Methods to reduce sea lice infestations on farmed salmonids in Ireland.

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Submission for Master of Science by Publication

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Foras na Mara
Marine Institute

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This thesis is dedicated to Carmel McCarney, for all her support and encouragement over the years.

Science is simply the word we use to describe a method of organising our curiosity.

– Tim Minchin

Research is what I'm doing when I don't know what I'm doing.

– Wernher von Braun

Declarations

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I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of M.Sc./ PhD is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ______________________ Candidate

ID No. _____ G00164552__________

Date: ________11/10/2018________

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Statement 1. Author contribution to the paper:

O'Donohoe, Pauline, & Tom McDermott. "Reducing sea lice re-infestation risk from harvest water at a salmon farm site in Ireland using a bespoke sieving and filtration system." *Aquacultural Engineering* 60 (2014): 73-76.

This study forms one of two themes presented in Chapter 2 of this thesis. Pauline O'Donohoe from the Marine Institute conceived this study and assisted by with Tom Mc Dermott of the Marine Institute carried out the field sampling. Pauline O'Donohoe drafted the full manuscript including all text figures and tables.

I agree with the above statement: Signed: Tom Mc Dermott

Name: TOM MC DERMOTT

Statement 2. Author contribution to the paper:

O'Donohoe, P., Kane, F., McDermott, T., & D. Jackson. "Sea reared rainbow trout *Oncorhynchus mykiss* need fewer sea lice treatments than farmed Atlantic salmon Salmo salar." Bulletin of the European Association of Fish Pathologists 36.5 (2016): 201-207.

This study forms the second of two themes presented in this thesis (Chapter 3). Pauline O'Donohoe from the Marine Institute conceived this study. Field sampling and data management was undertaken by Pauline O'Donohoe and Frank Kane, Tom Mc Dermott and Dave Jackson of the Marine Institute. Pauline O'Donohoe drafted the full manuscript including all text, figures and tables.

I agree with the above statement: Signed: Tom Mc Dermott

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I agree with the above statement: Signed: Frank Kane.

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I agree with the above statement: Signed: ____________________

Name: DAVID JACKSON

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1. General Introduction

The FAO predicts that an additional 42 million tonnes of farmed seafood will be needed by 2025 to meet the needs of an ever increasing global population. Aquaculture, is considered the fastest growing food-producing sector, and accounts for nearly 50 percent of the global food fish (FAO, 2016). Since 2013 aquaculture has become the main global source of fish for human consumption.

Atlantic salmon is regarded as one of the most successful aquaculture species. Production grew from 12,000 tons in 1980 to over 2.4 million tons in 2011 (Asche *et al*., 2013). The sustainability of the salmon farming industry relies on continued improvements in husbandry practices, veterinary medicines and management systems. The challenge for the salmon farming industry in the future will be to exploit the possibilities in the global market, at the same time keeping environmental impacts at acceptable levels and remaining economically viable. The major environmental challenges are interactions with wild salmon populations through genetic interactions and spread of disease and parasites (Torrissen, *et al*., 2011). One of the main challenges facing the salmon farming industry worldwide is that of sea lice infestation (Asche and Bjorndal, 2011; Nelson *et al.,* 2017). These challenges include the cost of treatments which prove to be increasingly expensive (Liu and Bjelland, 2014; Costello, 2009). Resistance to existing chemotherapeutants is also emerging as a more consistent threat to the predicted efficacy of some the medicines available (Aaen, Helgesen, Bakke, Kaur, & Horsberg, 2015; Jansen *et.al*., 2016). The limited choice of treatments available for use to combat sea lice infestations is a major obstacle for the industry (Lees, *et al*., 2008), particularly when fish are in any way health compromised e.g. in-appetence can render some in-feed treatments inappropriate.

Caligus elongatus Nordmann and *Lepeophtheirus salmonis* Krøyer are the two main species of sea lice are found to infest wild and cultured salmonids in Ireland (Jackson & Minchin, 1992). Commonly known as the 'salmon louse' *L. salmonis* parasitises only salmonids of the genera *Salmo*, *Oncorhynchus* and *Salvelinus* (Susdorf *et al.,* 2017) and is considered to be the more wide-ranging and persistent of the two species (Costello *et el*., 2004). *C. elongatus* has been found to infest more than 80 species of fish and is found in worldwide (Kabata, 1979*)*. *L. salmonis* is larger than *C. elongatus*, because of this size difference it is regarded as the more damaging of the two parasite species, it has also been found to be more prevalent on farmed Atlantic salmon (Jackson and Minchin, 1992; Jackson *et al*., 2005).

Finfish farming began on the west coast Ireland in 1972 (Jackson and Minchin, 1993). Production expanded to the Southwest and Northwest coasts in the early 1980's as harvest tonnages increased. In 2015 production of Atlantic salmon was over 13,000 tonnes (BIM, 2016) from 12 inshore bays along the Atlantic coast from Bantry Bay, County Cork to Lough Swilly, County Donegal. Finfish farming is carried out in three distinct geographical regions of Ireland, namely, the Southwest region (Counties Cork and Kerry. Figure 1), the West (Counties Mayo and Galway. Figure 2) and the Northwest (Co. Donegal. Figure 3). These separate regions are divided from each other with distances of c.160 km separating the Northwest from the West and c.200 km from West to Southwest.

The two main fish species commercially produced in Ireland are the Atlantic salmon *Salmo salar* and sea reared rainbow trout *Oncorhynchus mykiss (*O'Donohoe *et al*., 2017*).* Atlantic salmon is the more widely grown species with 13,116 tonnes being produced in 2015 as compared to sea reared rainbow trout production of 98 tonnes in 2015 (BIM, 2016). Sea reared rainbow trout were no longer farmed in Ireland after 2015 (O'Donohoe *et al.*, 2017).

The marine finfish farming industry has continually been under pressure from various biotic factors such as diseases and parasites including pancreas disease, amoebic gill disease, furunculosis, Infectious pancreatic necrosis virus and salmonid alphavirus. However, improved chemotherapeutants and improved fish husbandry methods have reduced the detrimental effects of these factors and have lessened the environmental and economic impacts of these diseases on the industry. Nevertheless, sea lice infestations have continued to be the most significant and expensive disease to combat to date. It has been estimated that sea lice parasitism resulted in US$436m worth of damages to the Norwegian salmon industry in 2011 (Abolofia *et al*., 2017). The total cost of sea lice control in Ireland was estimated to be €1,289,200 in 2006 (FAO, 2008). Additionally, sea lice infestation can act as a precursor to other infections, cause huge economic losses and can be extremely expensive to control.

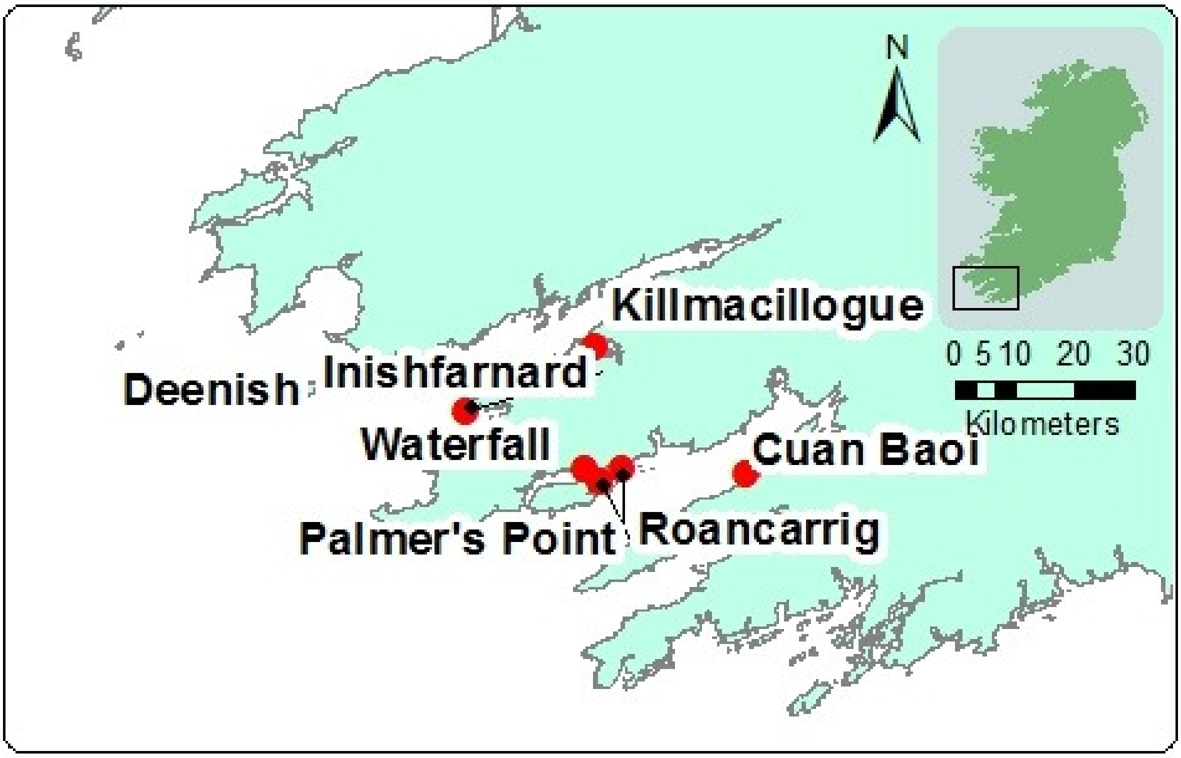


Figure 1. Location of fish farms in the Southwest region.

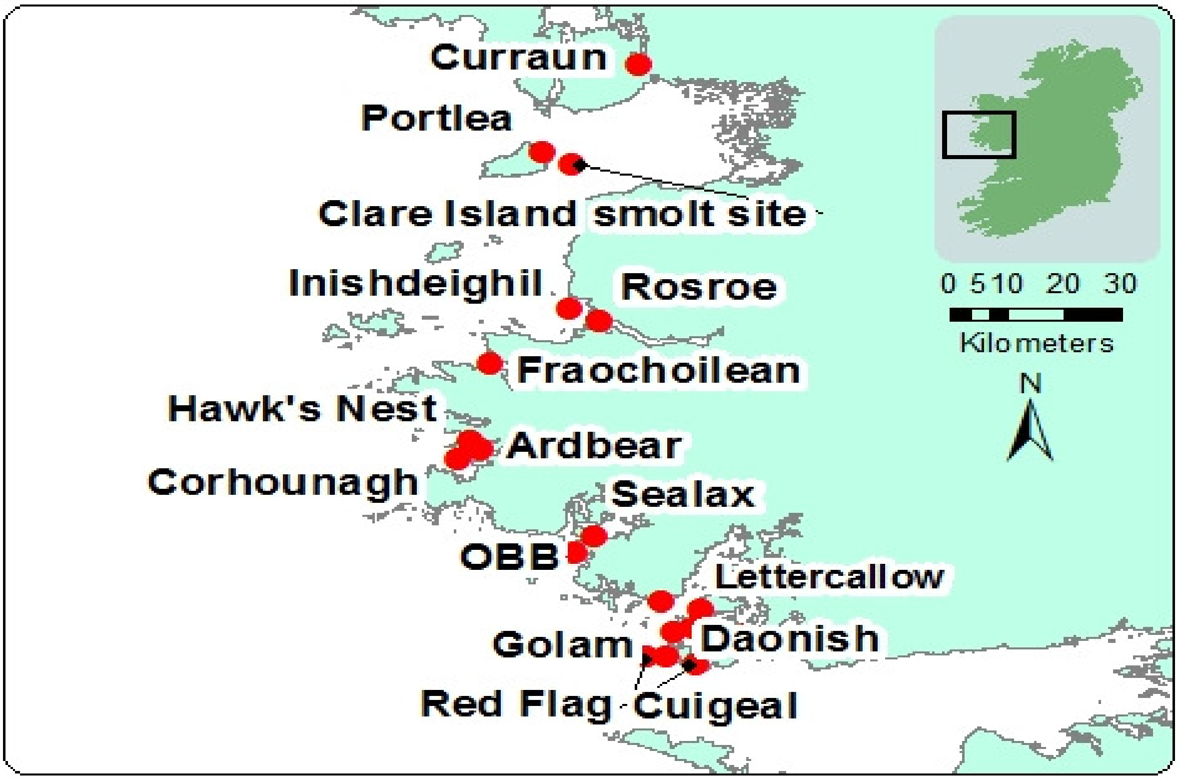


Figure 2. Location of fish farms in the Western region.

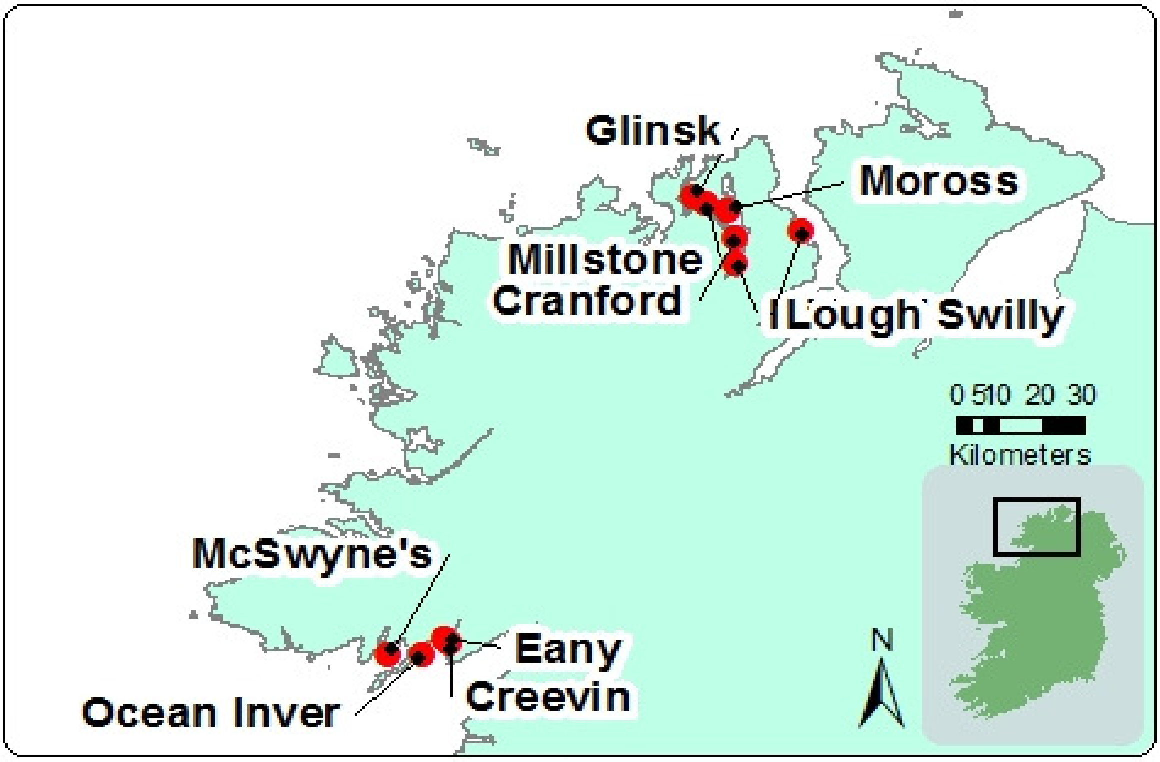


Figure 3. Location of fish farms in Northwest region. (**Maps generated using ArcGIS.**)

1.1 Study Objectives

Many chemotherapeutants and mechanical methods have been developed since the salmonid farming industry began, however sea lice still prove to be the one of the main threats to fish health and to the sustainable expansion of the industry. Significant transmission of sea lice between farmed finfish stocks occurs during handling, grading, treating and harvest of fish. The aim of this thesis is to describe novel methods to reduce sea lice transmission between farmed salmonids in Ireland. Methodology was applied to assess *in situ* physical controls.

Another key issue for finfish farmers is the necessity to use anti-parasitic medicines to combat sea lice infestations. This thesis investigates ways to reduce the reliance on chemotherapeutants through species diversification in the context of sea lice treatment regimens and stocking of production sites, potentially preventing further chemotherapeutant resistance issues and prolonging the efficacy of these products.

Two main themes are presented in this thesis:

1. A bespoke mechanical method of removing sea lice *Lepeophtheirus salmonis* and *Caligus elongatus*, at a harvest line on an Atlantic salmon production site was investigated to assess the effectiveness of a sieving and cartridge filtration system that had not been assessed previously. This novel approach to the reduction of sea lice abundance is designed to prevent the re-infestation of production stock on site during the harvest process. This methodology had not been previously applied to this system and is the only investigation to have been carried out on this novel regime. The objectives were to evaluate the levels of sea lice captured by the

sieving/filtration system, preventing their release back to the receiving water body during the harvest process and thus preventing transmission of sea lice back on the remaining salmon stocks pending harvest.

2. A long term temporal field study of sea lice abundance and sea lice treatment frequency at a fish farm site, which stocked both Atlantic salmon and rainbow trout concurrently, was carried out by the Marine Institute over a period of 14 years, 1999 to 2012 inclusive. Seven year classes of farmed Atlantic salmon and fourteen year classes of rainbow trout were examined. The frequency of sea lice treatments administered to these stocks were also observed. The investigation of this long term data set aimed to compare the inter species treatment regime employed to control sea lice infestation and to assess the implications in the context of husbandry and management approaches. The number of treatments carried out on each stock of fish were compared, while abundance of *L. salmonis* infestation was also assessed for each stock of fish.

1.2 Sea Lice Biology

Sea lice are wide reaching ectoparasites of marine fish species worldwide. It is estimated that these caligid copepods consist of approximately 559 species, which includes 37 genera (Ahyong *et al*., 2011).Two hundred and sixty eight are *Caligus* species (Boxshall, 2011) and 162 are *Lepeophtheirus* species (Chad & Goeff, 2011).

The impacts of infestation by these parasites can induce stress; create a reduced immune-response; cause inappetence and lead to animal welfare issues. The mechanical damage to the epidermis of the fish occurs during attachment and feeding (Kabata, 1979; Jones *et al*., 1990). Heavy infestations have been found to cause severe erosion around the head (Pike, 1989; Berland, 1993) because of the rich supply of mucus secreted by mucous-cell lined ducts in the head region (Nolan *et al*., 1999). Inflammatory responses and hyperplasia, which is enlargement caused by an abnormal increase in the number of cells in an organ or tissue and increases in stress hormones have been recorded in Atlantic salmon in response to infections with *L. salmonis* (Jones *et al*., 1990; Jonsdottir *et al*., 1992; Nolan *et al*., 2000). These responses can lead to an increased susceptibility to infectious diseases (MacKinnon, 1998). Heavy infestations of *L. salmonis* were found to cause fish mortalities in both laboratory and field studies carried out on hatchery-reared 1-year-old Atlantic salmon post-smolts (*Salmo salar* L.*)* in Norway (Finstad *et al*., 2000).

Initial research in to the life cycle of *L. salmonis* found that this parasite moulted through 10 stages to become mature adults (Johnson & Albright, 1991; Schram, 1993). However, Hamre *et al.* in 2013 found that there are only 8 stages (Figure 4), with no distinct moults occurring between the chalimus I and chalimus II stages, and chalimus III and chalimus IV stages. The life cycle therefore is made up of nauplius I and II, copepodid, chalimus I and II, preadult I and 2 and the adult stages (Figure 5). The nauplius I stage is planktonic having hatched from paired egg-strings. A moult takes place to develop to nauplius II, which is also planktonic, this stage is then followed by the copepodid stage, this infective stage seeks to find a host for attachment. The attached chalimus stages follow the copepodid stage. The chalimus then mature to the pre-adult phase. Two pre-adult stages exist before maturing to the adult phase. Adult females produce a number of batches of paired egg-strings, which hatch into the water column to produce the next generation of *L. salmonis* (Kabata, 1979; Schram, 1993). *L. salmonis* has a single host in its lifecycle and targets salmonid species only. Adult females achieve average lengths of 8mm-11mm and an adult male grows to mean lengths of 5mm-6mm (Schram, 1993). In adult females the genital complex is fully developed. However, this varies in size with age of female, whereas in younger females the egg-strings are shorter. Adult females are generally dark brown in colour. Adult males are similar in shape to pre-adult males, though the genital complex is fully developed, their colour varies from light to very dark brown. Pre-adults are free moving on the host, the genital complex is under-developed and their mean length ranges from c. 3.6mm to 5.2mm at I and II stages respectively. The chalimus stages are broader and more pear shaped than the copepodid stages, they can be sexually differentiated and they range in length from c. 1.1mm at stage 1 to c. 2.3mm at stage 2. Younger copepodids are free swimming and the older copepodids attach to the host, they are slender and oval-shaped, with a mean length of c. 0.7mm – 0.8mm. Free swimming planktonic nauplius I and II are almost translucent in colour they have a mean length c. 0.5mm – 0.6mm.

Sea water temperature regimes play an important role in the development of sea lice in the marine environment (Figure 6). An increase in water temperature accelerates the development process with the periods between mounts being significantly reduced. Johnson & Albright (1991) found that at 10°C, 40 days was observed for the development of adult males and 52 days for that of adult females on salmon. Sentinel cage studies in Ireland, where salmon smolts were introduced to sea sites that were in close proximity to active fish farms, showed levels of settlement in the order of 1.11 chalimus I per fish at water temperature of 10.4°C, with prevalence ranging from 56 – 71% (Jackson *et al*., 2012) after 21 days.

Sea lice only begin to feed once they attach to their hosts, mucus and epidermal cells of the host fish provide the main dietary requirements for sea lice (Wootten *et al*., 1982). *L. salmonis* are intolerant of low salinities (Pike and Wadsworth, 1999), they thrive on salmonid hosts in the marine environment and survive for only short periods of time once the host enters a river system (Kabata, 1979). In laboratory trials salinities of 29 ppt were found to severely affect the copepodid stage of *L. salmonis* (Bricknell *et al*., 2006). Free living sea lice display photo-tactic diurnal variation, migrating towards the surface in response to day light, with the opposite migration occurring at night time (Heuch *et al*., 1995). Nauplii and copepodids of *L. salmonis* have also been found to react to pressure, they will swim upward to areas of decreased pressure (Heuch *et al*., 1995). Infestation of *L. salmonis* on non-salmonid hosts is considered to be unusual and it is quite likely that hosts other than salmonids do not allow for development and survival (Kabata, 1979). Copepodids display strong activity and directional reactions to salmon conditioned waters (Bailey *et al.,* 2006). Boxaspen (2007) found that in the final stages before infection copepodids “taste” the fish to determine if they are about to settle on the correct host (Boxaspen, 2006)

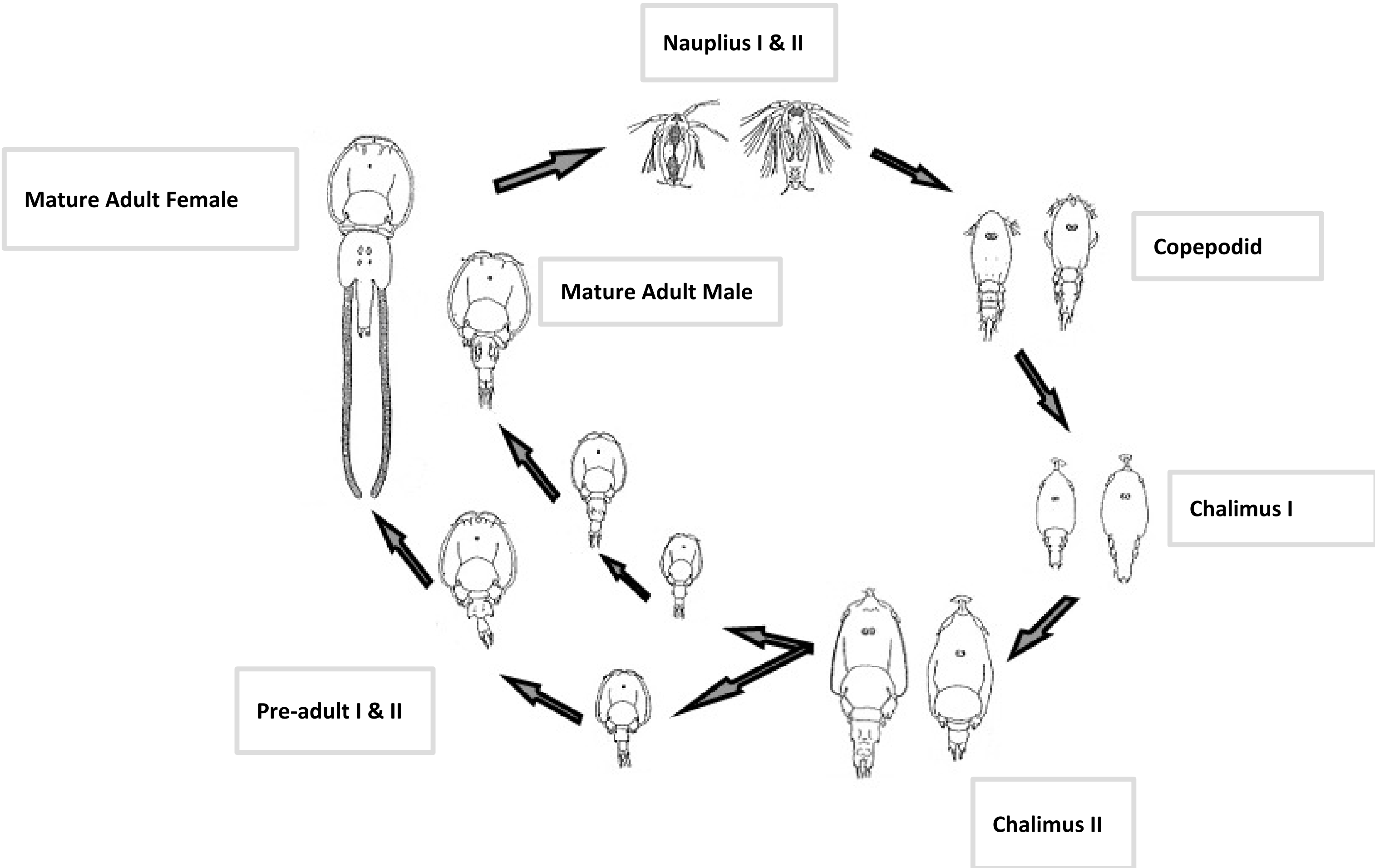
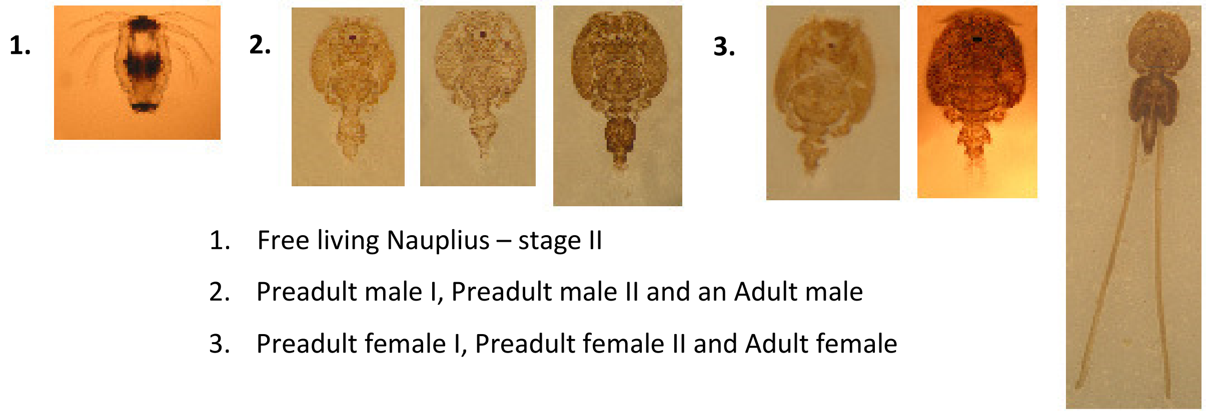


Figure 4. Life cycle of *Lepeophtheirus salmonis*. *(Not to scale).*



1. Free living Nauplius – stage II
2. Preadult male I, Preadult male II and an Adult male
3. Preadult female I, Preadult female II and Adult female

Figure 5 Photographs of *Lepeophtheirus salmonis*. (Not to scale).

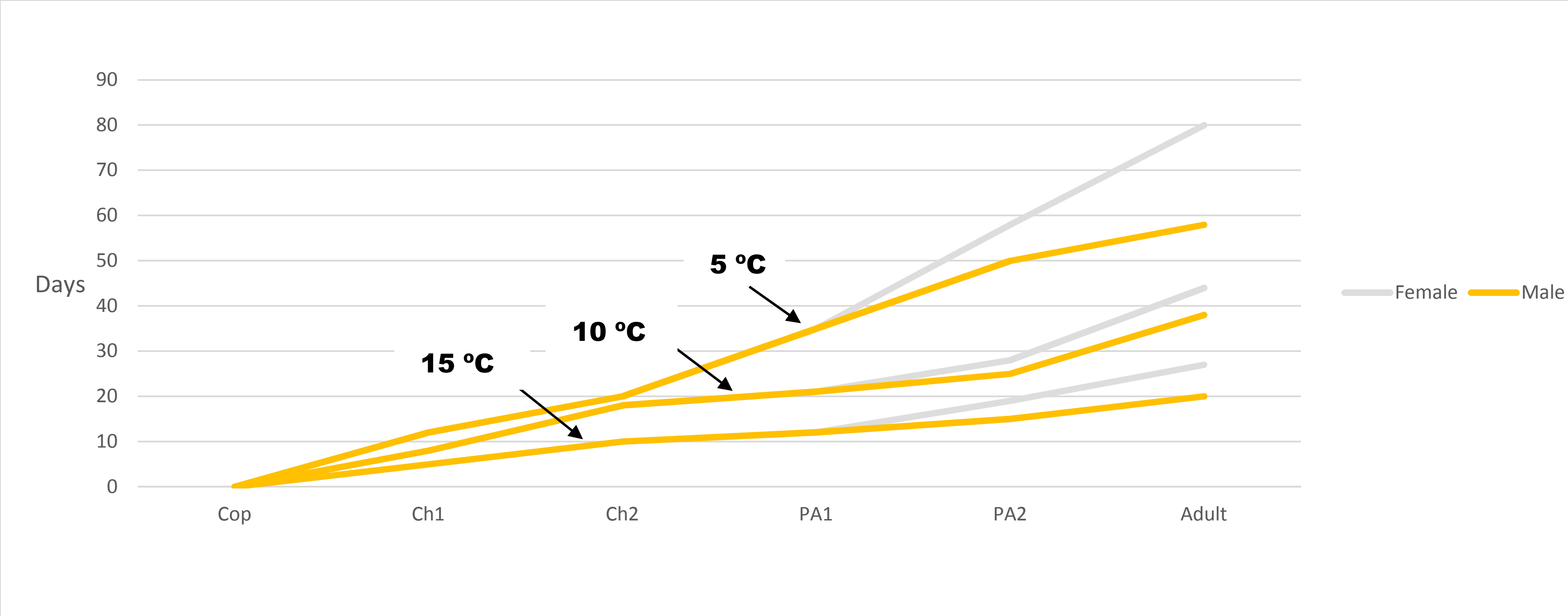


Figure 6. ***Lepeophtheirus salmonis*** **Development Plot over time @ 15°C, 10°C, 5°C.**

C. elongatus is not as host specific as *L. salmonis* (Kabata, 1979). Its hosts migrate widely. This mode of infestation is believed to account for the variable prevalence on farmed salmonids at different times of the year. *C. elongatus* is smaller in size than *L. salmonis,* averaging approximately 6-8mm in length (Hogans & Trudeau, 1989).

The life cycle of *Caligus elongatus* (Figure 7) comprises 8 developmental stages including two nauplii stages, one free living planktonic copepodid phase, four chalimi stages, followed by the mature adult stage (Piasecki & MacKinnon, 1995). Copepodids are infective, while all subsequent stages require host interaction.

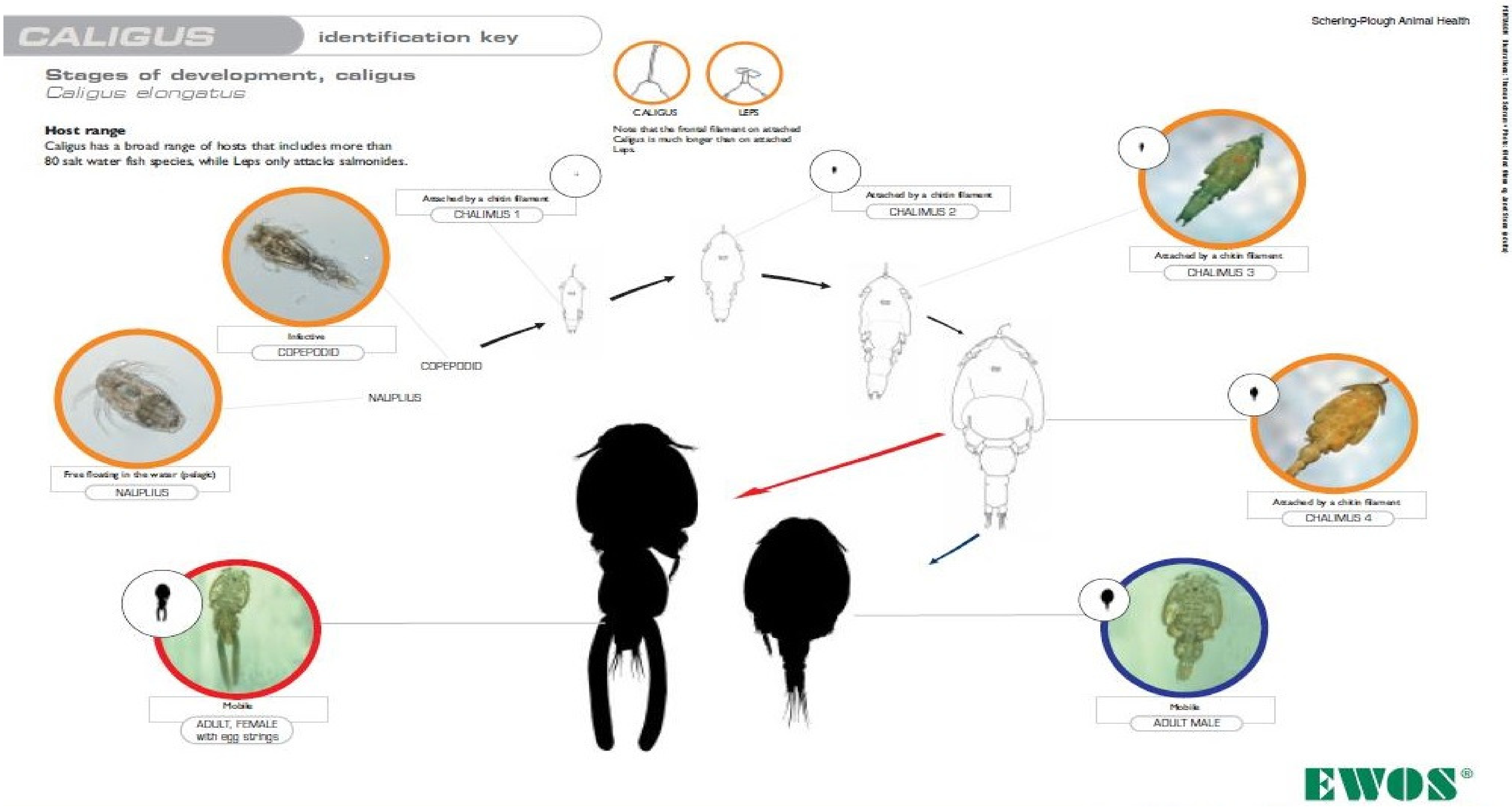


Figure 7. Life cycle of *Caligus elongatus (EWOS).*

1.3 Sea Lice Management and Control

Sea lice monitoring on finfish production sites in Ireland began in the early 1990s (Jackson & Minchin, 1993). This Sea Lice Monitoring Programme was extended to cover all fish farms off the coast in 1993 (Jackson *et al.*, 2002; Jackson *et al.*, 2005).

A formal protocol for this monitoring programme was put in place in May 2000 entitled '*Monitoring Protocol No.3 for Offshore Finfish Farms – Sea Lice Monitoring and Control*' (DMNR, 2000). This protocol set out the parameters and purpose of the monitoring programme outlining the objectives and the monitoring regime required.

The purposes of the monitoring are to provide an objective measurement of infestation levels on farms, to investigate the nature of infestations and to provide management information to drive the implementation of control and management.

This protocol included five principal components for sea lice control, namely (DMNR, 2000):

- Separation of generations.
- Annual fallowing of sites.
- Early harvest of two-sea-winter fish.
- Targeted treatment regimes, including synchronous treatments.
- Agreed husbandry practises.

Following a review of the systems and processes for controlling sea lice at marine fish farms in 2008 the Department of Agriculture, Fisheries and Food published a comprehensive range of measures to provide for enhanced sea lice control 'A strategy for the improved pest control on Irish salmon farms' (DAFF, 2008).

Results of the monitoring programme are sent to the relevant farm within 5-10 days of each inspection. A monthly report of results is circulated to relevant parties and the data is published annually (www.marine.ie; Copley *et al.*, 2001; McCarney *et al.*, 2002; O'Donohoe *et al.*, 2003-2018).

The salmon farming industry in Ireland employs many process and strategies for the control of sea lice infestation on stocks these include husbandry techniques, management practices, mechanical and non-medicinal treatments and the use of chemotherapeutants, both topical bath and in-feed. There are a limited number of veterinary medicines authorised to assist in the control of sea lice in Ireland (Table 1). Bath/topical treatments are administered by bathing the fish in specified concentrations of the treatment. Bath treatments are carried out using skirts or tarpaulins to enclose the salmon cages, the fish are corralled in to a concentrated space for the prescribed length of time or bath treatments can also be administered by use of well-boats. Chemotherapeutants incorporated into the diet are a very effective way to get the prescribed dose to the fish. Natural feeding hierarchy that exist within a cage and inappetence can lead to reduction in efficacy of infeed treatments. Ineffective treatments, both in-feed and topical can act as a cause of re-infestation and result in the development of resistance over time.

Cleaner-fish are increasingly being used for the control of sea lice in Ireland. These include various wrasse species, also lumpfish *Cyclopterus lumpus* are proving to be a suitable cold-water option for biological delousing of Atlantic salmon (Imsland, 2014). Lumpfish are currently being trialled on farms in Ireland as part of a sea lice management plan.

Non-medicinal methods of preventing and controlling sea lice infestations are being developed within the salmon farming industry. These methods include the use of water jets, delousing oils, optical delousing (Stingray Optical Delousing ™), fresh water bath treatments, thermal delousing (Steinsvik's Thermolicer ®) soft brush systems (Skamik ™) (Sletmoen, 2016) and the use of skirted cages (Stien *et al*., 2018). Some of these mechanical delousing methods are currently being used in Ireland. The use of filtration methods at harvest sites has also proven to be a very successful method for removing all stages of sea lice, including egg-strings; preventing sea lice from re-entering the water column and potentially re-infecting stocks adjacent to the harvest area (O'Donohoe & McDermott, 2014).

Compound	*Group*	*Licensing status*	*Delivery Method*	*Mode of action*	*Stages targeted*	*Withdrawal period*
Animal medicines						
Deltamethrin	Pyrethroid	Full MA	Bath	Interferes with nerve transmission by blocking sodium channels in nerve cells	Adults, Preadults. Chalimus unknown	5 degree-days
Emamectin benzoate	Avermectin	Full MA	In-feed	Interferes with neurotranmission disrupting nerve cells causing paralysis and death	All stages	Zero
Hydrogen peroxide	Oxidizer	Full MA	Bath	Gas embolism	Adults, Preadults	Zero

MA - marketing authorisation from the Health Products Regulatory Authority.

Table 1. Veterinary medicines authorised to assist in the control of sea lice on salmonids in Ireland (www.hpra.ie). (O'Donohoe *et al.*, 2018)

1.4 Research Experience

I am currently employed as a Team Leader with the Marine Institute (1999 to the present). My responsibilities include the management of the National Sea Lice Monitoring Programme and to actively participate, manage and coordinate research projects. I am responsible for Fish Health Management and Biosecurity of the aquaculture stocks and acts as the Health Products Regulatory Authority (HPRA) Compliance Officer for the Marine Institute. My role as the manager of the Sea Lice Monitoring Programme involves the co-ordination of sea lice inspections on finfish farms along the west coast of Ireland in line with 'Monitoring Protocol No.3 for Offshore Finfish Farms – Sea Lice Monitoring and Control' (DMNR, 2000) and 'A strategy for the improved pest control on Irish salmon farms' (DAFF, 2008). This work involves the quality control and of auditing of the data collected prior to reporting and liaising with the stakeholders concerned, also giving advice to Department of Agriculture, Food and Marine. My responsibility includes the management and co-ordination of the management cell process, a forum employed to address breaches of the protocol. I am author / co-author of the 34 scientific papers and reports (Appendix 1). I routinely give training courses to the salmon farming industry on the identification of sea lice species found on farmed salmonids.

I am currently and have been in the past involved in Research Projects and Aquaculture Platforms, these include: -

- InvertebrateIT – EASME/EMFF, Blue Technology (2017 – 2019),
- TAPAS - Tools for Assessment and Planning of Aquaculture Sustainability, H2020. (2016-2020),

- Ongoing participation in research into sea lice epidemiology; sea lice infestations of wild and farmed salmonids; control methods of sea lice on farms,
- International "SEARCH" project (2001 - 2004), duties included research, sample analysis and reporting,
- European AquaReg "RegEx" INTERREG IIIC project (2004 -2006) – Lead participant, duties included project administration, management of budgets, co-ordination of project partners, auditing of data collected, delivery of tasks and reporting,
- European AquaReg "SeaWomen" INTERREG IIIC project (2004 – 2006), duties included management of budgets, co-ordination of project partners, delivery of tasks and reporting,
- Comparelice/Interlice (2006 – 2009) – partner in international research and networking consortium led by Norwegian Institute of Marine Research and funded by the Norwegian Research Council, duties included networking with other researchers, assessment of research project, strategic planning for future research studies,
- Participant in European Aquaculture Technology and Innovation Platforms (EATIP),
- Organiser and participant in National and International Bioassay workshops,
- Attendee and presenter at international aquaculture conferences.

Qualifications include: -

B.Sc. (Hons) Degree in Marine Science. 1st Class Honour. University College, Galway. 1992 - 1994

N.C.E.A. Diploma in Applied Aquatic Science. Pass with merit. Regional Technical College, Galway. 1991 - 1992

Fish Farming Course, Bord Iascaigh Mhara. 1991

N.C.E.A. Certificate in Biology. Pass. Regional Technical College, Galway. 1988 – 1990

FETAC Level 5 Occupational First Aid

Dept. of Transport, Tourism and Sport, Short Range VHF Radio Certificate

Certificate of Proficiency in Personal Survival Techniques

National Powerboat Certificate – Level 2

Laboratory Safety Certificate

Health and Safety Representative Certificate

Bio-statistical Certificate, Statistics in Animal Health BARQA (2006)

Introductory Course to Biostatistics NUIG 2012

LAST Certificate for Experienced Researchers, Grandfather and Aquatic Modules

Biomark Pit Tagging Certification

Fish Anaesthesia Certification

2. Reducing sea lice re-infestation risk from harvest water at a salmon farm site in Ireland using a bespoke sieving and filtration system

O'Donohoe, Pauline, & Tom McDermott. "Reducing sea lice re-infestation risk from harvest water at a salmon farm site in Ireland using a bespoke sieving and filtration system." *Aquacultural Engineering* 60 (2014): 73-76.

Abstract

Water samples from the harvest water outflow of a salmon farm harvest line were sampled at different stages for the presence of sea lice before and after filtration to establish the quantity of sea lice that escaped back into the water column. During the processing of fish through the harvest line the mechanical abrasion experienced by the fish cause sea lice to be knocked off into the harvest outflow water, these lice have the potential to re-infest remaining stock on site. The use of two types of filtration systems at a harvesting site where *in situ* culling is on-going reduces the risk of re-infestation. In this site the sieve system was particularly effective. The reduction in sea lice numbers achieved by filtering discharge water using sieves was 89.5% using 1 mm screens and was over 99% using 80 µm filters.

2.1 Introduction

In some regions during the sea water production cycle, farmed Atlantic Salmon (*Salmo salar*) are prone to infestation with sea lice. The two species of sea lice of greatest concern are *Lepeophtheirus salmonis*, the salmon louse, which can occur on all salmonid species, and *Caligus elongatus*, which can affect over 80 species of marine fish. Sea lice are endemic ectoparasites which cause direct physical damage to fish and incur expensive treatment costs for the aquaculture industry. A combination of animal medicines and animal husbandry practices have traditionally been used to keep these parasites under control.

Jackson *et. al* (1997) noted a steep rise in the levels of sea lice during periods of harvesting, they found an increase in ovigerous and adult sea lice in routine sampling but not a build-up of juveniles, this was presumed to be as a results of lateral transfer. On some salmon farm sites along the west coast of Ireland, small scale onsite harvests are carried out on a weekly basis to meet market demands for organic salmon. A typical harvest for this site would be up to 30 tonnes per day, one day per week with approximately 8000 fish being processed per harvest. During the harvest process sea lice are knocked off their hosts by physical abrasion and become suspended in the harvest water. In order to reduce the risk of transfer of these sea lice between salmon being harvested and the remaining *in situ* stock, the use of sieves and filtration to remove sea lice from the harvest water has been employed.

The life cycle of sea lice has attached and mobile stages on the salmon so it is critical that the sieves and filters used are capable of catching all viable specimens to prevent re-infestation. Adult female lice extrude a pair of egg strings and the planktonic stages or nauplii hatch from these. Female adult *L. salmonis* have been recorded to live for up to 210 days and in that time can produce ten to eleven pairs of egg strings. Mean viable egg numbers per string have been recorded as 152 ($\pm$16) with a range from 123 to 183 at 7.2°C on farmed progeny (Heuch *et al.,* 2000). The generation time, from egg to mature adult *L. salmonis* has been recorded at 56 days and 52 days respectively for ovigerous females and adult males at 13.6°C (Tully, 1989) and 7.5 – 8 weeks at 10°C (Johnson & Albright 1991).

Initial attachment for the copepodid typically occurs on the fins of the fish (especially the dorsal, ventral and anal fins) or the scales (Wootten *et al.,* 1982, Tucker *et al.,* 2002). If the host fish is of an appropriate species the copepodid clasps the host tissue and then undergoes a moult to the first sessile stage in the life cycle. This chalimus stage attaches itself by means of a frontal filament (penetrative thread) which punctures the epidermis. Despite attachment chalimus can become detached by thrashing fish at harvest. The attached chalimus stages range in size from 1.1mm to 2.3mm length and 0.48mm to 1.34mm width (Johnson & Albright 1991; Schram, 1993). Sieves of 80µm are sufficient to remove nauplii, copepodids and chalimus stages from the water column when filtered. The mobile stages of *L. salmonis* include two pre-adult and the adult stages, these range in size from 3.6mm to 11mm in length and 4.46mm width (Johnson & Albright 1991; Schram, 1993). Screens or sieves of mesh size 1mm are sufficient to remove the mobile stages of *L. salmonis* from the discharge water; detached egg-strings will also be removed.

Sea lice levels on the stock of fish being harvested were counted prior to the harvest water sampling. These lice levels were recorded as part of the National Sea Lice Monitoring Programme (O'Donohoe *et al*., 2013).

This study aims to evaluate the levels of sea lice released back to the receiving water mass during onsite harvest of salmon. Fish pumps and airlift systems for grading, moving and harvesting farmed fish are used routinely in aquaculture. However, modification of these types of systems specifically for the removal of sea lice is novel. The objective of this investigation is to assess the modifications to existing ‘harvesting’ systems to produce an effective mechanical sea lice removal and collection system under normal field production conditions.

2.2 Materials and Methods

Harvesting is generally carried out on a weekly basis, to meet market demands. Salmon are first towed to land and netted by crane and brailer to a seawater harvest bin on the pier. Releasing the fish into the harvest bin and opening the harvest bin to process the fish results in excess chilled seawater water being forced along the assembly line; this water is collected and directed to the nest of mesh sieves by pipe (Figure 8).

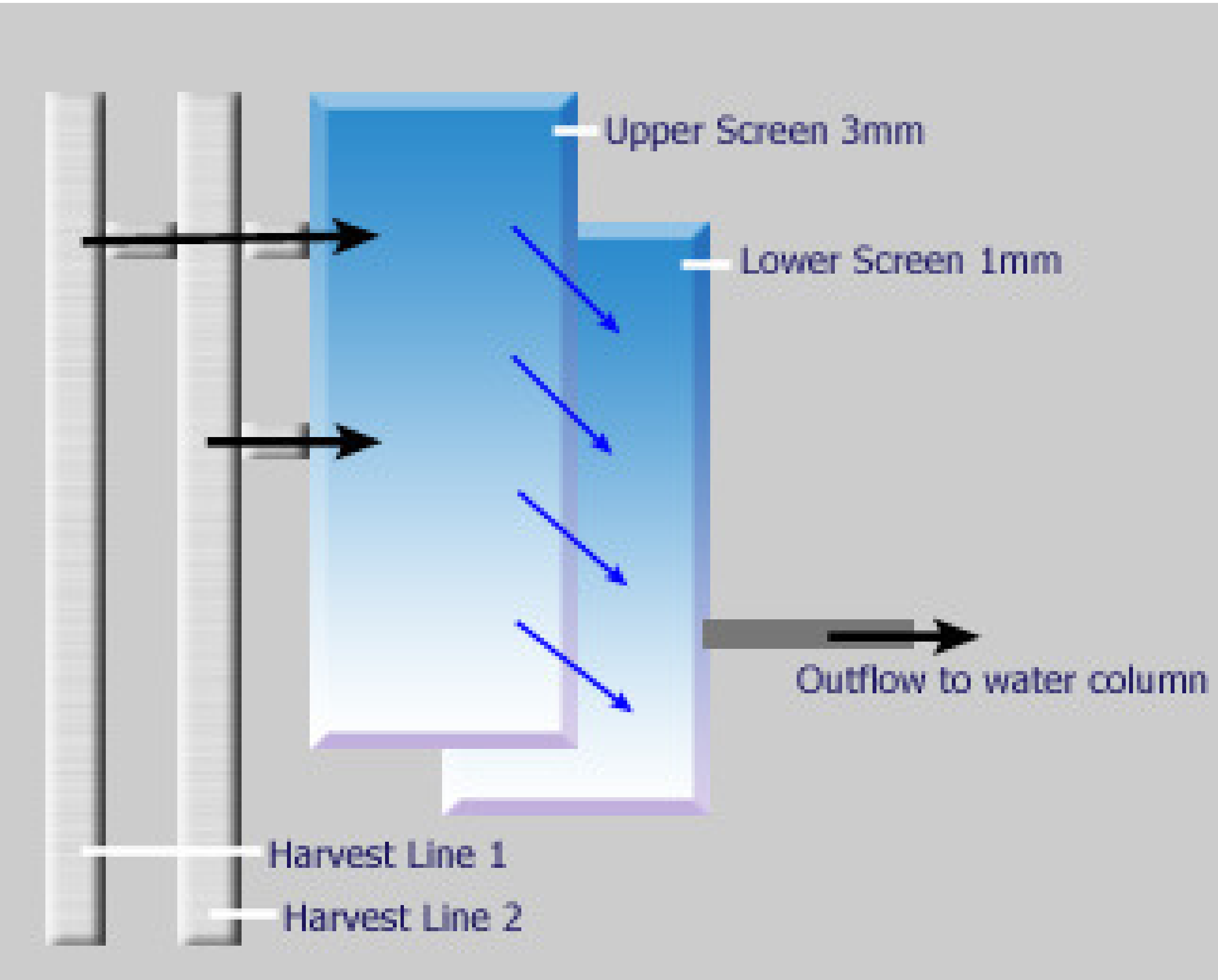


Figure 8. Schematic diagram of Stacked Sieve system, top sieve screen mesh diameter 3mm and lower 1mm diameter sieve screen

The water hits the largest screen (3mm sieve) set at 30° away from the incoming flow. A large surface area is utilised, this slowed the water passing through the screen and helps keep the egg strings intact while also improving the removal of adult sea lice. The top 3mm sieve is removable to allow for cleaning and disinfection. A second 1mm sieve at the base of the chamber and placed directly below the 3mm screen completes the sieving of the outflow water from the harvest bins, the outflow pipe releases sieved water back into water column (Figure 9).

Figure 9. Nest of sieves with outflow pipe releasing filtered water back into water column and Cartridge filter of 80µm

Harvest discharge water that is splashed on to the pier is collected by a series of sump-like drainage pipes embedded in the pier, this water is pumped through a cartridge filter of 80µm (Figure 9).

Samples were collected prior to sieving or filtration, after passing through the nest of sieves and finally after the 80µm cartridge filtration system. Twenty-two litres of water were collected per sample.

2.3 Results

A total of 15 mobile *L. salmonis* per fish was recorded at this production site approximately one month prior to water sampling (O'Donohoe *et al.,* 2013). Ten adult females *L. salmonis* were observed per fish, of these 5 were bearing egg-strings. *Caligus elongatus* were not found during this routine inspection.

The majority of sea lice found in the unfiltered samples were *L. salmonis*, a range of 60 – 89 individuals were found across the samples. Low numbers of *C. elongatus* were found in the unfiltered water, in the range of 1 – 2 individual lice (Table 2).

Lepeoptheirus salmonis						
Filtration	**Sample**	**Mobile lice**	**Attached and larval**	**Total**	**Eggstrings**	**Eggs**
Un-filtered	1	59	1	**60**	0	0
	2	68	2	**70**	0	0
	3	87	2	**89**	0	0
Nest of mesh screens	1	2	8	**10**	2	0
	2	4	7	**11**	2	2
	3	1	12	**13**	1	0
Cartridge filter	1	0	4	**4**	0	0
	2	0	0	**0**	0	0
	3	0	1	**1**	0	0

Caligus elongatus						
Filtration	**Sample**	**Mobile lice**	**Attached and larval**	**Total**	**Eggstrings**	**Eggs**
Un-filtered	1	1	0	**1**	0	0
	2	0	0	**0**	0	0
	3	2		**2**	0	0
Nest of mesh screens	1	0	0	**0**	0	0
	2	0	0	**0**	0	0
	3	0	0	**0**	0	0
Cartridge filter	1	0	0	**0**	0	0
	2	0	0	**0**	0	0
	3	0	0	**0**	0	0

Table 2. Numbers of *L. salmonis* and *C. elongatus* present in water per sample.

A small number of detached egg-strings (maximum 2) were found post sieve screening (Table 2). Two eggs were detected in one of the water samples which had passed through the sieve screens. No mobile lice were found in the water that had passed through the cartridge filter, a total of 5 attached and larval lice were found across the three water samples.

C. elongatus were not found in the sieved (3mm and 1mm) or filtered (80µm) water samples.

A reduction of 89.5% was achieved when the harvest water had passed through the nest of mesh screens a further 10.4% reduction was found in sea lice numbers once the water had passed through the cartridge filter.

2.4 Discussion

Up to ten pairs of egg-strings can be produced per adult female *L. salmonis* over a lifespan of over 200 days (Mustafa *et al.,* 2000). The removal of adult female lice from discharge water helps to reduce the infestation pressure on remaining stock on site. If this cohort of sea lice were to re-enter the water column the potential for re-infestation is greater especially at higher water temperatures. During the harvesting process, egg-strings become detached and have potential to make their way back to the water column thus providing the possibility of hatching and creating a new infestation challenge to the fish.

The construction and sequence of sieves and filters used for as sea lice removal from the water generated while harvesting was determined by trial and error until a final functioning design was achieved and put in to use. Differing mesh sizes, number and filter sizes were trialled until the current system was found to be the most appropriate. The sieving and filtration methods employed at this harvest site has proven to be a very successful method for removing all stages of sea lice including egg-strings, thus preventing sea lice from re-entering the water column. The mesh and filters sizes are appropriate for the achievement of a successful reduction in sea lice numbers of all stages. However, a small number of attached and larval lice were found post cartridge filtering this was most likely an anomaly of sampling or an indication that the cartridge filter needed to be cleaned or replaced.

In this farm situation a series of mesh screens and the use of a cartridge filtration system proved to be the right approach in reducing the levels of sea lice re-entering the marine environment. It shows that the collection and disposal of over 99% of sea lice is feasible along a harvesting line. This study demonstrates the benefits of employing a sieving and filtration system on harvest lines where the harvest water re-enters the water column, and is a valuable tool in the management and control of sea lice at finfish farm production sites. This pilot scale system has proven the concept of this type of approach and has the potential to be adopted for larger scale production sites, where the use of a revolving system could be developed or other bespoke structures.

3. Sea reared rainbow trout *Oncorhynchus mykiss* need fewer sea lice treatments than farmed Atlantic salmon *Salmo salar*.

O'Donohoe, P., Kane, F., McDermott, T., & D. Jackson. "Sea reared rainbow trout *Oncorhynchus mykiss* need fewer sea lice treatments than farmed Atlantic salmon Salmo salar." Bulletin of the European Association of Fish Pathologists 36.5 (2016): 201-207.

Abstract

A field investigation at a marine finfish farm site which stocked both Atlantic salmon and rainbow trout was carried out over a period of 14 years. Abundance of *Lepeophtheirus salmonis* at this site was found to be similar on both species, however, the quantity of sea lice treatments carried out on each stock of fish show a marked difference between species, with over three times the amount of sea lice treatments being carried out on salmon to maintain the same level of sea lice control. A different management regime had to be employed for the two fish species with a higher treatment effort being implemented for the salmon stocks to maintain sea lice infestation levels within the required thresholds.

3.1 Introduction

Sea lice cause damage to the host by grazing on mucus, epidermal tissue and blood. *L. salmonis* is regarded as the most important sea lice species with respect to disease (Jackson, 2011), and significant economic losses can be attributed to infestation of farmed fish by this parasite (O'Donohoe & McDermott, 2014).

Sea lice infestation can begin immediately after fish are put to sea, sources of this infestation can be from wild fish (Jackson *et al*., 2012), either indigenous anadromous sea trout *Salmo trutta* or returning wild or ranched Atlantic salmon. Neighbouring fish farm sites can also act as a source of sea lice infestation particularly if adjoining farm sites contain one-sea-winter fish or older (Jackson *et al*., 1997).

Studies carried out on prevalence and abundance of sea lice on farmed salmonids in Ireland have shown that Atlantic salmon experience higher sea lice infestation levels than rainbow trout (Jackson & Minchin, 1992). However, a Norwegian controlled infestation study (Gjerde & Saltkjelvik, 2009), where the predicted sea lice counts for salmon and rainbow trout of similar body weight were compared, the salmon count was lower than the count for rainbow trout.

Salmonid farming began in Ireland in the early 1970s. Salmon and rainbow trout have been produced in each of the three fish farming regions in Ireland over this period of time, on occasion within the same bays and infrequently on the same sites (O'Donohoe *et al*., 2005). Farmed rainbow trout stocks in Ireland did not breach the National treatment trigger levels (0.5 ovigerous *L. salmonis* per fish in March, April and May and 2 ovigerous *L. salmonis* per fish for the remaining months of the year.) for sea lice abundance in 2013 (O'Donohoe *et al*., 2014), while one sea-winter salmon were in breach of these levels for 18% of inspections in this period of time and two sea-winter salmon were in breach of the treatment trigger levels for 100% of inspections carried out in 2013.

Sea lice infestation levels tend to increase with increased lengths of time at sea (Jackson *et al*., 2000). While the husbandry of farmed salmon and rainbow trout are similar, one of the main differences is the shorter production cycle of trout in the sea. Salmon take longer than trout to grow to marketable size and this longer cycle at sea leads to heavier sea lice burdens on salmon, particularly two-sea-winter fish (Jackson *et al*., 2000), however rainbow trout show lower sea lice abundance than salmon (Jackson & Minchin, 1992). Rainbow trout have a thicker epidermal layer than salmon and produce more mucus cells per cross sectional area (Fast *et al*., 2002a). Slower development of sea lice coupled with delayed immune response parameters suggests that rainbow trout are slightly more resistant to sea lice infection than salmon (Fast *et al*., 2002b).

Greater knowledge of the infestation patterns of sea lice on rainbow trout may have implications for fish husbandry, fallowing of farm sites, treatment regimes, duration of production cycles and location of sites.

In order to investigate the infestation parameters and the underlying levels of susceptibility of Atlantic salmon and rainbow trout to *L. salmonis* a longitudinal study was carried out. This was based on an extensive data set of sea lice infestation parameters held by the Marine Institute, Ireland covering 14 years. The objectives of this study were to evaluate the abundance of *L. salmonis* on both species of fish and to assess and compare the sea lice treatment effort carried out on Atlantic salmon and rainbow trout stocks at one production site when the two species were farmed concurrently.

3.2 Materials and Methods

Sea lice data was obtained through the Marine Institute *Sea Lice Monitoring* Programme (DMNR Monitoring Protocol No.3. 2000) (O'Donohoe *et al*., 2014). Farmed stocks of salmon and rainbow trout in Ireland were inspected on 14 occasions throughout the year to monitor sea lice levels as part of this national programme. At each inspection 2 samples were taken for each generation of fish on site. Thirty fish were examined for each sample by anaesthetising each fish using tricaine methane sulphonate (MS222) in seawater. The seawater was sieved for any detached lice at the end of each sample. Each fish was examined individually for all mobile sea lice. The mean number of sea lice per fish was calculated (including the number of detached sea lice from the sieved seawater), results presented are mean total mobile sea lice levels for *L. salmonis* per fish.

Seven year classes/stock of Atlantic salmon AS1999 – AS2005 and 14 year classes/stock of rainbow trout RT1999 – RT2012 were examined at the one location in a bay off the west coast of Ireland. The abundance of *L. salmonis* on each stock of fish on site was measured for a period of 14 years, 1999 to 2012 inclusive. Salmon and trout were stocked concurrently at the production site until June 2006 after which only trout were stocked. Sea lice treatment data was obtained on a confidential basis from the farm in question for the purpose of this study to establish the numbers of treatments used in the period in question.

The data was statistically interrogated using Mann Whitney U test.

3.3 Results

A large data set of sea lice counts was used to determine the mean *L. salmonis* levels on stocks of salmon and trout at the production site from 1999 to 2012 inclusive (Figure 10). Mean sea lice counts were found not to be significantly different (p= 0.9110) between the two species of fish, salmon had a mean sea lice count of 2.59 ±4.24 *L. salmonis* per fish, rainbow trout had 2.12 ±2.74 *L. salmonis* per fish.

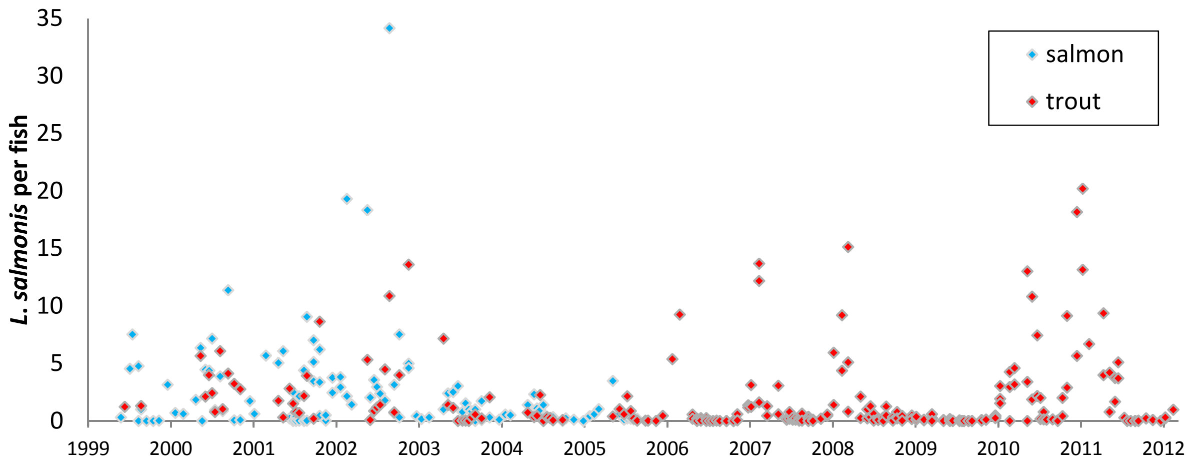


Figure 10. *L. salmonis* abundance on salmon and trout at a production site in western Ireland.

Maximum sea lice levels were recorded at 34.14 *L. salmonis* per fish for the salmon and 13.6 *L. salmonis* on the trout. At this production site salmon were grown at sea for approximately 15 months (mean 15 months) (max 16 months, min 14 months), whereas the trout production period at sea was approximately 10 months (mean 10.3 months) (max 12 months, min 9 months). Twenty-four sea lice treatments were carried out on the salmon stock from 1999 to June 2006 inclusive (Figure 11) at which stage the salmon were harvested out. Eight sea lice treatments were carried out on the rainbow trout stock in the same period. In 2005 no treatment was carried out on the trout. Each year class of salmon were administered an average 3.43 chemotherapeutants per production cycle, while the trout received an average of one treatment per cycle while stocked concurrently. At no stage were the trout treated more frequently than the salmon. Four sea lice treatments were administered from June 2006 until the end of 2012, when rainbow trout were the only species being farmed. The trout were treated on average 0.66 times per production cycle after 2006.

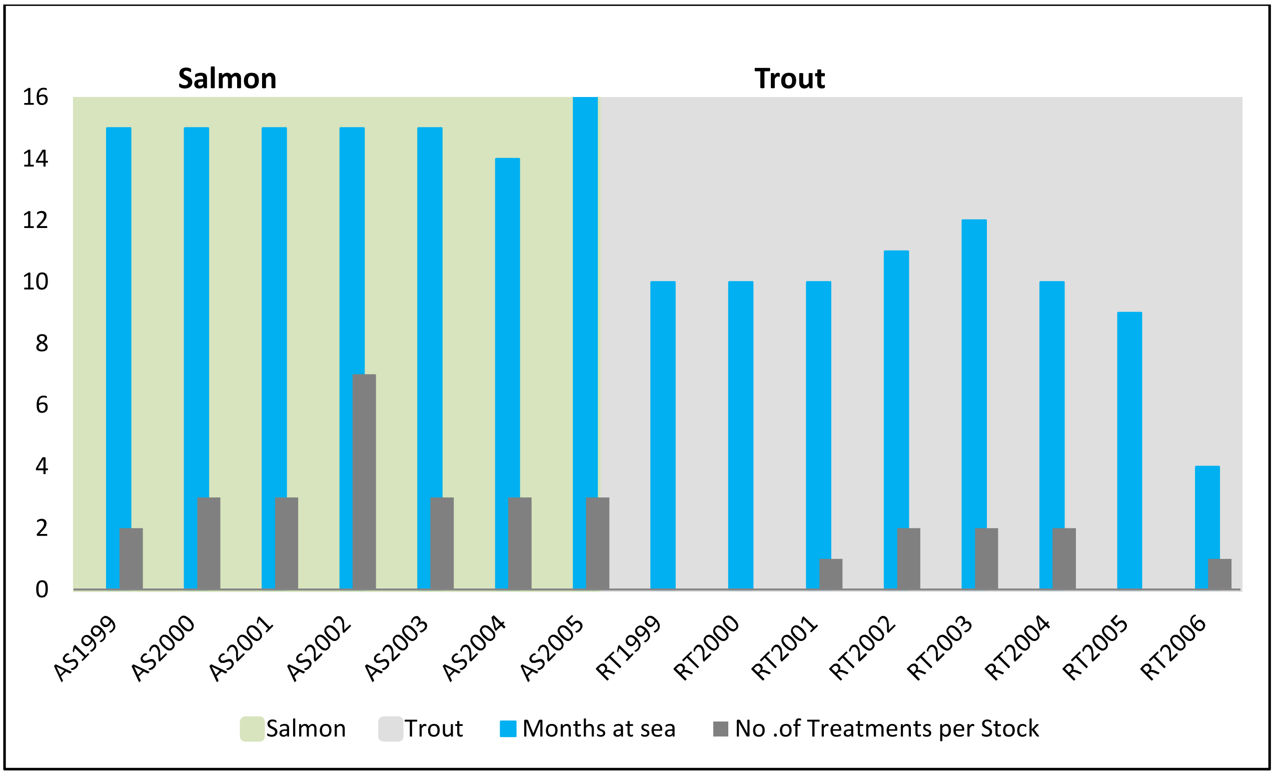


Figure 11. Sea age and numbers of treatments per year class of Atlantic salmon and rainbow trout at a production site in western Ireland from 1999 to June 2006.

3.4 Discussion

Atlantic salmon and rainbow trout were located on the same fish farm production site from 1999 to mid-2006. Without a quantitative assessment of larval *L. salmonis* in the water column the infestation pressure cannot be measured but it is reasonable to assume that the challenge from larval sea lice would be similar given the proximity of these stocks. Abundance of *L. salmonis* at this site was found to be similar on both species, however, over three times the number of sea lice treatments per cycle were used to treat the salmon to maintain the same level of sea lice control. The treatments regime implemented at this site for sea lice control was designed to maintain lice levels in line with those required by the Monitoring Protocol (Department of the Marine and Natural Resources (2000). The level of sea lice treatment effort required to maintain the lice levels on salmon within these thresholds was more than three times greater (mean of 3.4 treatments per production cycle) than that for trout (mean of 1 treatment per production cycle). The trout were treated on average 0.66 times per stock after 2006.

This study demonstrates that rainbow trout require fewer chemotherapeutants to manage and control sea lice challenges at sea. As sea lice treatments are a significant cost to the industry the reduced requirement for sea lice treatments over a production cycle represents a saving in production costs per kilo of fish produced. This may have management implications for the production of rainbow trout and salmon, farmed in isolation or together, and may inform treatment regimens and fallowing plans within sites or bays. This research suggests that farming one generation of salmon concurrently with a single generation of rainbow trout may prove to be a realistic approach with co-ordinated treatments plans for both stocks to maximise production capacity, in line with licence requirements or as a means to meet market demand. Recent research has shown that applying treatment at an early growth stage is more economical than at a later stage (Liu & Bjelland, 2014) and that during a two-year production cycle the first pair of treatments are best administered during the autumn of the first year at sea (Robbins *et al*., 2010). A strategic co-ordinated treatment approach may prove to be a viable economical option in bays where sea lice control has been problematic when differing year classes of salmon have been farmed. Two stocks, one of salmon and one of rainbow trout, could be a viable alternative production strategy to fill the production capacity in a bay while improving sea lice control. Resistance to sea lice chemotherapeutants has developed rapidly with the expansion of fish farming (Igboeli *et al*., 2014). In Norway reduced sensitivity towards hydrogen peroxide has been documented (Helgesen *et al*., 2015), also reductions in efficacy of other treatments such as pyrethroids, azametiphos and emamectin benzoate have been described previously (Grøntvedt *et al*., 2014; Helgesen & Horsberg, 2013; Sevatdal *et al*., 2005; Sevatdal & Horsberg, 2003). Extensive use of medicines has been a factor leading to the development of resistance (Aaen *et al*., 2015). This study shows that a reduction in the use of chemotherapeutants can be achieved by stocking rainbow trout. Polyculture of Atlantic salmon and rainbow trout could be an alternative to salmon monoculture production in areas where sea lice control has proven difficult. This approach could also have long term benefits in slowing the rate of potential resistance development.

4. General Discussion and Conclusion

All sustainable methods to reduce sea lice infestation are valuable to the finfish farming industry. Fish husbandry practices and integrated pest management systems, including bay management plans have proven to be key strategies in controlling sea lice infestations. This discussion will summarise and review the themes presented in the two previous chapters and the implications of the results obtained in the context of reducing sea lice abundance on farmed salmonids and reducing the use of chemotherapeutants for sea lice control.

It is important to note that sea lice resistance to chemotherapeutants has been a major problem for the industry over the last decade (Aaen, Helgesen, Bakke, Kaur, & Horsberg, 2015; Jansen *et.al*., 2016). No new pharmacological sea lice treatments, topical or oral, have been developed in the recent past and those currently in use have shown signs of emerging resistance in many fish farming areas (Grøntvedt *et al*., 2014; Helgesen & Horsberg, 2013; Sevatdal *et al*., 2005; Sevatdal & Horsberg, 2003). It has been found in previous studies that the efficacy of treatments has decreased over time (Lees, *et al*., 2008). The frequency of use of common sea lice medicines has also been shown to diminish the efficacy of these treatments (Denholm *et al*., 2002). Other risk factors are also to be considered when administering sea lice treatments e.g. the use of hydrogen peroxide as a sea lice treatment has been found to have very high risk associated with its application (Overton *et al*., 2018).

Mechanical methods for sea lice removal are becoming increasingly popular and some are proving likely to be a sustainable approach to manage sea lice infestations in conjunction with targeted sea lice chemotherapeutant treatments. At present sensitivity issues to common sea lice treatments in some production areas has paved the way for the development, and use of a number of non-medical treatments (Jackson *et al*., 2017). New mechanical and biological processes such as Sea Lice Skirts; Anti-Sea Lice Functional Feeds; Snorkel Cages; Thermal treatments (i.e. Thermolicer / Optilicer); Flushers (i.e. Hydrolicer, Flatsetsund Flusher); Lasers; Sea Lice Traps; Cleaner Fish; Deep Lights / Deep Feeding; Bubble Curtains; Hydrogen Peroxide (Global Salmon Initiative, 2017) have come on the market in the past few years allowing for greater sea lice control while avoiding the over use of chemotherapeutants. The use of warm water (Havardsson, 2013) and freshwater treatments (Reynolds, 2013) are also being used on an increasing basis however concerns are being expressed as to the long term effects these types of treatments will have on decreased sensitivity of sea lice (Ljungfeldt *et al*., 2016). Alternative approaches such as the use of snorkel cages (Stien *et al*., 2016) and cage skirt technologies show substantial potential for preventing significant levels of sea lice infestation (Stien *et al*., 2018).

This first theme of this thesis examines a bespoke mechanical method to reduce the pressures of re-infestation currently being employed at a harvest line in the West coast of Ireland. This investigation demonstrates the benefits of employing a sieving and filtration system on harvest lines where the harvest water re-enters the water column. Ninety-nine percent of sea lice, *L. salmonis* and *Caligus elongatus*, were removed from the harvest water which was re-entering the water column where salmon were being stocked.

A study carried out to assess the fish welfare impacts of one mechanical delousing technique – the Thermolicer by the Norwegian Veterinary group (Grøntvedt *et al.,* 2015) on rainbow trout found the greatest challenges impacting fish welfare was that of crowding and pumping fish during the delousing process. This sieving and filtration system is part of the harvesting process, while fish are gathered into a harvest cage and then netted by a crane system to the pier the stress caused by pumping fish is not part of this process and therefore alleviates added stress impacts.

This pilot scale sieving and filtration system has demonstrated that this type of process may have the potential to be adopted for larger scale production sites. This is a valuable tool in the management and control of sea lice at finfish farm production sites.

The second theme of this thesis set out to investigate the advantages of farming rainbow trout as an alternative to farming Atlantic salmon in the context of sea lice infestations and the use of sea lice treatments. It can be said that farming Atlantic salmon and rainbow trout both have their own benefits and challenges. However, farming rainbow trout has been shown to have some measurable husbandry advantages over that of Atlantic salmon. Environmental conditions can have differing effects on each species of farmed fish. Studies in Norway have shown that Atlantic salmon were faster growing than rainbow trout at higher salinities (Austreng *et al*., 1987). However, in less saline conditions, e.g. brackish waters, growth of rainbow trout was not diminished (McKay & Gjerde, 1985) and they were found to have better growth than that of salmon. Further research in Norway concludes that farmed Atlantic salmon have higher sea lice levels than rainbow trout when water temperatures are high (Jansen *et al*., 2012).

The weight and size of fish is linked to sea lice abundance in farmed species, larger fish have been found to carry higher intensities of infection (Lees *et al*. 2008b; Heuch *et al*. 2009; Jansen *et al*. 2012). Tucker *et al.* (2002) stated that the size of the available surface area of a potential host has a marked effect on the numbers of ectoparasites it can support. Production cycles of Atlantic salmon and rainbow trout tend to differ in Irish waters. Generally, rainbow trout have shorter production periods in marine finfish farms in Ireland than that of Atlantic salmon. Some Atlantic salmon stocks can remain at sea for up to 24 months as two-sea-winter stock, whereas rainbow trout are farmed at sea for periods of up to 14 months and have never been recorded at sea as two-sea-winter fish in Ireland (O'Donohoe *et al.,* 2015; O'Donohoe *et al.,* 2016; O'Donohoe *et al.,* 2017).

In this thesis the analysis of a long term data set has shown that the levels of infestation of *L. salmonis* on both farmed Atlantic salmon and rainbow trout were similar at one finfish production site in Ireland. The most notable observation between the two stocks was in the number of chemotherapeutants administered to these stocks of fish over the period of co-production at the same site. The Atlantic salmon stock was observed to have received twenty-four pharmacological sea lice treatments whereas the rainbow trout received only eight treatments. A different sea lice treatment regime was employed for the two fish species with a higher treatment effort being implemented for the Atlantic salmon stocks to maintain sea lice infestation levels within the required thresholds. In a case study carried out in three different fish farms sites in Ireland (Jackson *et al.,* 1997) on rainbow trout and Atlantic salmon farmed in adjacent cages, the levels of infestation of *L. salmonis* on the salmon stocks were found to be significantly higher than that of the rainbow trout stocks. The levels of *L. salmonis* on the salmon were noted to be remarkable as the salmon were being treated for sea lice infestation while the rainbow trout were not. This is in keeping with the findings of this thesis.

There are a limited number of active ingredients currently being used in sea lice chemotherapeutants, for that reason an appropriate administration regime is required to maintain the efficacy of these treatments in to the future (Lees *et al.,* 2008). A reduction in the use of sea lice chemotherapeutants could be achieved by stocking rainbow trout. A further reduction in the use of sea lice chemotherapeutants being administered to rainbow trout could also be achieved by using the mechanical methods of delousing discussed previously in this thesis. The adaptation of management strategies to allow for stock rotation and alternative mechanical delousing regimes in bays would help to preserve the lifetime of sea lice chemotherapeutants currently in use. There would be particular advantages for rainbow trout farmers to employ this novel mechanical sieving and filtration method to reduce transmission of sea lice at harvest thus reducing infestation pressure on remaining stocks at the production site.

Rainbow trout do not achieve as high a market price as Atlantic salmon, in January 2016 farmed Atlantic salmon were marketed at €5.15/kg and rainbow trout at €3.20/kg (FAO 2016). However, given that sea reared rainbow trout thrive at lower salinities, have shorter production cycles and have less sea lice infestation problems at higher sea temperatures than Atlantic salmon, the practice of farming of rainbow trout instead of Atlantic salmon could prove to be more economically worthwhile given that sea lice management would be more cost effective. The control of sea lice on Norwegian salmon farms was found to cost 10% of the overall production costs (Iversen *et al.,* 2015), given that rainbow trout require far less treatment than Atlantic salmon, the economic benefits of farming rainbow trout may prove to be more financially advantageous than that of Atlantic salmon production. Evidence of potential savings is unavailable as there is a paucity of financial information available for rainbow trout production costs.

Polyculture of Atlantic salmon and rainbow trout could prove to be an alternative to salmon monoculture, however this may have implications for bay management arrangements. Alternate stocking of the two species may also be a consideration in farming areas where sea lice control has proven problematic. This alternate stocking approach would allow for the principles of bay management processes, such as separation of generations (Jackson *et al.,* 2002) to be met while reducing environmental impacts; preserving the efficacy of chemotherapeutants and maintaining sea lice control. This approach may also have implications for the development of Integrated Multi-Trophic Aquaculture (IMTA) systems where the reduction in the use of chemotherapeutants of the higher trophic species such as salmonids, would be desirable in order to reduce residue effects on the lower trophic species.

4.1 Conclusion

In conclusion, it can be seen from many years of data that sea lice infestation is a management challenge of farmed salmonids in Ireland. The data presented in this thesis shows that farmed salmonids are under constant challenge from sea lice infestation. Alternative fish husbandry, fish handling and site management methods can be employed to counteract this challenge and mitigate recurrent damage and loss.

- ❖ The results of the first theme of this thesis regarding the mechanical removal of sea lice using a bespoke sieving and filtration system have shown that taking precautionary measures at harvest time is warranted and may also have implications for other fish handling occasions, such as grading; treating; weighing, health and gill condition checks. Bespoke sieving and/or filtration systems are to be encouraged at harvest sites to remove sea lice thus preventing transmission to remaining stocks. Various devices e.g. skimmer; scrubber; laser, are currently being developed and trailed by the industry to physically remove sea lice from farmed fish, future work could include assessments of these new technologies in Ireland, as Irish salmonid farms are considered to be a more exposed production environment than other salmonid farming countries (BIM & MI, 2006).

- ❖ The second theme of this thesis demonstrates that the use of rainbow trout as an alternative production stock can reduce the reliance on chemotherapeutants. The benefits of farming rainbow trout include lower costs compared to Atlantic salmon in terms of production cycle and sea lice control. Rainbow trout could prove to be a viable, less costly, less problematic source of fish protein for an ever increasing world aquaculture market.

Sea lice continue to be a major challenge for the salmonid farming industry, every effort needs to be investigated and pursued to address this challenge, this thesis has endeavoured to demonstrate two differing approaches to reduce sea lice infestation and to lessen the reliance on medicinal sea lice treatments.

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6. Appendices

Appendix 1

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