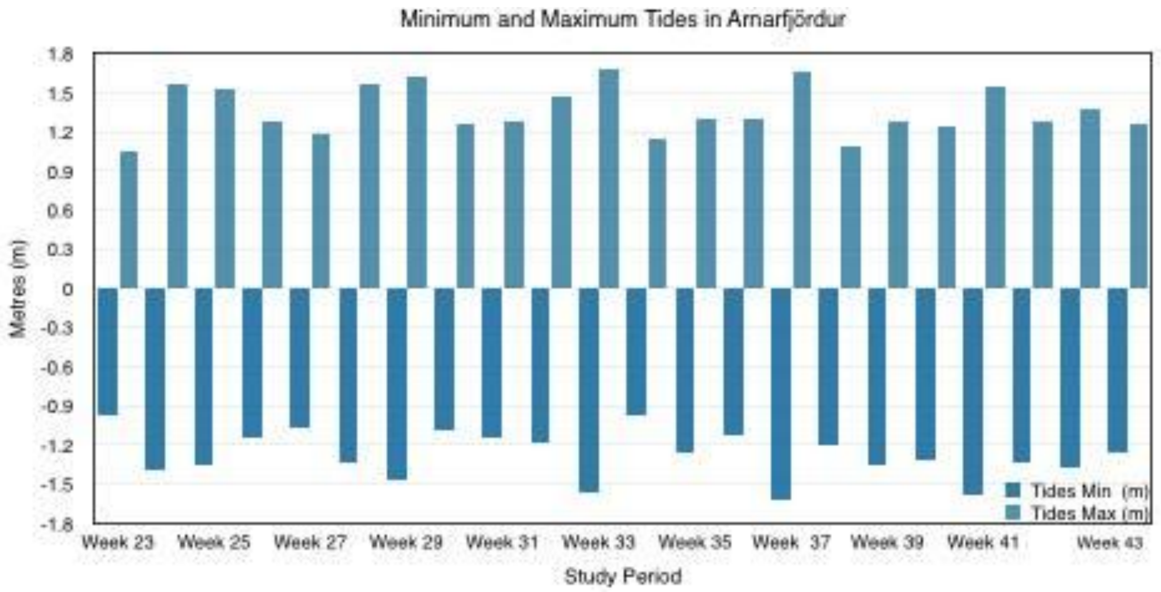

Figure 9*: Data summarized from the Arnarfjördur tide measurements. Summary of weekly minimum and weekly maximum tides from the 22 week study period from the beginning of June to the end of October. This information illustrates the weeks with the highest tidal range, which can be observed as week two, three, six, seven, ten, eleven, fifteen and nineteen. (Source: Author)*

This information is important for the scope of the paper and is therefore also included here as a summary of hydrographic conditions within Arnarfjördur. It is important to note that the tidal measurements are also connected to pertinent current information; as the current system within Arnarfjördur is influenced by the tidal cycle within the fjord. Two studies have provided measurements of current flow from within Arnarfjördur, one located in Haganes and the other located in Fossfjördur; both in the southern branch and located close to the Arnarlax and Fjarðdalax aquaculture farms respectively. Haganes current measurements which were taken in October of 2013 by placing a current meter at 22 m depth which was then programmed to record the direction and strength every meter throughout the water column, extending to the surface (Arnarlax, 2014). The average speed was 9 cm/s, 8 cm/s and 8 cm/s for the respective 5 m, 15 m and 10 m depths. The maximum speed was 32 cm/s, 29 cm/s and 32 cm/s for the respective 5 m, 15 m and 10 m depths. The highest directions for 5 m depth were 0-15º and 330-345º. The highest directions for 15 m depth were 0-15º, 330-345º and 345-360º. The highest directions for 20 m depth were 0-15º, 15-30º, 330-345º and 345-360º (Arnarlax, 2014). These directions correspond to a northern trajectory; however it must be acknowledged that these measurements were only taken in October and that the current meter was located at 22 m depth which may have had an affect on the validity of the measurements from above. Fossfjördur current measurements which were taken from December 2010 to the end of January 2011 by placing an Acoustic Doppler Current Profiler (ADCP) near the existing aquaculture farm (Allison, 2012). Measurements were taken at a depth of 15 m, 34 m and 58 m. The average speed was 4.2 cm/s, 3.8 cm/s and 3.5 cm/s for the respective 25 m, 34 m and 58 m depths. The maximum speed was 21.5 cm/s, 14.7 cm/s and 15.5 cm/s for the respective 15 m, 34 m and 58 m depths. The highest direction for was 184º, 198º and 201º for the respective 15 m, 34 m and 58 m depths (Allison, 2012). These directions correspond to a southern trajectory, opposite to that which was recorded in the Haganes current measurements. It is important to note that these measurements were taken at different times, by different methods and at different depths; in general the current flow is linked to the tidal rhythm of the fjord, it is divided between the northern and southern branches of Arnarfjördur and is defined as well-mixed water system.

For the purpose of this paper, other hydrographical data was also collected. This data includes temperature measurements from an aquaculture site within Arnarfjördur **(Figure 10)** and also hydrodynamic model output data from research being conducted at the University of Iceland both of which are private and inaccessible by the public. However, for the purpose of this paper access has been granted, from the Fjarðalax aquaculture company, to summarize the temperature measurements from their Fossfjörður site located in the southern-most branch of Arnarfjördur. Hydrographic conditions presented above are a summary of a 22 week period explicitly focused on for the purpose of this paper. However, the resourced for how and where to access data are provided and can be applied to many regions throughout Iceland, not only Arnarfjördur. Although some data may be restricted, the majority of information is freely provided by the Icelandic institutions and organizations, allowing for easily accessible and up-to-date measurements of various hydrographical conditions throughout the country.

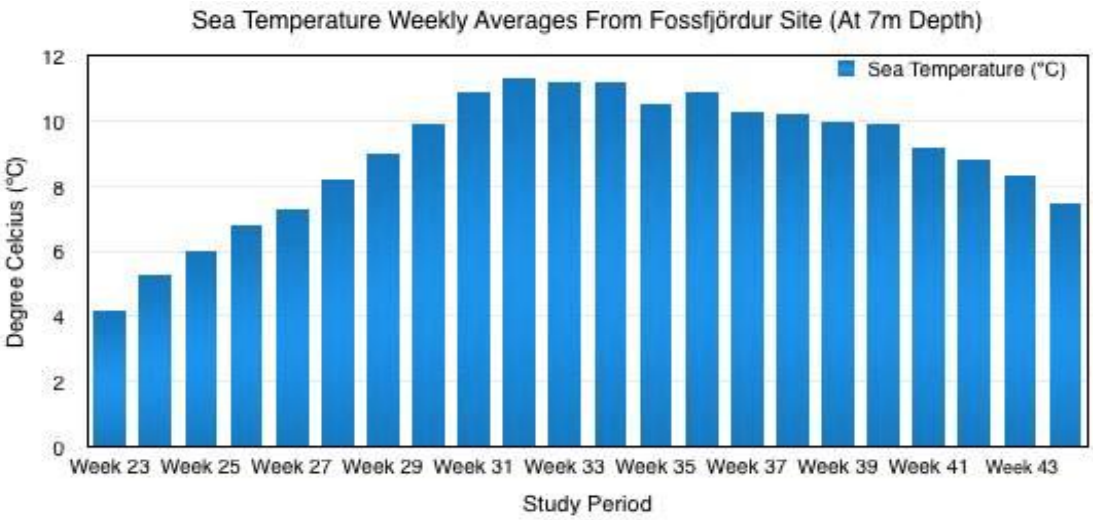

***Figure 10**: Data summarized from the Fjarðalax aquaculture company Fossfjörður aquaculture site. Summary of weekly temperature data from the 22 week study period from the beginning of June to the end of October. This data illustrated the warmest weeks, which occur between week 29 and week 44 with the most critically warm weeks occurring between week 31 and week 36*

3 Research methods

3.1 Pre-study evaluation

In the month of May a pre-study evaluation was conducted. This involved meetings/field surveys with Norwegian aquaculture specialists and an Icelandic aquaculture industry representative. This evaluation involved discussion of the methodology which would be used to conduct the study; most importantly a selection of sampling months, site location, number of sites, amount of cages at each site and finally amount of fish used. **Figure 11** shows the proposed sites which were decided in this meeting, selection was based on location to the two aquaculture farms and the current system of the fjord.

Figure 11: *Map of Arnarfjörður with proposed sites and two aquaculture farms. Site (A) located in Fossfjordur in the most inner southern branch of Arnarfjördur, Site (B) Located in Hjalli between the two aquaculture sites, Site (C) Located in Haganes, the most sea-ward location and Site (D) located in the most northern branch of Arnarfjördur (Created with Google Maps by Author).*

After deciding on each site, they were visited to determine if they would be appropriate for sentinel cage placement and access by boat. Following a visit to each proposed site, two of the 4 sites were not appropriate for use. Site C was proposed to be located on the outer fjord side of Bildudalur however once observations were made it was determined that the location would be a challenge for sentinel cage moorings as well as the site would be directly located in the way of the main shipping route. Site C was therefore re-evaluated for the final selection of the sites. Site D, the control site, was proposed to be placed in the northern branch of Arnarfjörður, after visiting this site it was determined that the distance from the other 3 sites was too far by boat and by car. This site was therefore re-evaluated for the final selection of the sites.

The number of sampling months however, is something which changed. In the pre-evaluation study the number of periods had been proposed to ideally be four, however this changed once the study began due to certain limitations and general progress of the study, this is again something which is discussed below. All other aspects discussed were considered suitable and therefore left unchanged.

3.2 Study area

Arnarfjörður is the second largest fjord located in the northern Westfjords region of Iceland (65°45’N 23°40’W). The fjord system is roughly 30 km long and 10 km at its widest point. Arnarfjörður is characterized by a large bay with two distinct branches, Borgfjörður and Dynjandisvogur to the North and Suðurfirðir to the South. Suðurfirðir is composed of four smaller fjords, Fossfjörður, Reykjafjörður, Trostansfjörður and Geirþjófsfjörður. Arnarfjörður is a glacial fjord, with a depth of roughly 40 m at the mouth, extending into roughly 110 m at its deepest point. The fjord is generally deep, with steep drop-offs extending to between 90 and 110 m. There is several fresh-water inputs from the surrounding mountains, with outflow from a couple of main rivers. The fresh-water outflow and sea water is well mixed within the fjord, which can be attributed to the current flow and depth profile. The surface current movement travels inward along Arnarfjörður and splits into two current movements following the two branching North and South fjords. Arnarfjörður is used for various activities such as multiple forms of fishing, small dredging operations, calcified sea weed extraction, outdoor recreation and fish farming. The most important activity, in terms of this paper, is two Atlantic salmon fish farming sites which are currently operating. The two farms are located in the Suðurfirðir branch of the Arnarfjörður system. One farm is owned and operated by the company Arnarlax, located near the southern branches outer edge in Otradalur, and produces 1500 tonnes of Atlantic salmon. The second farm is owned and operated by Fjarðalax, located near the southern branches inner fjord of Fossfjörður, and produces 3500 tonnes of Atlantic salmon. Both companies use Saga strain Atlantic salmon and production has increased continuously over the past two years; and plans for expansion are still in progress. Within the fjord system native populations of wild salmon, sea trout and Arctic charr can be found. There is also one river located in Trostansfjörður which is stocked with Atlantic salmon smolts by local residents.

3.3 Temporal period

The moorings were placed at sea in the end of June. Once the moorings were placed and the sites set up for sentinel cage attachment the three periods were organized beginning in July. The first batch of Atlantic salmon smolts were received on the 1st of July and stored until being placed at sea for the 3 data collection periods. The second batch of salmon smolts were received in the middle of August and stored until being placed at sea for the final period. The first period began on the 8th of July and smolts were left at sea for data collection for a full 3 weeks (21 day) and then removed from sea. The second period began on the 8th of August and smolts were again left at sea for a full 3 weeks (21 days) and then removed from sea. The third and final period began on the 1st of September and smolts were again left for a full 3 weeks (21 days) and then removed from sea.

3.4 Salmon smolt transportation and storage

Salmon smolts originated from a Fjarðalax land-based hatchery located in the South of Iceland in Þorlákshöfn. Transportation of the fish was done by the transport ship Papey owned and operated by Hraðfrystihúsið-Gunnvör hf. Salmon smolts were roughly 150g in weight. The smolts were transported the roughly 400 km by sea from Þorlákshöfn and the ship docked in Bildudalur where they were unloaded and prepared for further transport **(Figure 12).**

Figure 12*: Delivery of Atlantic salmon smolts to Bildudalur harbour from the Fjarðalax aquaculture company, via the transport ship Papey (Source: Author)*

The smolts were removed from the storage tank on the ship with hand nets and placed into a waiting land-transport storage container. The land-transport storage container was a large 60-80 cubic litre transport container which was located on a large flatbed truck on the Bildudalur dock next to the ship **(Figure 13).**

Figure 13: Land transport container, with mesh covering and oxygen input. Used to transport Altnatic salmon smolts from Bildudalur harbour to Tálknafjörður land-based storage tank (Source: Author)

The container was filled with water with a salinity of roughly 20-25 psu and oxygen was pumped into the container with an oxygen tank through a tube placed in the container. Once all of the fish were placed in the storage container, roughly 1000 fish, the container was sealed with a cover and transported the roughly 20 km to Tálknafjörður to be placed in a land-based storage tank. The land-based storage tank **(Figure 14),** which was roughly 2 m in diameter and 1.5 m deep, was prepared prior to arrival of the smolts by filling it with water with a psu lower than 15 and a mesh cover. Once smolts arrived in Tálknafjörður the mesh cover on the storage tank was removed and the smolts were transferred from the land-transport container to the storage tank.

***Figure 14**: Land-based storage tank, located in Tálknafjörður. Both fresh and saltwater were added to allow for a salinity lower than 15 psu (Source: Author)*

Fish were kept in the storage tank for roughly 2 weeks before half of them were placed in sentinel cages at sea. The other half was kept for period 2, they were in the storage tank for roughly 6 weeks before they were placed in sentinel cages at sea. Following placement of the second period more fish were needed for period 3, roughly 400 salmon smolts were transferred from an Arnarlax land-based hatchery in Tálknafjörður which provided smolts raised from the same eggs as those provided for the first two periods. Transportation was done in the same method as above, however only land-transport was required. All of the smolts were stored in the Tálknafjörður land-based storage tank in the same manner, under salinity lower than 15 psu and a temperature of between 8 and 10 ºC, covered with thick mesh to reduce light. They were given a small amount of feed to keep them alive, but only enough as to minimize the growth as much as possible, and monitored every couple of days to make sure they looked healthy and allow for any dead smolts to be removed from the tank.

3.5 Sentinel cage placement

A series of 4 sentinel cages were placed at 4 locations within Arnarfjörður, extending from low exposure to high exposure and 1 control site. Site A is located in Fossfjörður in the most southern fjord of the Suðurfirðir branch. This is in the inner fjord down-current from two aquaculture farms, by boat located roughly 6.0 km from the Arnarlax aquaculture farm and 1.5 km from the Fjarðalax aquaculture farm. These aspects are the reasons why site A is the high exposure site. Site B is located in Otradalur in the most southern fjord of the Suðurfirðir branch. Located, by boat, roughly 1.0 km parallel to the Arnarlax aquaculture farm and 3.0 km from the Fjarðalax aquaculture farm. These aspects are the reasons why site B is the medium exposure site. Site C is located in Bildudalur along the southern coast of Arnarfjörður near the outer part of the fjord mid-way to open sea. This is located up-current from the 2 aquaculture farms, by boat 3.5 km from the Arnarlax aquaculture farm and 7.5 km from the Fjarðalax aquaculture farm. These aspects are the reasons why site C is the low exposure site. Site D is located in Trostansfjörður in the more northern section of the Suðurfirðir branch. This is located north of the main current running along the southern coast, by boat roughly 8.5 km from both the Arnarlax aquaculture farm and the Fjarðalax aquaculture farm. These aspects are the reasons why site D is the control site **(Figure 15).**

Figure 15*: Final sites for sentinel cage sampling of Arnarfjörður.. Site (A) located in Fossfjordur is the high exposure site. Site (B) located in Hjalli is the medium exposure site. Site (C) located in Haganes is the low exposure site. Site (D) located in Trostanfjordur is the control. The two aquaculture farms are also identified (Created with Google Maps by Author)*

For site A, B and D four moorings weighing roughly 60 kg and 4 weights weighing roughly 6 kg, were loaded onto a 4 m long hard body boat with a 15 horse power motor in Fossfjörður; to be referred to as the black boat from now on **(Figure 16).** The moorings were placed at a depth of approximately 10-15 m and separated by a distance of roughly 100 m from each other along the coast. For site C the same moorings were loaded onto a larger 7-8 m long hard body boat with a 200 horse power motor. Moorings were attached to a 16 mm danline rope, for each mooring one of the 6 kg weights was attached roughly 2 m above to act as a buffer; the weights and rope were then dropped over board and once they hit the bottom they were then attached at the surface to a 57 cm diameter size buoy. Excess rope was left to extend from the buoy for the sentinel cage attachment set-up to be done later.

Figure 16*: The black boat loaded with equipment needed to place moorings at one site. Visible are 60 kg moorings, buoys, danline rope (Source: Author)*

After the placement of the moorings each site was set up for the attachment of the sentinel cages **(Figure 17)**; 8 size 10 cm diameter buoys, 4 small 5 kg weights and 4 size 31 cm diameter buoys were loaded onto the black boat in Fossfjörður and were transported to site A, with the process being repeated for each site subsequently. For each of the four sentinel cage sites, 2 size 10 cm diameter buoys were placed 1 m apart on the excess rope from the initial mooring placement. The rope was then fastened to a 31 cm diameter size buoy, 2 m of rope was left for the sentinel cage attachment.

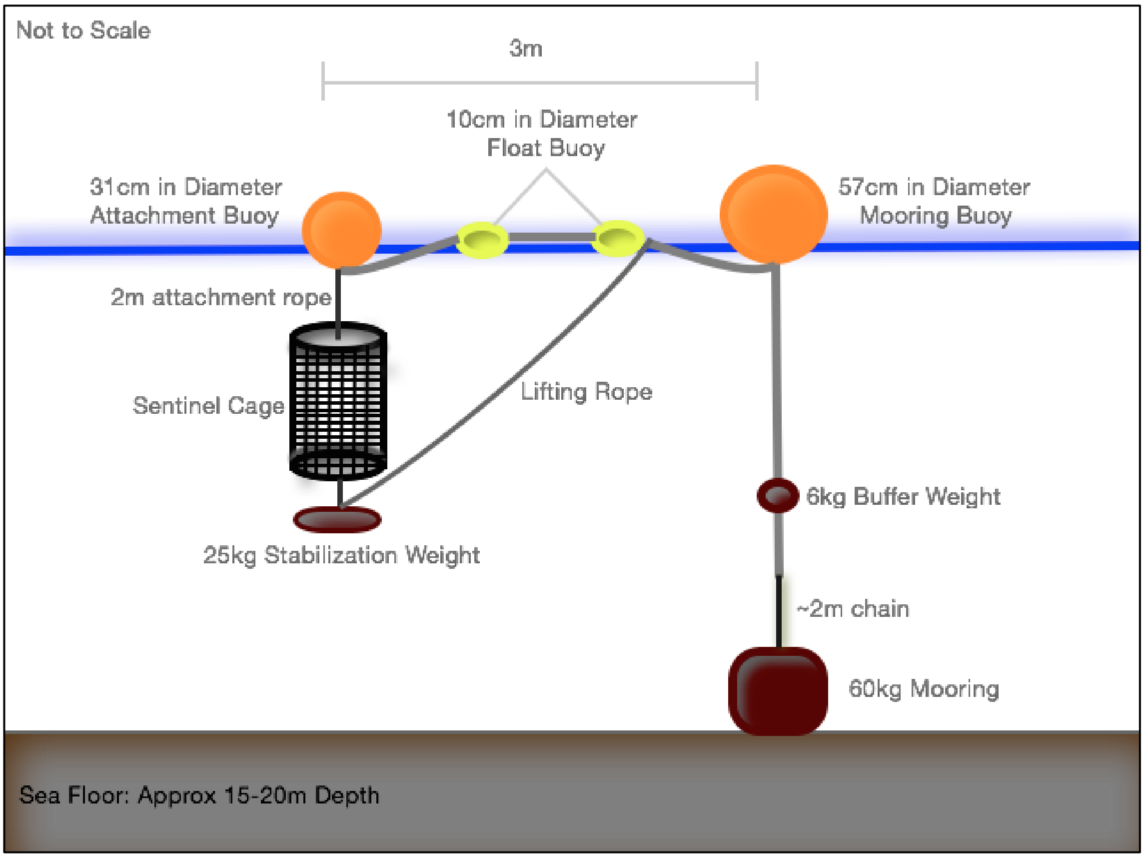

***Figure 17**: Diagram of sentinel cage setup, All parts of the setup are labelled and can be referred to based on descriptions above (Source: Author)*

3.6 Data collection

3.6.1 Sentinel cage data collection

The sentinel cages were built by the company Fjarðanet which has a factory in Ísafjörður, the construction of the sentinel cages was based on Norwegian design, completed cage shown in **Figure 18.**

Figure 18*: Completed construction of sentinel cage from Fjardanet, based on Norwegian design (Source: Author)*

The structure of the sentinel cages can be described in three sections, the bottom, middle and top. The bottom of the cage is made up of 1 polyvinyl chloride pipe ring 1m in diameter, wrapped in 18 mm size netting. The 18 mm size netting was then attached to the netting around the pipe and sealed at the bottom, extending roughly 0.5 m. The middle of the sentinel cage was made of roughly 1.5 m wide netting attached to the netting on the bottom pipe. The top of the sentinel cage was the same as that of the bottom, a 1 polyvinyl chloride pipe ring 1 m in diameter was wrapped in 18 mm size netting and the 18 mm size netting was then attached to the netting around the pipe. The top of the sentinel cage was however, not sealed shut but equipped with a draw-string closure and two ropes were also attached to the top ring and then bound by another rope to allow for attachment to the mooring sites. The top netting is able to be raised over the attachment ropes and the draw-string closure allows for a seal of the cage for closure.

Fish were prepared and transported from Tálknafjörður at the end of the first week of each month. One site was prepared and transported at a time. For each site, 108 fish were used, 27 fish placed in each of the 4 cages. Bags were prepared one site at a time at the storage tank location. A roughly 50 cm wide roll of plastic was used to make 4 individual bags of roughly 1.5 m in length and roughly 25 cm in diameter creating a double layer bag effect. One bag at a time was placed in a container, in order to make the movement of the bag manageable once salmon smolts and water are added. Water was added first, roughly 12 litres of fresh water and roughly 30 litres of salt water, creating a depth of roughly 1 m. This increased the salinity to roughly 20 psu to acclimate smolts to higher salinity, for a maximum of 2-4 hours, before going into the sea. Water depth in the storage tank was reduced slightly to make it easier to retrieve smolts out of the storage tank. Fish were taken out of the storage tank with the use of a 3 mm mesh size hand net, 2-3 fish were taken out at a time and placed into the plastic transport bag until 27 fish were reached. An oxygen tube was then placed in the bag, oxygen was entered until the bag was fully inflated, and then the bag was tightened and sealed with tape and string **(Figure 19)**.

Figure 19*: Transport bag, with 27 Atlantic salmon smolts and roughly 30 litres of water with a salinity of approximately 20 psu in order to acclimate smolts to sea before placement (Source: Author)*

The bags were then placed in a transport truck and ready for transport. The 4 bags were transported from Tálknafjörður to Fossfjörður, removed and again placed individually in the container for a more manageable movement. The bags containing the Atlanic salmon smolts, along with 4 sentinel cages, were then placed in the black boat. Transportation from Tálknafjörður to Fossfjordur took roughly 30-40 minutes, driving over a mountain pass for roughly 20 km. The entire process from retrieving the smolts, placing them in the bags, transporting them and getting them to see took roughly 4-5 hours.

Once at the site, the first sentinel cage was attached. Attachment of the sentinel cages was done using the additional 2 m of rope which was left extending from the 31 cm diameter size buoy. The top of the sentinel cage was fastened to the 2 m of additional rope and then a 5 kg stabilization weight was fastened to the bottom of the sentinel cage. The sentinel cage was then dropped partially overboard so that 60-70 percent of the cage was submerged, while the top ring remained on the edge of the boat. One bag was used per cage, therefore depositing 27 fish in each cage. The bags were placed through the top ring, the bottom of the bag was cut open with the use of a small knife by which all of the fish were deposited into the cage. The draw-string closure of the bag was then tightened, the cord was wrapped around the mesh of the cage to add another level of security from possibility of escape. Once the cage was successfully sealed then the fish were visually monitored to evaluate health and lowered slowly into the water remaining located roughly 2 m below the surface of the water **(Figure 20).**

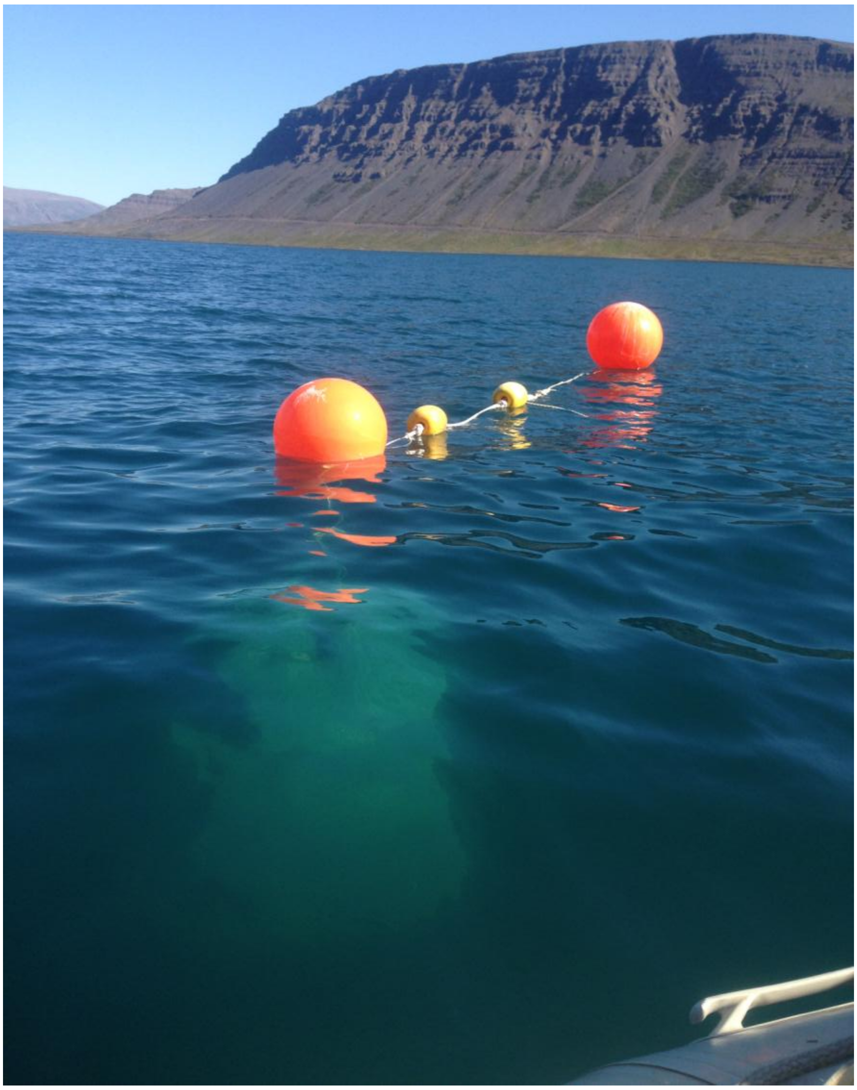

Figure 20*: Sentinel cage after fish have been placed, you can visibly see the surface structure and cage placement in the surface water (Source: Author)*

Three weeks or 21 days after the fish and sentinel cages were placed at sea they were removed. Two boats were used depending on availability, the black boat and a 3m long soft body, hard bottom boat with a 25 horse power motor was used to go from Fossfjörður to each individual site, placed in the boat was roughly 150 small 10 litre plastic bags, labels, permanent markers, knives, a hand net with 3 mm mesh size and a cooler for storage. Once at the site the sentinel cages could be reached from the 31 cm diameter size buoy and lifting rope and raised above water onto the edge of the boat. The stabilization weight which was attached to the bottom of the sentinel cage was then detached and stored in the boat for easier access until all the fish were collected. The draw-string on the top of the sentinel cage was then opened allowing for access to the fish inside. The fish were removed individually using a hand net with 3 mm mesh size and then placed individually in 10 litre plastic bags. Once in the bags the fish were euthanized immediately. The net was then checked for any lice which may have fallen off of the fish and if any were found they were placed in the individual plastic bag belonging to the fish. Once each fish was placed in an individual plastic bag, all of the individual plastic bags were then placed in one large plastic bag and labeled with the site, cage number and date **(Figure 21).** The labeled bags of fish were then placed in the cooler.

Figure 21: *Atlantic salmon smolts which were collected after 3 weeks (21 days) of exposure, euthanized and placed in individual plastic bags. Stored by cage and labelled with date and site (Source: Author)*

Once all fish were collected from the cage, the cage was then detached from the 2 m long rope. The cage was then placed in the boat and the stabilization weight was re-attached to the 2 m long rope. The weight and rope was then dropped overboard and left below the surface for sentinel cage attachment at the next data collection period. Following the collection of the fish from all 4 sentinel cages, the cooler was then removed from the boat in Fossfjörður and transported to the laboratory in the Arnarlax factory located in Bildudalur.

Following period 1, two minor adjustments were made to the sentinel cages to make them more stable in the water, this was done before the cages were put back at sea for period 2. When the cages were removed from the water for cleaning, in between period 1 and 2, holes were drilled into the bottom ring of the sentinel cage to allow for the cage to sink properly and to ensure more stability in the cages structure while at sea. When cages were returned to sea for period 2, new weights were taken out to replace the 5 kg stabilization weights attached to the bottom of the sentinel cage. The new stabilization weights were roughly 25 kg and attached in the same manner as the previous weights. This again was done to ensure stability of the sentinel cages in the water and reduce the impact from storm surges and strong winds. A rope was attached from the stabilization weight to the first 10 cm diameter size buoy extending from the large 57 cm diameter size mooring buoy, this was done to make it easier to lift the weight and sentinel cage out of the water.

3.6.2 Temperature and salinity data collection

Temperature and salinity data was collected from each of the four study sites, at a depth of zero point one, one, two, three, four and five meters. Collection was done on the 24th of October, following completion of the sentinel cage data collection. Ideally collection would have been done during each of the study periods, this was not possible and is discussed in the limitations section below. The temperature and salinity data was collected by using the following device: Conductivity Meter - Cond 3110 (WTW), placed over the side of the black boat which was used to get to and from the four study sites.

3.7 Sentinel cage cleaning

Sentinel cages were removed monthly at the end of the data collection period, removal was done using the black boat from Fossfjörður. Cages were raised from the water via the 31 cm diameter size buoy and lifting rope, after the fish were removed for data collection the cages were ready for removal from the water. The sentinel cages were individually lifted onto the edge of the boat, the stabilization weight was detached from the bottom of the sentinel cage and temporarily placed in the boat. The sentinel cage was then detached from the 2 m long rope extending from the 31 cm diameter size buoy and placed in the boat. The stabilization weight was then attached to the 2 m long rope extending from the 31 cm diameter size buoy and dropped into the water to submerge it until the next attachment cycle.

The cages were then transported to shore and placed in the back of a transport truck, the cages were then driven to the Arnarlax factory located in Bildudalur. Cages were cleaned at the Arnarlax factory using a pressure washer, cages were placed on a make-shift hanging rack which was raised above the ground roughly 1m by using pallets stacked on top of one another. Pallets were placed with enough space for the cage to hang freely on the hanging rack which stood on top of the pallets **(Figure 22).** The cages were then cleaned individually with the pressure washer from top to bottom. The nets were made to be free from any dirt or debris which may have attached and left to dry inside of the factory.

Figure 22: *Cleaning of sentinel cage at Arnarlax facility. (Source: Author)*

3.8 Lab analysis

Following the data collection at the end of each monthly period, the fish were analyzed in a make-shift laboratory at the Arnarlax factory in Bildudalur. The laboratory included a desk, chair, solid white plastic examination container 50 cm by 30 cm in size, microscope, microscope slides, scientific tweezers, ruler, magnifying glass, flashlight, a water source, sink and a freezer. Fish were brought into the laboratory following data collection, if multiple sites were collected in one day and could not all be analyzed then 1 site was placed in the freezer for analysis the following day. For those fish which were frozen they were removed from the freezer on the day of analysis and thawed for roughly 2 hours or until de-thawed and analysis proceeded as normal.

The analysis process was repeated for each fish throughout the entire data collection process. For each bag of fish, which was labelled with a specific site, cage and date, the fish were analyzed individually. Fish were removed from their individual bag and placed on the desk on a white piece of paper, this was to make any lice which may come off during analysis easy to spot. The clear plastic bags which the fish were placed in individually, were examined thoroughly for any sea lice which may have fallen off of the fish during transport and would have collected into the bag. All lice which were found in the plastic bag or on the paper were placed on a microscope slide and examined under the microscope at 20x magnification. The fish were then analyzed with the use of a flashlight and any sea lice found were placed on a microscope slide. In order to make it easier to identify small sea lice in the early stages of their life cycle, the fish was then placed in the 50 cm by 30 cm solid white plastic examination container with 10 to 15 cm of water. By placing the fish in the water any sea lice which were still attached would partially float and be more visible, as well as some lice may detach and float in the water making them easy to locate. The sea lice found were again placed on a microscope slide and examined under the microscope at 20x magnification, for lice in the early stages in the life cycle 50x magnification was used for identification.

Sea lice were identified visually based on specific characteristics which are displayed in the EWOS sea lice identification key which was developed in the 1998 National Strategy for Sea Lice Control. These specific characteristics were also based on detailed identification characteristics discussed in the Schram (2004) article *Practical identification of pelagic sea lice larvae*. Identification was done in collaboration with a study on sea lice infection rates on wild salmonids conducted during the same period in the same area (Karbowski, 2015) and was consistently used throughout the two studies. For each life cycle stage these specific characteristics can be described to differentiate between *Lepeophtheirus salmonis* and *Caligus elongatus* as well as between each specific life cycle stage within each species.

Nauplius 1 are small almost entirely clear or translucent and can be identified based on the color and location of pigmentation. Nauplius 1 of *L. salmonis* are characterized by black pigment which is visible around the eyes, dorsally and posteriorly as well as brown pigment which is found in the middle and evenly on both sides of the cephalothorax with all appendages lacking pigmentation at this stage. Nauplius 1 of *C. elongatus* are distinctly different from *L. salmonis* identifiable by the red pigment located on the anterior and on the ventral surface of the cephalothorax as well as a dark red pigment along the sides and posterior end (Schram, 2004).

Nauplius 2 are slightly larger, oval and slender still appearing translucent and can be identified based on the colour, location of pigmentation and shape of the cephalothorax. Nauplius 2 of *L. salmonis* are easily identified by black pigment around the eyes as well as posteriorly in bands across the cepholothorax and two distinct brown pigmented C-shaped figures located centrally on each side in the middle of the cepholothorax, appendages still lacking pigmentation (Schram, 2004).

Copepodids are again slightly larger, oval and slender in shape with pigmentation beginning in the cepholothorax and can be identified by the change in shape of the cepholothorax. Copepodids of *L. salmonis* are easily identified by two red eyes, a cepholothorax which is pointed at the anterior end, widest at the middle and a narrow somewhat pointed posterior end, with distinct C-shaped dark brown pigmentation. Copepodids of *C. elongatus* are easily identified by dark red eyes, a cepholothorax which is widest just above the middle, two distinct notches at eye level and near the anterior of the cepholothorax and 3 distinct patched of red pigmentation (Schram, 2004).

Chalimus 1 are again slightly larger, elongating vertically and the first visual sign of a frontal filament is evident (Costello, 2006). Chalimus 1 of *L. salmonis* are easily identifiable from other *L. salmonis* life cycle stages and from *C. elongatus* by a series of characteristics. The identification characteristics which distinguish Chalimus 1 *L. salmonis* from Chalimus 1 *C. elongatus* are the red eyes located mid-cepholothorax, the wide cepholothorax shape, pronounced frontal filament and lack of frontal notch near the eye level of the body. The identification characteristics which distinguish Chalimus 1 *L. salmonis* from Chalimus 2 *L. salmonis* are the longer but narrower frontal filament and lack of posterior cepholothorax segmentation (Schram, 2004).

Chalimus 2 are again slightly larger, elongating vertically as well as widening mid-cepholothorax. At this stage the identification characteristics which differentiate *L. salmonis* from *C. elongatus* are easily to distinguish. Chalimus 2 of *L. salmonis* are identifiable from Chalimus 1 due to a visibly distinct posterior cephalothorax segment, widened cephalothorax, lines extending the posterior cephalothorax segment up to the eye level vertically along the cephalothorax, as well as extended narrow fourth leg-bearing segment. Chalimus 2 of *C. elongatus* are much smaller than Chalimus 2 of *L.*

salmonis, they are easily distinguishable from other life cycle stages of *C. elongatus* by the beginning stages of a posterior cephalothorax segment and increasingly pronounced frontal notch located just above the eyes (Schram, 2004).

Chalimus 3 of *C. elongatus* are significantly bigger than Chalimus 2 of *C. elongatus*. Chalimus 3 are also easily distinguishable by their pronounced frontal filament, pointed anterior of the cephalothorax, extended posterior cephalothorax segment and elongated fourth leg-bearing segment. Chalimus 4 of elongatus are significantly bigger than Chalimus 3 of *C. elongatus*. Chalimus 4 are also easily distinguishable by their widened cephalothorax, pronounced frontal filament, pronounced frontal antenna, developed posterior cephalothorax segmentation and a circular bulge to the posterior cephalothorax segmentation, narrowing near to the fourth leg-bearing segment (Schram, 2004).

L. salmonis has 2 pre-adult life cycle stages for both males and females which are larger, distinctly wider with a round shape cephalothorax and have a flat shape cephalothorax with red pigmentation. Male pre-adult 1 are easily identifiable by four distinct bump-looking characteristics on the anterior of the cephalothorax by the frontal plates, a wide and round shape cephalothorax, red pigmentation which has not progressed to dark red and along the fourth leg-bearing segment, genital complex or abdomen, without any distinguishable characteristics. Male pre-adult 2 are easily identifiable by two distinct bump-looking characteristics on the anterior of the cephalothorax by the frontal plates, a wide and round shape cephalothorax, a darker red pigmentation and a distinctly short fourth leg-bearing, genital complex and abdomen segment, with two visible lines located vertically. Female pre-adult 1 are easily identifiable by a slightly narrow anterior cephalothorax, a wide mid to lower cephalothorax and red-orange pigmentation and a distinctly short posterior with a slight pointing down and outwards of the bottom edges of the genital complex. Female pre-adult 2 are easily identifiable by two distinct bump-looking characteristics on the anterior of the cephalothorax by the frontal plates, a wide and round shape cephalothorax, a darker red pigmentation and an enlarged genital complex and abdomen, with more developed and large pointing of the bottom edges of the genital complex (Schram, 2004).

L. salmonis and *C. elongatus* both have 1 adult life cycle stage for both males and females. The male and female adult stage of *L. salmonis* is easily distinguished from the male and female adult stage of *C. elongatus* by the larger size, much darker red pigmentation and flat shape cephalothorax. The adult male *L. salmonis* is identifiable by dark red pigmentation and round shape cephalothorax and a very distinctly shaped genital complex which is narrow at the front of the genital complex then extending to a rounded and wide mid genital complex and again narrowing at the end of the genital complex. The adult female *L. salmonis* is identifiable by a very dark red almost brown pigmentation, very large genital complex, which has four distinct circular characteristics and developing or developed egg strings visibly extending from either side of the genital complex. The adult male *C. elongatus* is identifiable by an oval shape cephalothorax, light orange cephalothorax color with red spotting over it entirely, distinct mid-cephalothorax lines the same on both sides of the cephalothorax, a wide and large upper genital complex segment and very distinct frontal plates extending out of the middle of the cephalothorax curving outwards along the cephalothorax. The adult female *C. elongatus* is very similar to the adult male only larger, with a developed and large genital complex and developing or developed egg strings visibly extending from either side of the genitical complex (Schram, 2004).

3.9 Modelling sea lice movement

There are various types of models which have been used to model the movement of sea lice, this method of predicting dispersion has increased in popularity over the last 10 years and is now thought to generate fairly realistic results (Asplin et al., 2014; Stucchi et al., 2011). If the results are hoped to be as comprehensive and accurate as possible then some form of hydrodynamic model, as well as a type of lice biology model, will be needed (Amundrud & Murray, 2009; Asplin et al., 2011). The sea lice movement models which are used will depend on access to data, local preference as well as availability and applicability of previously developed models. As these can be complex and have high variation, examples will be given of species modelling techniques used from different research studies.

In a paper by Gillibrand and Willis (2007), they rely on a coupled hydrodynamic louse transport model; the purpose of this model was "to investigate the influence of physical forcing and larval behavior on the dispersal of sea louse larvae from a point source in an idealized coastal inlet” (Gillibrand & Willis, 2007). The model requires data inputs from two key areas of hydrodynamics and sea louse behavior processes; specifically input data for wind, freshwater runoff, tidal currents, temperature-dependent growth, mortality, salinity preference and diel vertical migration. The hydrodynamic model is outlined as being a “3D free-surface z-coordinate primitive-equation model, the prognostic variables are water level (η), water temperature (T), salinity (S) and the 3 components of velocity u, v, w along the horizontal axes x and y and vertical axis z (positive upward)” (Gillibrand & Willis, 2007). The particle transport model is then embedded within this model utilizing values of temperature, salinity and velocity. This complex manner of modelling sea lice movement is comprehensive; and suggested to not only increase confidence in predicting sea louse distribution, but also improve the ability to predict transmission rates within salmonid farms and between salmonid farms and wild salmonid populations (Gillibrand & Willis, 2007).

In a paper by Amundrud and Murray (2009), they rely on a three-dimensional circulation model previously validated by Gillibrand and Amundrud (2007); coupled with a biophysical particle tracking model, the purpose of which was “to trace the dispersion of sea lice from points representing farm sites” (Amundrud & Murray, 2009). The three-dimensional circulation model requires several types of input data; specifically tides, winds, freshwater inputs and the density of offshore coastal waters (Amundrud & Murray, 2009). The three-dimensional hydrographic model used is a baroclinic coastal ocean model known as the GF8 (Amundrud & Murray, 2009). Jones and Beamish (2011) state that the model is “based on hydrostatic solution with the Bousinesq approximation to the equation of mass, momentum, and density conservation first developed by Backhaus (1985), solved on an Arakawa C-grid”. The biological particle tacking model will then calculate the movements, maturation and mortality of the particles which represent sea lice larvae (Amundrud & Murray, 2009). The biological particle tracking model is then embedded within the three-dimensional circulation model, utilizing the output values (Amundrud & Murray, 2009). This type of model has also been used by Salama et al. (2014). However, they have expanded it to be applicable on a much larger scale fjord.

A final example of models used to predict sea lice movement is described in Asplin et al. (2014), they rely on a coastal ocean model, fjord model and salmon lice growth and advection model; the purpose of which was to predict the dispersion of sea lice within various Norwegian fjords (Jones & Beamish, 2011). The coastal ocean model and the fjord model are based on the Regional Ocean Model Systems (Haidvogel et al., 2008). This is described as a "three-dimensional, free-surface, primitive equation numerical model using a generalized terrain-following s-coordinate in the vertical" (Asplin et al., 2014). The models require several types of input data; specifically atmospheric data, river data, current hydrography, water level, turbulent length scale and turbulent kinetic energy (Jones & Beamish, 2011). The salmon lice model uses hourly output values of currents, salinity and temperature generated by the fjord model (Asplin et al., 2014). The salmon lice model, when coupled with some form of circulation model, is one of the most comprehensive predictions used for sea lice movement and dispersion. The comprehensiveness of the model is described by Asplin et al. (2014), as it simulates the diel vertical migration of sea lice, the first three pelagic larval stages of the lice and it generates hourly output of particle position, age, temperature and salinity. Coupling hydrodynamic or circulation models with a sea lice dispersion models, and also including environmental and larval behavior, increases the accuracy for the prediction of sea lice distribution (Gillibrand & Willis, 2007).

3.10 Data analysis

Data analysis was done using both the statistical computing and graphical software R and Microsoft Excel. A Kruskal-Wallis test was performed, testing if there is a difference in lice abundance between sites per month and also between months if all sites are included. The level of significance used was $p < 0.05$, therefore if the value is lower than 0.05 a statistical significance is observed. All of the figures created for the data analysis were done using R. Statistical significance refers to a result that is not likely to have occurred randomly. The death rates, damage types, abundances and prevalence were done with Excel. All of the tables created for the data analysis were done using Excel.

There are few key definitions which need to be provided when referring to lice counting, these are abundance, prevalence and intensity which are outlined by Bush et al. (1997). Abundance is considered to be the lice number per sampled fish. Prevalence is the proportion of infected individuals from the entire sample, calculated per respective time period and site. Intensity is the mean number of infectious species (sea lice) per each infected host (salmon smolt), calculated per site per month.

3.11 Limitations

This project is to the best of my knowledge the first of its kind to be done in Iceland, therefore some obstacles and challenges were to be expected. One of the biggest limitations to this research project was the weather, the ability to go out to sea was limited by the amount of storm surges and strong winds which are typical characteristics of Icelandic weather. The weather limitation meant that placement of the salmon smolts in the sentinel cages could only take place when weather permitted, making a fourth period in October impossible to conduct.

There were also some technical limitations to the research, access to a boat, use of a boat and size/equipment of the boat was another difficult limitation. The black boat from Fossfjörður was only able to be moved in and out of the water with the use of a CAT tractor, this was only able to be operated by Fjarðalax employees and the time and use was restricted to their activities. The 3 m long soft body, hard bottom boat with 25 horse power motor from Fossfjörður was also only able to be moved in and out of the water with the use of a CAT tractor, which again was operated by Fjarðalax employees and the time and use was restricted to their activities, however this boat was more easily able to be tied to ropes and left at shore making it slightly more accessible. For either boat the size was too small and not that well equipped for this project, the boat also needed to be unloaded and reloaded every time it was used which took away valuable day-light hours.

A final limitation to this research project which should be discussed is the short period of time which was available before data collection began. Preparation was delayed by resource limitation, a factor which was a continual challenge throughout the project. This lead to the first period of data collection being delayed by 1 week, extending into period 2 and 3; however, not influencing the 21 day exposure period.

4 Results

The death rates, ratio of total fish mortality per site, are summarized in **Table 3** for the three sampling months, for all four sites. The month with the highest death rate was July with 0.82, followed by September with 0.57 and August with 0.41. The site with the highest death rate was site C with 0.99 occurring in July, this was followed by site B with 0.94 also occurring in July. If all months are considered than site C has the highest death rate averaging at 0.7, closely followed by site B at 0.64 with site A and D resulting in 0.57 and 0.49 respectively.

Table 3*: Summary of death rates, ratio of total fish mortality per site, including values per month and per site, with a value of 0 meaning all fish survived and a value of 1 meaning all fish died. (Source: Author)*

	July	August	September	Average (For all months)
Site A	0.52	0.52	0.68	0.57
Site B	0.94	0.32	0.66	0.64
Site C	0.99	0.65	0.46	0.70
Site D	0.83	0.17	0.48	0.49
Total (mean)	0.82	0.41	0.57	0.60

There were 731 lice collected in total, of that the majority were of the species *C. elongatus*, comprising 97 percent of the total, 7 of the lice were of the species *L. salmonis* comprising 1 percent of the total and 14 of the lice were unidentifiable comprising the remaining 2 percent of the total. All of the 7 *L. salmonis* were collected in August, and the distribution of *C. elongatus* was 19 in July, 387 in August and 204 in September. There was one fish found to have an abundance higher than 0.1 lice per gram, with 8 lice on a 78 g fish, while there were 28 fish found to have an abundance higher than 0.05 lice per gram.

The prevalence, ratio of infected individuals from the entire sample, is summarized in **Table 4** for the three sampling periods, for all four sites. The month with the highest mean total prevalence was September with 0.72, followed by August with 0.66 and July had the lowest with 0.16. The site with the highest prevalence was site A with 0.91

occurring in September, this was closely followed by site D with 0.89 in September. If all months are considered, then site A has the highest prevalence with an average of 0.63, followed by site B with an average of 0.58 and site D and C with an average of 0.56 and 0.3 respectively.

Table 4: *Summary of sea lice prevalence, the ratio of infected individuals from the entire sample. Values given per site, per month, including total mean and average for all months. (Source: Author)*

	July	August	September	Average (For all months)
Site A	0.15	0.83	0.91	0.63
Site B	0.29	0.82	0.62	0.58
Site C	0.00	0.42	0.48	0.3
Site D	0.22	0.58	0.89	0.56
Total (mean)	0.16	0.66	0.72	0.51

The lice abundance, mean number of lice on all fish sampled in one group, is summarized in **Table 5** for the three sampling months, for all of the four sites. The month with the highest mean total abundance was September with 1.71, followed by August with 1.60 and July had the lowest with 0.23. The site with the highest abundance was site A with 2.60 occurring in September, this wasn't closely followed by any other site, only site A again in August with 2.56. If all months are considered than site A has the highest abundance with an average of 1.79, followed by site B with an average of 1.30 and with site D and C resulting in an average of 1.19 and 0.43 respectively.

Table 5: *Summary of abundance, the lice number per sampled fish. Values given per month, per site, including total mean and average for all months. (Source: Author)*

	July	August	September	Average (For all months)
Site A	0.21	2.56	2.60	1.79
Site B	0.43	2.14	1.32	1.30
Site C	0	0.63	0.67	0.43
Site D	0.28	1.06	2.23	1.19
Total (mean)	0.23	1.60	1.71	1.18

The intensity, mean number of infectious species (sea lice) per each infected host (salmon smolt), is summarized in **Table 6** for the three sampling periods, for all four sites. The month with the highest mean total intensity was August with 2.25, followed closely by September with 2.21 and July had the lowest with 1.03. The site with the highest intensity was site A with 3.09 occurring in August, this wasn't followed closely by any other site, only site A again in September with 2.84. If all months are considered, then site A has the highest intensity with an average of 2.44, followed by site B with 2.08 and site D and C with an average of 1.86 and 0.96 respectively.

Table 6: *Summary of intensity per month, the mean number of infectious species (sea lice) per each infected host (salmon smolt). Values given per site, per month, including total mean and average for all months. (Source: Author)*

	July	August	September	Average (For all months)
Site A	1.38	3.09	2.84	2.44
Site B	1.50	2.60	2.13	2.08
Site C	0.00	1.50	1.39	0.96
Site D	1.25	1.83	2.50	1.86
Total (mean)	1.03	2.25	2.21	1.83

The frequency of lice occurring within a site is summarized in **Figure 23,** this is done for the three sampling months for all four sites. July has the lowest frequency, the majority of the lice were found at site B and only a very small amount found within A and D. August and September have similar frequency of lice for all three sampling months, site A has the highest frequency for both months, site B has a higher frequency in August while site D has a higher frequency in September. The highest lice found per fish was 8, and this occurred in both site A and B for the month of August.

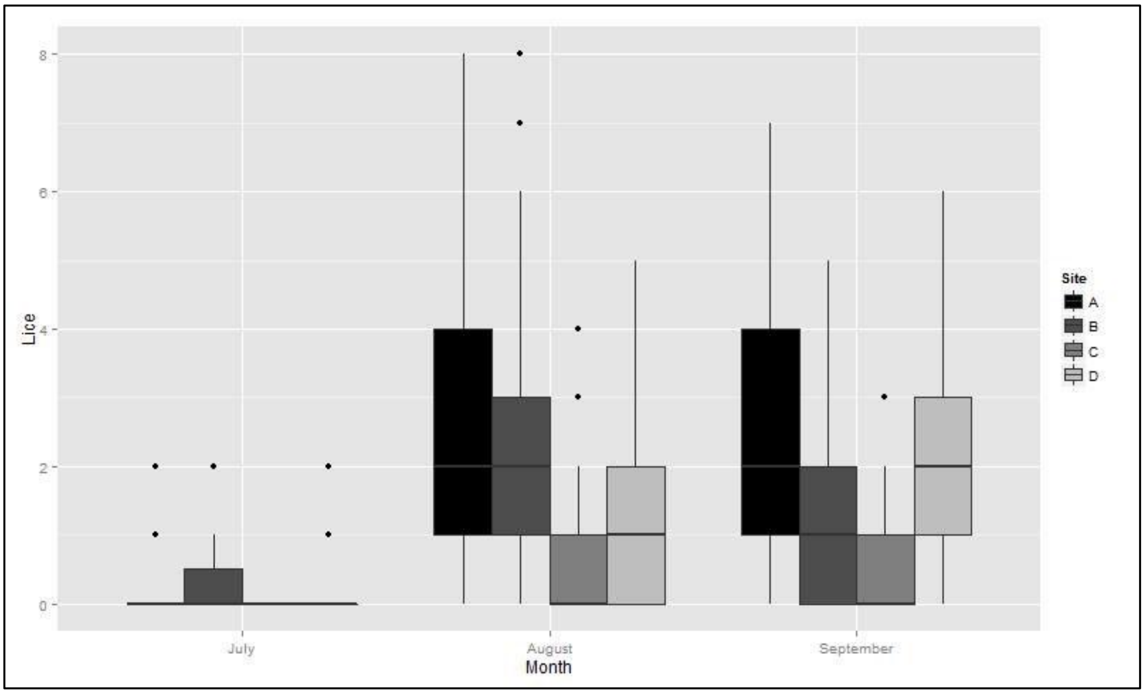

***Figure 23**: Summary of life cycle abundance per month, values given per site. Each month has four columns displaying the frequency of lice per site (Column 1) site A, (Column 2) site B, (Column 3) site C and (Column 4) site D. (Source: Author)*

The frequency of both the chalimus and adult life cycle stages of the sea lice collected are summarized in **Figure 24**, this is done for the three sampling months for all four of the sites. In July it was observed to be almost entirely adult lice in all. The highest frequency of chalimus is observed in September for three of the four sites, while it is highest in August for site B. The frequency of adult sea lice decreases for both August and September, with the lowest frequency observed for 3 of the 4 sites, while it is lowest in August for site B. In general the frequency of adults decreases following the three sampling months, accompanied by an increase in chalimus.

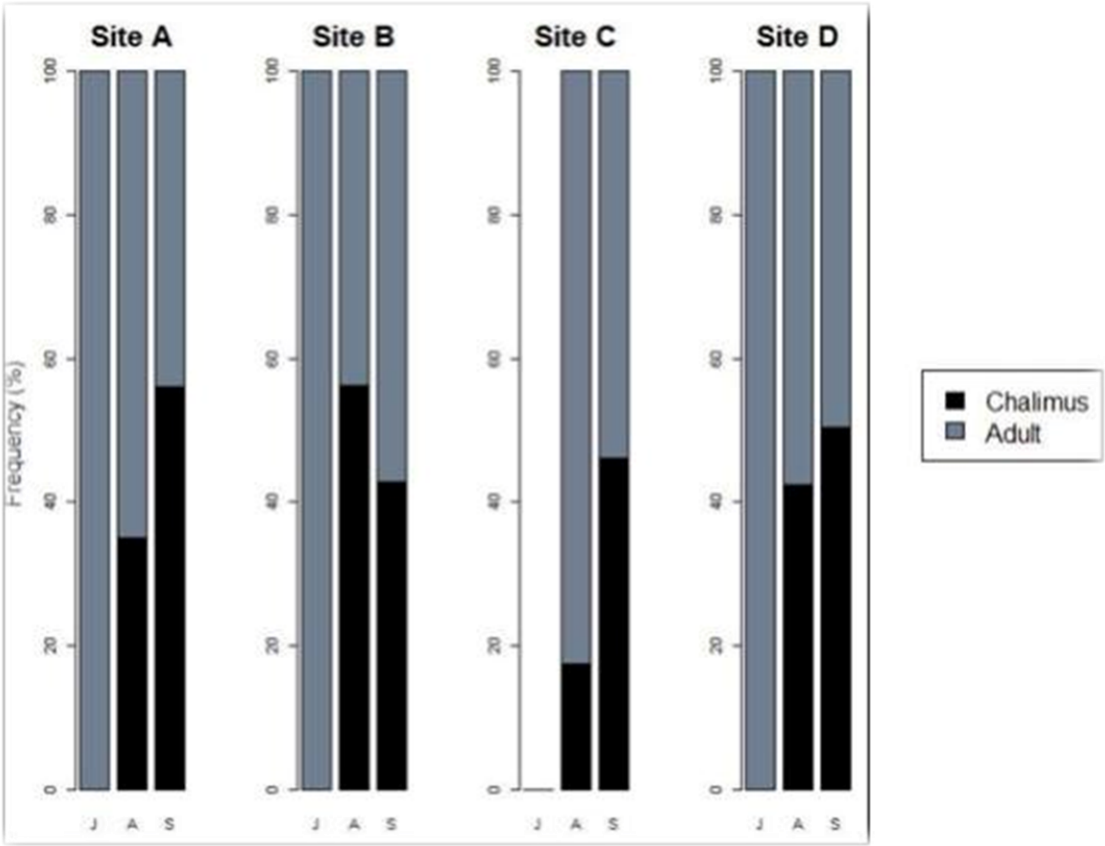

***Figure 24**: Summary of the frequency of lice, per month and between sites. Grey is adult and black is chalimus. The three columns show the three sampling months; (J) June, (A) August and (S) September. (Source: Author)*

The mean lice number per fish of each life cycle stage is summarized below for *C. elongatus* **(Figure 25)**, as it accounted for the majority of the sea lice collected. The mean number per fish has been calculated for the three sampling months, and for all four of the sites. The sea lice life cycle stage with the highest mean for both August and September was chalimus 4, while in July the life cycle stage with the highest mean was adult female. The mean number of each life cycle stage per site varied quite considerably, site A and B had high means for chalimus 4, adult male and adult female in August, with chalimus 4 being the highest. This was similar in September, however the mean for site B decreased by roughly half for chalimus 4 and adult male, but remained comparably consistent for adult female. Site C is observed to have lower means than all other sites, over all three sampling months. Site D is observed to have higher means than C, but lower than A and B in August, and lower than A and higher than B in September. The highest observed mean for a life cycle stage for site D is adult female in July, adult male in August and adult female and chalimus 4 in September.

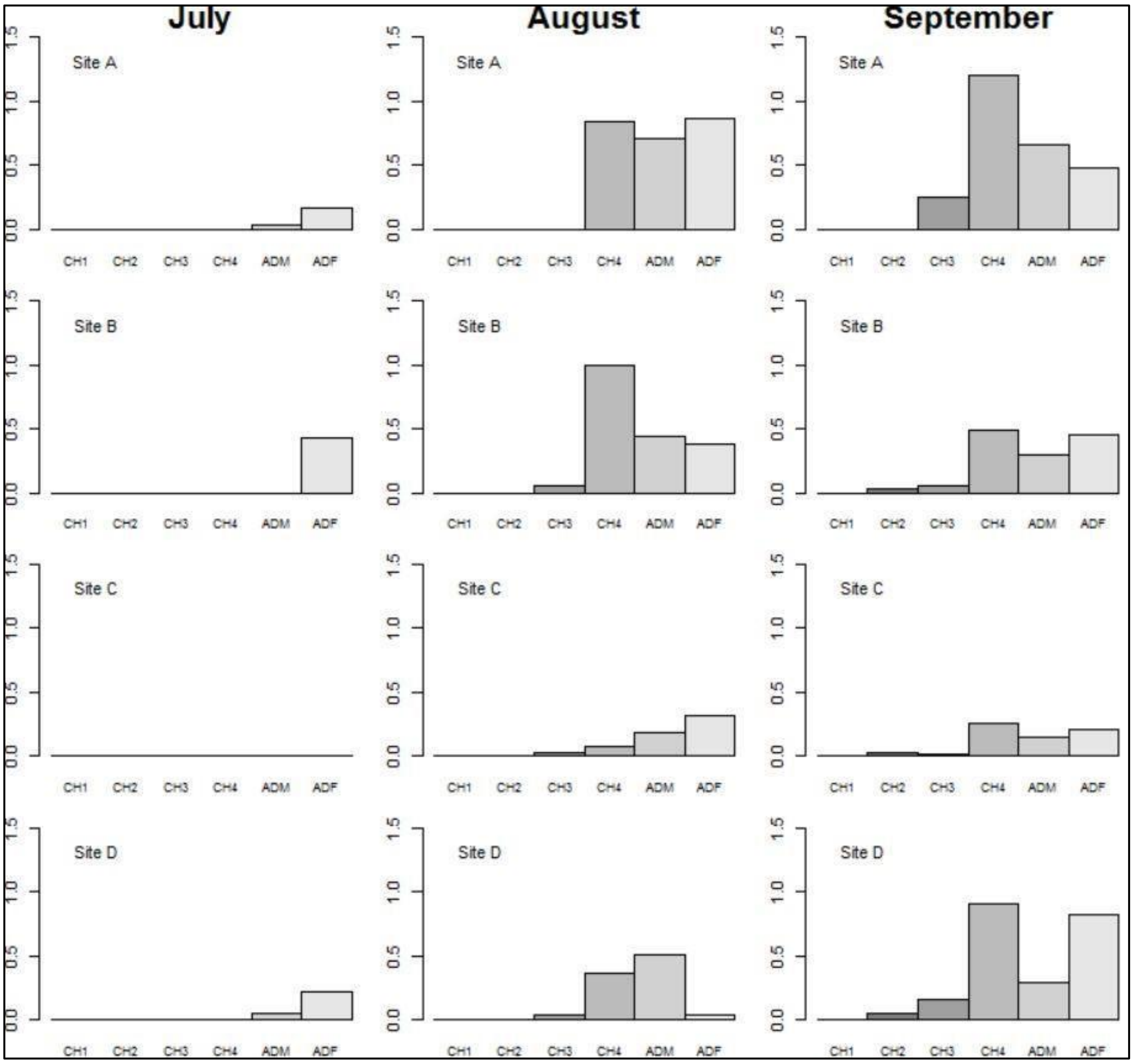

Figure 25*: Summary of mean number per fish of each life cycle per month, values given per site. Only Caligus elongatus are summarized as Lepeophtheirus salmonis only accounts for 7 out of 731 lice. (CH1) chalimus 1, (CH2) chalimus 2, (CH3) chalimus 3, (CH4) chalimus 4, (ADM) adult male and (ADF) adult female. (Source: Author)*

A first Kruskal-Wallis test was done, for the three sampling months, with all the sites included. The significance level was set at p-value < 0.05, therefore if the value is lower than 0.05 a statistical significance is observed. July is highly insignificant with a p-value of 0.75. August however, has a p-value smaller than 0.0001 and is therefore highly significant. September is also highly significant with a p-value of 0.0001 observed again. Therefore, August and September represent a significant result; meaning that differences in sea lice loads for the three sampling months, between the four sites, have to be recognized as valid.

A second Kruskal-Wallis test was done, between the three sampling months, with all sites included. The significance level was set at p-value < 0.05, therefore if the value is lower than 0.05 a statistical significance is observed. There is a p-value lower than 0.0001 therefore, there are highly significant differences. There is a significant difference in lice abundance between the months of July and August (p-value < 0.0001), there is also a significant difference in lice abundance between July and September (p-value < 0.0001). There is however, no significant difference in lice abundance between August and September (p-value = 0.57). Therefore, a significant result is represented; meaning that differences in sea lice loads, between July and both August and September, have to be recognized as valid.

A third Kruskal-Wallis test was done between the four sites, with July, August and September included. The significance level was set at p-value < 0.05, therefore if the value is lower than 0.05 a statistical significance is observed. For all comparisons in July, p-values were higher than 0.3; representing a non-significant result. August lice loads are significantly different between site A and B vs. C and D, with site A and B having higher lice levels than site C and D. The p-values for these comparisons were all lower than 0.0001, representing a high significance. September sea lice loads are significantly different between site A vs. B and C. The p-value for the comparison of site A and B being lower than 0.001 and the p-value for the comparison of site A and C being lower than 0.0001; both representing a high significance. September sea lice loads are also significantly different between site D vs. C, with site D sea lice loads being significantly higher than site C (p-value < 0.0001). Significant p-values were also found for the comparison between site B and C (p-value < 0.05) and site B and D (p-value < 0.01). Therefore, test results between the four sites, with August and September included, represent a significant result. This means that differences in sea lice loads between the four sites have to be recognized as valid.

The damages to the fish are summarized in **Table 7** for all fish throughout the entire study. There were 223 damages in total, with body damage accounting for the highest amount with 165, followed by pectoral fins with 137 and pelvic fins, caudal fins and lice damage with 46, 40 and 73 respectively. There were 27 accounts of sea lice damage without sea lice being present on the fish. These results include multiple damages occurring on a single fish.

***Table 7**: Summary of damages to fish over the course of the entire study, values given per area damaged as well as damage specifically from sea lice. (Source: Author)*

	Damages
Pelvic Fin	46
Pectoral Fin	137
Caudal Fin	40
Body	165
From Lice	73
Total	223

The average length and weight of the fish are summarized in **Table 8** for the three sampling months. July had the smallest average length and weight with 19.98 cm and 78.21g respectively. The length and weight increased throughout the study months, in August the length and weight increased to 20.76 cm and 83.08g respectively. September had the largest increase in length and weight to 21.24 cm and 103.9g.

***Table 8**: Summary of average length and weight of sentinel cage fish with values for the 3 months of the research study.(Source: Author)*

	Average Length (cm)	Average Weight (g)
July	19.98	78.21
August	20.76	83.08
September	21.24	103.91

***Table 9**: Salinity and temperature measurements conducted at the 4 sampling locations on October 24th, 2014 (Source: Author).*

Site	Name	Latitude	Longitude	Depth (m)	Salinity (psu)	Temperature (°C)
A	Fossfjordur	65°36'94	23°33'39	0.1	34.0	7.6
A	Fossfjordur			1	34.0	7.9
A	Fossfjordur			2	34.1	8.1
A	Fossfjordur			3	34.1	8.2
A	Fossfjordur			4	34.1	8.2
A	Fossfjordur			5	34.1	8.2
B	Hjalli	65°39'06	23°32'49	0.1	34.1	7.8
B	Hjalli			1	34.2	7.9
B	Hjalli			2	34.1	7.9
B	Hjalli			3	34.1	7.9
B	Hjalli			4	34.1	7.9
B	Hjalli			5	34.1	7.9
C	Haganes	65°41'08	23°34'64	0.1	34.0	7.4
C	Haganes			1	34.0	7.5
C	Haganes			2	34.1	7.6
C	Haganes			3	34.1	7.6
C	Haganes			4	34.1	7.7
C	Haganes			5	34.1	7.8
D	Trostansfjordur	65°37'63	23°34'87	0.1	33.9	7.4
D	Trostansfjordur			1	34.1	7.9
D	Trostansfjordur			2	34.1	8.1
D	Trostansfjordur			3	34.1	8.2
D	Trostansfjordur			4	34.1	8.2
D	Trostansfjordur			5	34.1	8.1

Temperature and salinity both rose with an increase in depth. The salinity is consistent throughout all sites at 34.1 psu; however, it shows slight variation within the first meter of the water column. Temperature is consistent throughout all sites, with the biggest difference recorded at a depth of 3 m for site A and C with a temperature of 8.2 and 7.6 respectively **(Table 9).**

5 Discussion

5.1 Sea Lice Assessment

One of the main points for discussion important to this study, is based on the abundance of sea lice found on the sentinel cage smolts. Sea lice abundance, which is the average number of lice per sampled fish, was found to be substantially higher for both August and September than for July, when all sites are considered (**Table 5**). These abundance observations are comparable to the results from the second Kruskal-Wallis tests done, which analyzed between months with all sites considered; whereby there is a significant difference between July and August and July and September but not between August and September. Therefore, this specific Kruskal-Wallis test corroborates the result from the abundance observations allowing for a more founded discussion.

These results may signify that the abundance of sea lice in the water column is substantially higher during the months of August and September, as they are able to complete life cycle development more quickly in warmer waters (Johnson & Albright, 1991; Costello, 2006); as higher average temperatures will result in shorter generation times and an increase in sea lice abundance. Further, it has been observed in several studies that hatching time substantially decreases in temperatures below 10 ºC (Boxaspen & Naess, 2000). This is particularly important, as during this study average sea surface temperatures changed quite quickly between June and the end of October. In July, temperatures were consistently below 10 ºC; however, they were increasing continuously from the beginning of June so that by August and September sea surface temperatures did rise above 10 ºC, staying above or within this range until the end of September when it dropped quite steadily below 10 ºC to 7 ºC (Figure 10).

However, a second possibility is that these results may also be, in part, skewed by the death rates of sentinel cage Atlantic salmon smolts. As most of the fish died during the first sampling period, there were less available fish for exposure and sampling; potentially having an impact on the abundance recorded. Similar sentinel cage studies were conducted in Scotland (Salama et al., 2013) and Norway (Bjørn et al., 2011) mortality having been observed in the former; with one in ten cages being lost and one in ten cages having experienced complete mortality, attributed to severe winds. A research study by Jackson et al. (2012) also attempted to assess the mortality observed in various types of sentinel cages. Therefore, it is not uncommon for death rates to be considered when using sentinel cage sampling of sea lice abundance in the water column. The death rates could be suggested to have skewed the observation towards there being higher abundance observed in August and September, due to the higher death rates for the month of July with a value of 0.82 out of 1.

This possibility of death rate influencing abundance measurements is challenged by the fact that August if all sites are considered, had a lower death rate than September, yet a lower abundance of sea lice as well. If based on the assumption of increased death rate resulting in decreased abundance, September should have had a lower abundance than August. However, the sea surface temperature may provide an answer for this issue with death rate being the main influence for abundance differences. Temperatures continually increased from June onwards with August having the highest sea surface temperatures; therefore, sea lice production and generation times would have increased in number and speed as temperatures warmed. With cold June temperatures leading to minimal lice abundance in July, warmer July temperatures leading to a more substantial increase in lice abundance in August, and peak August temperatures leading to an even more substantial increase in lice abundance for September. It is important to note that mean lice abundance in August and September were very close with 1.6 and 1.71 respectively, which was also observed in temperature with only a roughly 1 ºC difference between the two months.

The mean lice abundance between months was considered above, with the important aspect for possibilities influencing the abundance of sea lice in the water column having been addressed. When the mean lice abundance between sites is considered however, these possible influencing factors are not of any substantial concern. As although it is possible to suggest death rates may have had an impact on the abundances recorded per month; this is not the case for between sites, as death rates were relatively similar throughout the sites, if all months are considered, and especially if only August and September are considered. This is suggested to be the same for sea surface temperature, as the four sites throughout the fjord are recorded to experience relatively similar temperatures.

It can therefore be suggested, that the results from abundance values per site, as well as the frequency per site, should be considered as a viable assessment of the site with the highest sea lice occurring within the water column. According to the results in **Table 5,** this puts sites A and B into focus as they had the highest abundance.

The highest abundance being found at site A and B is of considerable importance for the purpose of this study, as they are the two sites located closest to the two aquaculture farms and are designated as the medium and high exposure sites corresponding to site B and A respectively. This could correspond to several other studies done in Ireland, Scotland and Norway, which suggest that the increase in concentration of hosts from salmon farms has increased lice abundance in the waters adjacent to these farms (e.g. Butler, 2002; Gargan et al., 2003; Heuch & Mo, 2001; Tully, Gargan, Poole, & Whelan, 1999).

However, although the highest average abundance corresponds to the two sites located in closest proximity to salmon farms, this may not be the result of the increased abundance based on increased host availability. This is due the suggestion that limited production will not satisfy a substantial increase in host availability and subsequent sea lice production. This has been used to explain the lack of sea lice problems on salmonids in countries with production less than 8000 tonnes (Costello, 2009b). From this study, the suggestion of a correlation between results of a high abundance nearest the salmon farms is also challenged by the fact that the second highest average abundance, within sites for the three sampling months, is observed to be site D, the control site for this study, with a value of 2.23 and is the third overall highest average abundance with a value of 1.19.

Although this information is important for the consideration of sea lice abundance in relation to salmon farms, it must also be noted that this is the first year of sampling as well as the first cycle of production of salmonids within this fjord. It has been suggested from several research studies that farms are only substantial sources of sea lice abundance at certain times in the production cycle (Penston et al., 2008) with the beginning of the production experiencing relatively minimal sea lice abundance as the fish are stocked sea lice free. This changes however, during the second year of the production cycle; as several research studies have also shown that the abundance of sea lice on farms is typically higher in the second year of production (Lees, Gettinby, & Revie, 2008; Revie, Gettinby, Treasurer, Rae, & Clark, 2002).

This can also be observed in the sea lice count data from both the Fjarðalax and Arnarlax farms located in the fjord; summarized in **Table 1** and **2.** The data suggests that lice abundance on the farms has not reached a level of concern. Fjarðalax has only 8 lice which were recorded in August out of 36 sampled fish and 45 lice which recorded in September out of 24 sampled fish. Arnarlax has only 1 lice which was recorded in July and August out of 25 and 17 respective sampled fish, 11 lice which were recorded in September out of 20 sampled fish and 30 lice which were recorded in October out of 20 sampled fish. These numbers are substantially lower than lice levels which, under regulation, prompt treatment in salmonid aquaculture regions such as Norway (Finstad et al., 2011).

Another main point of discussion, is the abundance of certain life cycles throughout the three sampling periods and also between sites over the three sampling periods. One of the first things is that for July only adult sea lice were found, which may be attributed to longer generation times resulting in prolonged sexual development and inability of the lice to complete a full cycle due to the lower sea surface temperatures (Johnson & Albright 1991). The fact that only adult sea lice were found means that lice attached immediately following placement in the sentinel cages at sea; developing into adult stage during the 21 day sample period. This also means that the sea lice were unable to complete a full generation cycle during that time, as no sea lice life cycle other than adult were collected. If a complete generation cycle occurred, there would expect to be nauplius or early stage chalimus sea lice found. This therefore, supports the suggestion of longer generation times resulting in prolonged sexual development and inability of the sea lice to complete a full life cycle (Johnson & Albright, 1991).

The abundance changes in August and September however, with a general decrease in adult sea lice and increase in chalimus occurring. A change like that could be attributed to a rise in sea surface temperatures leading to an increase in initial reproduction with a shorter reproduction time (Costello, 2006). This would in turn lead to a rise in individuals able to reproduce in the water column. Abundance of certain life cycle stages also differs between the four sites over the sampling periods, with many different stages being present at certain sites or sampling periods but only few stages being present at others. Due to those differences, the mean abundances per life cycle stage vary between sites and sampling periods. As this mechanism could also be influenced by the differences in death rates, it will not be considered for further analysis in this study.

A final point of discussion, for this section, is the very high proportion of C.elongatus found versus the few *L. salmonis* found. *C. elongatus* is almost the entirety of the sample collected, accounting for 97 percent and *L. salmonis* only accounting for 0.01 percent with the rest unidentified. This could suggest that no impact has been observed from the salmon farm activity as once sea lice development has progressed on salmonid farms. *L. salmonis* usually dominates over *C. elongatus* (McKenzie, Gettinby, McCart & Revie., 2004). This could however, be part of a normal succession as infestations on salmonid farms typically begin with *C. elongatus* which are later to be replaced by *L. salmonis* which then will continue to be the dominant species observed (McKenzie et al., 2004).

This is also observable from the Fjarðalax and Arnarlax sea lice count data, summarized in **Table 1** and **2**. Fjarðalax recorded only one *L. salmonis* sea lice out of 53 total; this was an adult male recorded in September. The remaining 52 sea lice recorded were *C. elongatus*; however, no distinction between life cycle stage or sex is made. Arnarlax recorded only three *L. salmonis* out of 43 total; these were two chalimus I-IV recorded in August and October and one adult female recorded in July. The remaining 40 sea lice recorded were *C. elongatus*; however, no distinction between life cycle stage or sex is made. Arnarlax does however, distinguish between life cycle stage for L. salmonis; identifying chalimus I-IV, pre-adult and adult. This sea lice count data from Fjarðalax and Arnarlax reflects the results from the sentinel cage sampling data from this study; *C. elongatus* are the dominant species, observed in substantially higher proportion than *L. salmonis*.

It can be suggested from this sentinel cage study observations that the abundance or prominence of sea lice in the surface current of Arnarfjörður is low, especially if the most parasitic *L. salmonis* species is considered, with only 7 lice being found over a three months sampling period and out of the 731 Atlantic salmon smolts which survived and were analyzed. It is important to note however that although the abundance was low, that the relative abundance to *L. salmonis* of *C. elongatus* with 710 of the latter observed may suggest some potential increase in the future. As mentioned above, *C. elongatus* will typically be the first sea lice found on salmonid farms, but it will later be replaced by *L. salmonis* (McKenzie et al., 2004). This may therefore, be an initial observation of an abundance in sea lice developing in this region; however, it may also be the natural sea lice load as both species are naturally occurring in the wild (Penston et al., 2008; Urquhart et al., 2008). Future research will need to be conducted to collect more data and address this further, some suggestions will be given later in this paper.

5.2 Hydrodynamic model feasibility

The sentinel cage sampling method for sea lice has been used in many other studies, which attempted to assess the prominence of sea lice in the water column; as well as various studies, which used sentinel cages sampling as a validation method for hydrodynamic modelling projections. Bjørn et al. (2011) used sentinel cage sampling, as well as gill-netting, to assess the differences in infection pressure throughout a Norwegian fjord. For this section of the study, particular reference should be given to the study of Salama et al. (2013); which used sentinel cage sampling, as well as plankton trawls, to validate a biophysical sea lice dispersal model for a loch in Scotland.

Various types of hydrodynamic models were mentioned throughout this paper, and for the purpose of assessing the feasibility of using a hydrodynamic model in Arnarfjörður Iceland the inputs necessary for running such a model need to be considered. Although it may vary slightly between models, typically a few key data inputs are needed. The key data inputs are wind, freshwater runoff, currents, atmospheric data, sea temperature, tides and bathymetry (Asplin et al., 2014; Gillibrand & Willis, 2007). As a matter of feasibility, some of these input data requirements are available online through various Icelandic resources, or through contact with the Meteorological Office of Iceland or the Marine Research Institute of Iceland.

Specific data which is easily accessible is atmospheric data, wind, tides, sea temperature and bathymetry. This information is from different areas within Arnarfjörður or off of the sea-ward coast of Arnarfjörður; something which should be considered for the validity of the hydrodynamic model. Air temperature data, summarized in **Figure 6**, should be considered as valid. This data comes from a weather station located in Bildudalur, within Arnarfjörður; and is easily accessible both online and by contacting the Icelandic office of Vegagerdin directly. Although this data is not one of the key inputs for hydrodynamic modelling, it may add another dimension of validation for the rest of the inputs.

Wind data, summarized in **Figure 7** and **8**, should be considered as highly useful for hydrodynamic modelling; as well as a valid source of both wind speed and wind direction data. This data also comes from the weather station located in Bìldudalur, within Arnarfjörður; and is easily accessible both online and by contacting the Icelandic office of Vegagerdin directly. This data is one of the key inputs for hydrodynamic modelling; it would be easily accessible up-to-date data, freely available for use in a hydrodynamic model.

Tide data, summarized in **Figure 9**, should be considered as highly useful for hydrodynamic modelling; however, validity of the data is dependent on the location of tidal measurements. This data comes from the outer sea-ward area of Arnarfjörður. Therefore, it is from within the fjord; however, tidal data from further in Arnarfjörður would be better when considering using the data for a hydrodynamic model.

Sea temperature data, summarized in **Figure 10**, should be considered as highly useful for hydrodynamic modelling; as well as a valid source of data. This data comes from the Fjarðalax aquaculture farm, and therefore is easily accessible for the company; however, this data may be more difficult to access for someone trying to independently use it for a hydrodynamic model. This data is therefore a good beginning point for sea temperature data access; however, ideally the data would be from various regions and depths throughout Arnarfjörður. A more valuable source of sea water temperature data would be if a continuation of measurements were taken from the sentinel cage monitoring, summarized in **Table 9**. These measurements provide data from various regions throughout Arnarfjörður; at various depths, ideally occurring once a month.

There is also a hydrodynamic model which is already privately available for Iceland. This can be accessed in cooperation with the University of Iceland; however, it is not free to access and therefore the feasibility will depend on the need for the model and if it outweighs the expense. The model does provide a prediction of temperature, salinity, flow and mixing with a 1 km resolution and 2.5 vertical resolution; which could be highly valuable for modelling sea lice movement in surface currents in Arnarfjörður. This is especially valuable when coupled with a particle transport model (Gillibrand & Willis, 2007) or a more precise salmon lice growth and advection model (Asplin et al., 2014). One key data input that is missing is freshwater runoff, which was not accessible for this fjord. This could however, be due to the fact that there are a couple of rivers within the fjord and they are only quite small.

Feasibility by means of access to data, is therefore suggested to be quite high. The validity of the data however, will depend on its positioning near or within Arnarfjörður. If cooperation is considered with the University of Iceland, than development of a hydrodynamic model for the fjord would be possible; within a relatively short time-frame. Also, it would provide the basis for modelling the dispersal of sea lice throughout the fjord. Feasibility is therefore needed to be considered; between the need for the model and the expenses, both of resources and financially.

It can be suggested, based on this study, that sea lice are not observed to be a serious problem within Arnarfjörður. This however, is only the first year of production; so an increase in sea lice at this point would not be typically observed, especially considering there are only two farms in operation with approximately 500 thousand and 1 million fish stocked which is roughly 4500 tonnes in total production. The lack of sea lice can change however, as is typically observed with the second year of production; leading to an increase of sea lice in the water column (Lees et al., 2008; Revie et al., 2002). Therefore, expending resources within these first couple of years may be extremely valuable in assessing the abundance of sea lice; as well as the dispersal of sea lice throughout Arnarfjörður. In most countries with salmonid aquaculture, sea lice epidemics occurred prior to hydrodynamic modelling being done. Modelling is now used to assess the sea lice dispersal and abundance, in order to provide information on high risk areas and high risk times of the year so treatment can be applied (Adams, Black, MacIntyre, MacIntyre, & Dean, 2012; Salama & Murray, 2011; Salama et al., 2013). If hydrodynamic modelling is done in Arnarfjörður, it is possible that the aquaculture companies will be able to have high risk areas identified before epidemics are common (Salama et al., 2013). This would allow for the use of management measures which are alternative to chemical treatment; which is most commonly needed in salmonid aquaculture regions, once epidemics have occurred (Revie, Gettinby, & Wallace, 2003).

6 Future research and management

When considering future research, sentinel cage sampling is of high importance. Sentinel cage sampling should be continued throughout the years, as this study has recorded a baseline for the abundance of sea lice within areas of Arnarfjörður, before salmonid production has substantially developed. Gill-net sampling of the abundance of sea lice on the wild population within Arnarfjörður was done at the same time and in the same areas, this should also be continued as it has also recorded a baseline for sea lice abundance and level of infection. If these data is recorded, continuously from the first production cycle throughout the life of the aquaculture farm, it allows for development of management, especially if coupled with the use of a hydrodynamic model and a variation of a biological model. Hydrodynamic modelling has been a key tool in sea lice management, providing a quite accurate prediction of critical sites or areas within a fjord with substantial aquaculture development (Salama & Murray, 2011; Salama et al., 2013). This is of particular importance for placement of cages and distance between farms, as it is possible to assess the dispersal and movement away from farms as well as between them.

When management is considered, there are various other measures which need to be discussed. These management measures fit into two categories, pre-infestation and post-infestation. Pre-infestation management measures are particularly important for this study; based on the suggestion that the sea lice abundance in Arnarfjörður is low and if the production of 7500 tonnes, distributed over three years, is considered; sea lice might not reach the abundance needed for epidemics to occur within the fjord (Costello, 2009a). In this case, only a few key research and management tools would be needed, focused on monitoring or evaluating the sea lice abundance and pre-emptive actions such as fallowing and single-year production (Penston et al., 2008; Salama et al., 2013).

Continued monitoring should be done as a pre-emptive monitoring measure. This can be through sentinel cage or gill-net sampling, as mentioned above. However, it could also include monitoring which is done at the aquaculture farms themselves. This type of monitoring is currently in practice; however, this is typically only done once a month. Therefore, future management should consider increasing this aquaculture farm monitoring to being more frequently done. Ideally, Icelandic aquaculture farms should attempt to reach the same monitoring levels as for sea lice counting in Norway. Aquaculture farm monitoring in Norway takes place weekly, with twenty-five fish counted per six cages (Salama et al., 2011).

Another pre-emptive monitoring measure which should be done is fallowing of the aquaculture farm sites. This practice is common in the majority of aquaculture production regions; with fallowing periods needed to be at a minimum between 4-6 weeks to break the production cycle of sea lice (Costello, 2006). In Iceland, the typical fallowing period minimum is much higher than this; with salmonid farms in Arnarfjörður having a minimum fallowing period of roughly nine months (Jón Örn Pálsson, personal communication, April 7, 2015).

A final pre-emptive management measure which should be considered, is a single-year production cycle regime. This type of production cycle regime is thought to be an effective management measure as it minimizes transmission of sea lice to hosts; as well as the impact of sea lice to the aquaculture farms (Salama et al., 2013). In many salmonid aquaculture regions a two year production cycle is common practice; as is the case in many farms in Scotland (Salama et al., 2011). In Iceland, a two year production regime is currently practiced in some areas; such as Arnarfjörður (Jón Örn Pálsson, personal communication, April 7, 2015). A two-year production regime may lead to an increase in lice levels on the farms following the first-year of the production. Therefore, a single-year production may be a viable option for deterring any initial infestation on the farms in Arnarfjörður.

Post-infestation measures are generally of high importance for most salmonid aquaculture regions. Most concerning, in regions where salmonid aquaculture does continue to develop, and reaches production above the suggested 8000 tonnes a year threshold (Costello, 2009b). In this case, post-infestation management measures will need to be implemented. Ideally, an integrated management approach would be used; combining monitoring with fallowing and chemical treatments or some other form of control such as cleaner fish (Torrissen et al., 2013).

There is another post-infestation management measures which should be considered. Specifically, the use of coordinated management between aquaculture farms within a fjord system. Distance between farms is known to affect the level of sea lice within a fjord system (Serra-Llinares et al., 2013). For this reason, some salmonid aquaculture regions with sea lice infestation problems have developed coordinated management practices amongst the farms within a fjord system. Using coordinated management, as a future management practice, is of particular interest for the salmon aquaculture farms. If Arnarfjörður is to reach post-infestation levels of sea lice, then coordination between the two salmon aquaculture farms will be key; due to their location and distance between them. Coordinated management can be done in different manners; however, in Scotland Farm Management Areas (FMAs) have been successful. This was done by outlining a Code of Good Practice and subsequent management practices to be done for all farms in the FMAs (Salama et al., 2013). Also successful, are Disease Management Areas (DMAs); important for the management of diseases which are of concern when dispersed (Salama et al., 2013). Therefore, if the aquaculture farms within Arnarfjörður could develop a coordinated management plan; the ability to protect the farms against sea lice infestation may be increased substantially. It is important to note, that integrated management and coordinated management could be used simultaneously; allowing for a more efficient management of sea lice within Arnarfjörður.

7 Conclusions

This study has provided a base-line for the assessment of sea lice abundance within Arnarfjörður, in the Westfjords of Iceland. It can be suggested that the prominence of sea lice is low, especially if the species *L. salmonis* is considered. Two areas have been observed to have the highest abundance of sea lice; these two areas are representative of the medium and high exposure sites and are located closest to the aquaculture farm. Various reasons have been suggested as to why this is the case; challenging the link between abundance and location to the farm sites. If production remains at its current level, the fjord and the aquaculture companies may not be faced with the threat of sea lice epidemics; as low production areas have not been observed to experience high sea lice abundance. However, if salmonid aquaculture does continue to develop and increase the production within the fjord; the risk of sea lice epidemics will increase, as well as the need for monitoring and management. The feasibility of applying a hydrodynamic model and a biological model to this fjord has been discussed; its feasibility would increase, relative to the increase in need to identify and predict high risk areas to farms. Research studies such as sentinel cage sampling and gill-net sampling, evaluating the abundance of sea lice or infestation rate within a fjord; coupled with hydrodynamic and biological particle modelling, are key tools which can be used to monitor the impact from sea lice and the potential risks which may develop in the future.

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