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An Evaluation of Antiparasitics Used to Treat the Sea Louse, Caligus rogercresseyi, in Chilean Salmonid Farming

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An evaluation of antiparasitics used to treat the sea louse, *Caligus rogercresseyi*, in Chilean salmonid farming

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Executive Summary

In order to demonstrate the proposed need for increased company transparency regarding pesticide application, this report first examines the other top salmon producing countries: Norway, Scotland, and Canada. Chile currently has one of the largest ratios of applied pesticides to harvested salmon, which is a direct result of *C. rogercresseyi* resistance to virtually every anti-louse pesticide. This, along with the environmental impact that pesticide application has on important non-target species in Chilean fisheries, indicates that additional research on company data surrounding farming practices, which must be made transparent and publicly available, is crucial to the management of sea louse infestation in Chilean salmon farms.

Sea lice pose a global threat to open-net salmonid farming. Chile is the second largest salmon producer in the world, and, given that salmon production provides a significant contribution to the nation's economy, they have a vested interest in mitigating sea louse infestations and environmental impacts to ensure the longevity and sustainability of the industry. However, this will not be possible without increased research on the underlying mechanisms behind sea louse infestations, which can more effectively inform governmental regulation of salmon farming. This research requires greater transparency on pesticide practices and sea louse monitoring data from Chilean salmon farms.

Currently, the preferred anti-louse treatment method in most farms is pesticide application. However, two of the most prevalent species of sea louse, *Lepeophtheirus salmonis* and *Caligus rogercresseyi*, have historically and continue to experience declines in their sensitivity levels to these available chemical treatments. While some countries, such as Norway and Scotland, have attempted to deal with this issue by utilizing cleaner fish, thermal, and mechanical delousing methods, there are concerns surrounding higher mortality rates for farmed species as well as general welfare issues.

In 2019, the following pesticides were applied throughout salmon farms in Chile: azamethiphos, emamectin benzoate, deltamethrin, lufenuron, and hydrogen peroxide. Throughout farms in the major salmon producing regions of Los Lagos, Aysén, and Magallanes, sea lice currently show either high levels of resistance or signs of sensitivity loss, which poses a problem for current and future sea louse management. Additionally, all of these pesticides have negative environmental impacts on non-target species that are important for Chilean marine ecosystems, most notably crustaceans.

In the most recent year with pesticide data for Norway, Chile, Scotland, and Canada – the top salmon producing countries – Chile had the highest ratio of pesticides applied to biomass of fish farmed (when excluding hydrogen peroxide, which is not always used to treat sea lice). The larger quantity of pesticides that were required to control sea louse populations in Chile indicates a high level of sea louse resistance, which poses a major concern for sustainability and efficiency of the industry.

Historically, a lack of publicly available data in Chile prevented scientific research and hindered government regulation from keeping up with the growth of the salmon industry, and this lack of regulation led to industry setbacks such as an outbreak of infectious salmon anemia (ISA) in 2007 (Poblete et al. 2019). Additionally, national databases in other countries have proved to be

extremely important as they allow for in-depth analyses of industry-wide salmon farming processes that can illuminate underlying issues (Overton et al. 2019). The lack of transparency in regard to data and farming practices has the potential to harm Chilean sales to major salmon consuming countries. Recently, ethical and environmental standards have become a greater concern for consumers in some of Chile's biggest markets, meaning consumers may be less likely to purchase salmon from Chile due to the lack of transparency surrounding farming practices (Poblete et al. 2019).

Taking steps to increase transparency would bring Chile closer to taking a global leadership role in sustainability and sea louse management. Countries have only recently begun to explore non-medicinal treatments and chemical alternatives to government approved pesticides, but these options are not readily available and may pose unforeseen risks to marine ecosystems. As such, research dedicated to understanding treatment constraints and developing alternative treatment methods could improve the financial and environmental sustainability of salmon production and improve consumer perceptions abroad.

Key Findings:

- Currently, all salmon-producing nations are grappling with sea louse infestations. Even in countries where pesticides are less widely used for sea louse mitigation, the alternative treatments present higher mortality rates in farmed fish as well as animal welfare concerns.
- The anti-louse pesticides used in Chile in 2019 were azamethiphos, emamectin benzoate, deltamethrin, lufenuron and hydrogen peroxide. Sea lice are already either showing high levels of resistance or the beginning of a loss in sensitivity to all of these compounds. Additionally, these pesticides pose a threat to non-target species important in Chilean marine ecosystems.
- In 2018, the most recent year with data available for all top salmon producing countries, Chile was the nation with the highest ratio of exclusively anti-louse pesticides applied to biomass of fish farmed. The necessity for this large quantity of pesticides indicates a high level of sea louse pesticide resistance in Chilean farms.
- Historically in Chile, a lack of data access hindered government regulation and prevented scientific research from keeping up with salmon industry growth (Poblete et al. 2019). National databases in other countries have proved to be extremely important as they allow for an in-depth analysis of industry-wide salmon farming processes that can illuminate underlying issues (Overton et al. 2019).
- Ethical and environmental criteria have become a concern for consumers when purchasing salmon products. An increase in transparency surrounding farming practices will likely increase demand from consumers in the United States, Japan and the European Union (Poblete et al. 2019).

Key words: *Caligus rogercresseyi, salmon, Chile, transparency, aquaculture*

Background

Aquaculture has become a globally important industry as demand for fish products grows at a rate almost twice that of global population growth (FAO 2020a). As of 2018, global aquaculture production was valued at USD 250 billion and accounted for 46% of total fish production (FAO 2020a). Of this production, the Atlantic salmon (*Salmo salar*) has become the largest fish commodity by value, partially as a result of an increased demand from markets in almost every world region (FAO 2020a). However, capture fisheries are not able to keep up with Atlantic salmon demand, so approximately 70% of all salmon is produced from aquaculture (Poblete et al. 2019).

Salmon farming can only occur in relatively sheltered areas, like fjords, lochs or bays, which limits the number of locations that can successfully produce salmon (Poblete et al. 2019). Therefore, as demand has grown, countries with favorable conditions have been able to capitalize on salmon farming; in particular, Norway, Chile, Scotland, Canada and the Faroe Islands (Poblete et al. 2019; Iversen et al. 2020). Of these countries, Norway and Chile account for the vast majority of salmon production, which has resulted in Atlantic salmon being the most important aquaculture product by value for both nations (Poblete et al. 2019). Therefore, understanding the risks posed to these nations fish production is necessary because if production declines in either country, there are global market implications (Iversen et al. 2020).

Following the exponential increase in production in the 1990s, Chilean production of salmonid species (the Atlantic salmon, Coho salmon (*Oncorhynchus kisutch*) and Rainbow trout (*Oncorhynchus mykiss*)) has grown into a multibillion-dollar industry (Iversen et al. 2020; FAO 2020a). High consumer demand in Japan, the United States and the European Union allowed Chile to generate USD 4,497 million in 2014, a value which has only increased over the years (Poblete et al. 2019). However, these nations have recently shown consumer demand for greater transparency in salmon products, which many news publications have found lacking in Chilean companies (Sapag 2020). Therefore, if Chilean companies want to take full advantage of high product demand, they will need to increase company transparency in regard to production (Poblete et al. 2019). Additionally, while Chile is the second largest producer of salmon in the world (following Norway), Poblete et al. (2019) predicts that their output volumes would have increased at a faster rate if scientific research and governmental regulations had kept pace with industry growth. So, while there have been significant investments in production technology, parasite and disease issues have overshadowed this progress and have limited Chilean aquaculture industry growth (Iversen et al. 2020).

High production also comes with a high risk of disease and parasites. The main parasites plaguing global and Chilean aquaculture are sea lice; specifically, ectoparasites from the Caligidae family affect salmonid species in Chile (Sandra Bravo 2003). Their life cycle, which varies depending on temperature and salinity, is completed in around 32 days from egg extrusion to mature adults in one of the main salmon production regions in Chile, Region X (Sandra Bravo 2010). They do not have any intermediate hosts and go through eight exoskeletal shifts (Sommerset et al. 2020); two free swimming naupliar stages, one infective copepodid stage, four chalimus stages and finally an adult stage (Venmathi Maran et al. 2013). In one study, at the adult stage, female sea lice produced around 11 generations each with approximately 31 eggs per egg string after one copulation event (Sandra Bravo 2010). After hatching, planktonic nauplii larvae can travel up to 30 kilometers (Salama et al. 2013). Additionally, adult sea lice are able to survive in seawater up to 7 days without a host (Sandra Bravo 2010). Both of these traits allow for sea lice to easily travel between farms and hosts, which makes regional infestations difficult to control.

Introduction

Sea lice infestations and treatment

Almost immediately after salmonid farming began in Chile in the early 1980's, caligus species from the Caligidae family were present in open net pens (Boxshall and Bravo 2000). The first large scale sea louse infestation was by *Caligus teres* and was found in the spring of 1987 after the commercial scale production of rainbow trout began (Sandra Bravo 2003). Later on, in 1997, *Caligus rogercresseyi* was discovered and infected salmon and rainbow trout at high rates (Sandra Bravo 2003). However, these biological problems didn't become a major issue for Chile until the late 2000's (Iversen et al. 2020). Currently, the main treatment method for sea lice management in Chile are antiparasitics. In 2019, the compounds applied as both bath and in-feed treatments were azamethiphos, emamectin benzoate, deltamethrin, lufenuron and hydrogen peroxide (Table 1).

Table 1. The history of applied pesticides in Chile from 2011 to 2019 (Servicio Nacional de Pesca y Acuicultura 2020).

	2011	2012	2013	2014	2015	2016	2017	2018	2019
Emamectin Benzoate	✓	✓	✓	✓	✓	✓	✓	✓	✓
Cypermethrin	✓	✓	✓	✓	✓	✓	✓	✓	
Deltamethrin	✓	✓	✓	✓	✓	✓	✓	✓	✓
Diflubenzuron	✓	✓	✓	✓	✓	✓		✓	
Azamethiphos			✓	✓	✓	✓	✓	✓	✓
Lufenuron					✓	✓	✓	✓	✓
Hydrogen Peroxide								✓	✓
Hexaflumuron							✓		

Economic impact of sea lice

While historically the majority of production costs have been fish feed, the cost of antiparasitic treatment has become a major cost component in recent years (Abolofia, Asche, and Wilen 2017; Costello 2009). In Norway in 2011, the economic impact of sea lice was estimated to be 8.70% of total production value, which illustrates the economic implications sea lice infestations has on the industry (Abolofia, Asche, and Wilen 2017).

Economic losses from sea lice have mostly been due to treatment costs, management strategies, a decline in fish growth rates and increasing host susceptibility to other diseases (Sandra Bravo 2003; Costello 2009). The increasing treatment cost is partially due to pesticide resistance, which occurs when less sensitive individuals survive and reproduce after treatments, enabling populations to adapt and no longer be affected by treatment (Agusti et al. 2016). This reduction in sensitivity has spread into almost every salmon farm in Chile and has been exacerbated by the close proximity of farms and high density of fish, which sea lice can travel between easily (Agusti et al. 2016; Poblete et al. 2019). Additionally, when comparing sea lice costs in different countries, Costello hypothesized that the factor that determines the magnitude of a sea lice epidemic may not be the total production, but instead the density and quantity of farming sites (Costello 2009). Therefore, addressing sea louse infestations in Chile requires more research on how to manage the implications of high farm density (Chávez-Mardones et al. 2017).

The primary method of sea louse control in Chile is chemical treatments, so increased sea louse resistance means that farmers are forced to either increase the amount of pesticide applied or to find another pesticide (Hannisdal et al. 2020). As there are a limited number of pesticides licensed for sea lice treatment, the overuse of any given pesticide is inevitable, which in turn increases the risk of antiparasitic resistance (Lam et al. 2020).

High farm density is already the reason for the majority of environmental impacts from aquaculture in Chile, so the increase in pesticide application is only amplifying these impacts (Poblete et al. 2019). Therefore, a high farming density likely results in both high sea louse resistance and greater ecological impacts, which is a concern for Chile economically.

Report outline

Overall, sea lice pose one of the biggest risks to the global and Chilean salmon industry (Costello 2009). Therefore, further research is needed to understand how to best manage infestations in Chile, which requires greater transparency on the part of Chilean salmonid companies. This would simultaneously benefit scientific research and companies, as consumers begin to pay greater attention to transparency in the production process.

The following report will first, document the methods for obtaining pesticide treatment data and the total biomass harvested in each country. Then, this report will review the data for each of the top salmonid producing countries to evaluate the relative quantities of pesticides used to treat sea lice. This will provide context for the level of resistance in Chile and also the various treatment strategies to approach sea louse infestations, which could inform future directions of Chilean aquaculture. Then, this report will review the mechanisms by which *C. rogercresseyi* develop resistance to pesticides currently used in Chile. Considering that resistance may be transferable within and between the major pesticide compounds (pyrethroids, organophosphates and avermectins), it is important to be aware of the current level of pesticide resistance to determine what resistance may look like in the future (Olaussen 2018). Then, a review will be done on future sea louse treatment options to understand the difficulties in bringing new pesticides and treatment techniques to market. Finally, this report will explore the potential of Chile to become a global leader in sustainability and sea-louse management, which will increase their consumer base and decrease their production costs, ultimately maximizing the economic benefits of Atlantic salmon farming.

Methods

Data Collection Methods

Norway

To compare the pesticide indices of the top salmon producing countries, data was obtained from a variety of mainly governmental sources. The data for Norway on pesticide quantities and biomass produced was obtained from a report entitled "The Health Situation in Norwegian Aquaculture 2019" written by the state-run Norwegian Veterinary Institute (Sommerset et al. 2020). Table 2.1 in this report contains the biomass, and the "Harvested, tons" values, which were collected for all marine species ("Salmon", "Rainbow trout" and "Marine species (halibut, char, cod, other)"). Table 2.5 contained anti-salmon lice medication values and all except praziquantel were included in analysis. This is because praziquantel is an anti-tapeworm pesticide and therefore does not reflect sea lice treatment. Only the "Pharmaceutical products prescribed" data is available, so these values for azamethiphos, cypermethrin, deltamethrin, diflubenzuron, teflubenzuron, emamectin benzoate and hydrogen peroxide were evaluated get the total kilograms of active substances prescribed in Norway for each year. All pesticide quantities were converted into grams.

However, hydrogen peroxide data was only available as the summed value of treatment for amoebic gill disease and sea lice treatment. This means that the hydrogen peroxide values are not solely reflective of sea lice treatment. Amoebic gill disease has heavily impacted Norwegian salmon farms in recent years at the same time that chemotherapeutic treatment for sea lice has declined. This has resulted in a large uptick in the amount of hydrogen peroxide application, as it is used to treat amoebic gill disease (Hjeltnes et al. 2019). The majority of pesticide application in Chile is targeted at sea lice, so this analysis aims to quantify the pesticides used for sea lice treatment in other countries. Hydrogen peroxide is also a bath treatment, meaning that it is measured in extremely large quantities and is not as easily comparable between locations. Therefore, two comparisons were done. One with hydrogen peroxide and one figure without the inclusion of hydrogen peroxide. Doing this enables us to see how the pesticide indices for countries compare in terms of how much sea louse resistance is present (which will be reflected in the quantity of pesticide applied).

Chile

Oceana, an international NGO dedicated to ocean conservation, provided the quantities of pesticide used in Chile (Servicio Nacional de Pesca y Acuicultura 2020a). They obtained the data by submitting an official request for this information to the National Fisheries Service, which is the Servicio Nacional de Pesca y Acuicultura (SERNAPESCA) in Spanish, through the Transparency Act portal. The pesticide quantity data from this acquired data was converted into grams. Additionally, the biomass farmed was obtained from the 2019 report produced by SERNAPESCA (Subdirección de Acuicultura Departamento de Salud Animal 2020).

Scotland

Data on the pesticide quantity applied in Scotland was downloaded from the "Fish Farms Monthly Biomass and Treatment Reports" webpage on Scotland's aquaculture website (Scottish

Environment Protection Agency 2020). Deltamethrin, cypermethrin, azamethiphos, teflubenzuron and emamectin benzoate quantities were summed in grams for all of the sites in Scotland for each year. The fish production for each year was collected from the "Scottish Fish Farm Production Survey 2019" produced by Marine Scotland Science and included Rainbow trout, Atlantic salmon, Brown trout/Sea trout, Lumpsucker and Wrasse species and Halibut for the year 2016 (Munro 2019, 2020). The data only included halibut production for 2016 because in 2017, 2018 and 2019, only one company produced halibut. This means that publishing production data would have revealed data for an individual company, which Scotland cannot do. However, this value was likely small and would not have affected the overall pesticide to production ratio.

Canada

The pesticide quantities were collected from the "Marine Finfish" data sets, which are available for 2016, 2017 and 2018 (Fisheries and Oceans Canada 2020). These data sets contained data for all sites in Canada, and values for emamectin benzoate, ivermectin, azamethiphos and hydrogen peroxide were summed to get the total amount of pesticides applied in Canada each year. Praziquantel was again not included because it is not a pesticide that is used to treat sea lice. The data for biomass farmed in Canada was obtained from the Fisheries Division of Food and Agriculture Organization of the United Nations (FAO 2020b). The biomass farmed is listed by each species, so all marine finfish species values were included and added together ("Atlantic bluefin tuna", "Atlantic cod", "Atlantic salmon", "Atlantic salmon", "Chinook(=Spring=King) salmon", "Coho(=Silver) salmon", "Marine fishes nei", "Rainbow trout", "Salmonids nei"). These species were included because the quantity of pesticides applied is for the marine finfish species that are farmed.

Results

Antiparasitic application in top salmonid producing countries

Understanding the condition of sea lice infestations in Chile requires putting it into context with the other top salmon producing countries. Again, Norway is the largest producer of farmed salmon, followed by Chile, Scotland and Canada (Love et al. 2020; Iversen et al. 2020). The following section will assess the treatment strategies of these countries to understand how each country attempts to combat louse resistance and economic losses.

The quantity of applied pesticide used to treat sea lice can be an important indication of the degree of louse resistance. This is because as sea lice become more resistant, farms either have to increase the amount of pesticide they applied or change treatments. Therefore, while there may be other pesticides used in these countries, they were not included in the following comparisons. This enables the figures to exclusively visualize the degree of sea louse resistance. Additionally, data was not consistently available during the same years for all countries. Norwegian data was available up until 2018, Chilean and Scottish data were available up until 2019 and Canadian data was only available from 2016 until 2018. Therefore, a lack of data outside of these ranges does not imply that a country had zero pesticide application.

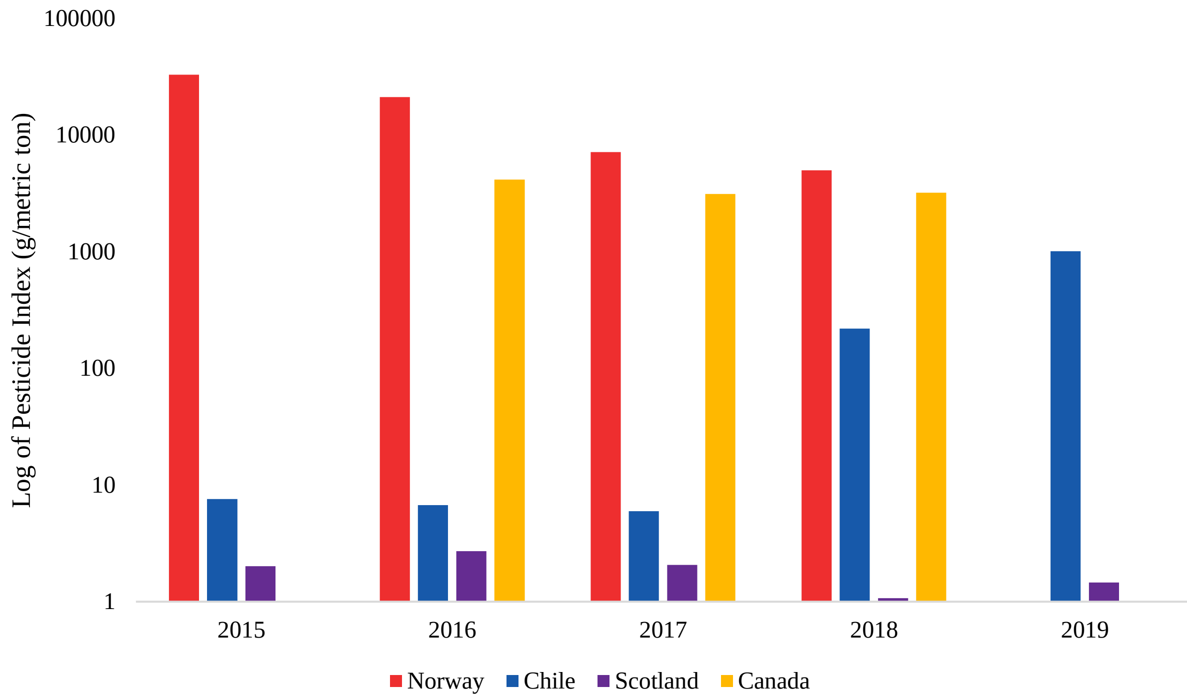

Figure 1. Pesticide indices (grams active ingredient / metric ton of salmon produced) of Norway, Chile, Scotland and Canada in marine finfish farms (Sommerset et al. 2020; Servicio Nacional de Pesca y Acuicultura 2020a; Subdirección de Acuicultura Departamento de Salud Animal 2020; Fisheries and Oceans Canada 2020; FAO 2020b; Scottish Environment Protection Agency 2020; Munro 2019, 2020). This figure includes all pesticides that could potentially be categorized as anti-louse even if not all applications were administered to treat sea lice. Specifically, hydrogen peroxide was included even though it can also be used as an anti-fungal treatment. In this figure, Norway consistently has the highest ratio of pesticide applied to biomass farmed, largely attributed to the high levels of hydrogen peroxide applied. Chile had a large increase in the amount of pesticide applied in 2018 and 2019, also largely due to a reintroduction of hydrogen peroxide. However, Norway and Canada did not have data available for all five of these years, so a lack of data does not imply that a country had zero pesticide application.

When including hydrogen peroxide, in 2018, Norway had the greatest pesticide application in relation to the quantity of fish farmed, followed by Canada and then Chile (Figure 1). During the span of available data, Scotland had the lowest pesticide indices while Norway and Canada had the highest indices (Figure 1). While Chile appears to have a relatively low pesticide index compared to the other countries in 2015, 2016 and 2017, their pesticide index jumped up in 2018 and 2019 to almost reach Canadian and Norwegian values (Figure 1). However, Figure 1 does not give an entirely accurate picture as Norway, Canada and Chile currently use hydrogen peroxide, while available data in Scotland did not include hydrogen peroxide, even if it was applied. This is because data was not available for treatments that were applied in wellboats. Therefore, to standardize pesticide application, a figure without hydrogen peroxide was created (Figure 2).

Hydrogen peroxide is a bath treatment and requires much higher quantities of applied pesticide compared to other compounds (Hannisdal et al. 2020). The difference is so drastic that 1 kg of hydrogen peroxide, a bath treatment, can treat 33 kg of fish while 1 kg of deltamethrin, which is also a bath treatment, treats up to 17 million kg of fish (Hannisdal et al. 2020). This means that including hydrogen peroxide will skew our understanding of how much pesticide is being applied. Additionally, hydrogen peroxide is not exclusively used for sea lice treatment: in Norway, it is predominately used to treat amoebic gill disease, and in Canada, it is used for antifungal purposes. This becomes a problem for an analysis focusing on sea lice because they do not specify the amount of hydrogen peroxide used for each purpose. Therefore, we cannot be entirely sure that the pesticide indices that include hydrogen peroxide accurately reflect sea lice treatment and resistance. Figure 2 illustrates the pesticide indices without hydrogen peroxide to account for this potential discrepancy.

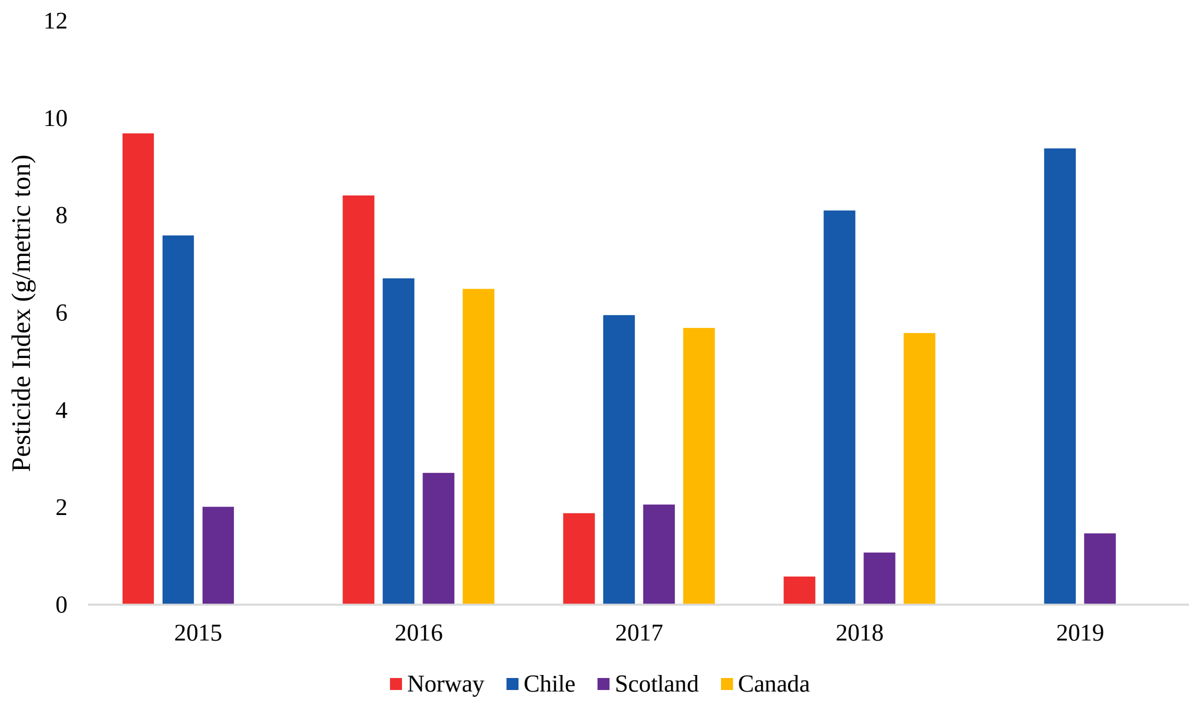

Figure 2. Anti-louse pesticide indices (grams active ingredient / metric ton of salmon produced) of Norway, Chile, Scotland and Canada in marine finfish farms excluding hydrogen peroxide application (Sommerset et al. 2020; Servicio Nacional de Pesca y Acuicultura 2020a; Subdirección de Acuicultura Departamento de Salud Animal 2020; Fisheries and Oceans Canada 2020; FAO 2020b; Scottish Environment Protection Agency 2020; Munro 2019, 2020). This figure gives a more accurate comparison of sea lice resistance, as the majority of hydrogen peroxide applied in Norway and Canada was not to treat sea lice and this figure only includes pesticides where all applications were to manage sea lice. While Norway has the highest pesticide quantity in 2015 and 2016, they were surpassed by Chile in 2017 and 2018.

Figure 2 gives a more accurate depiction of the pesticide application in each country. When hydrogen peroxide is not included in Chilean pesticide quantities, the pesticide use remains relatively stable, with some increase from 2017 to 2019 (Figure 2). In 2015 and 2016, Norway had the largest pesticide index, but after 2016, Chile had the largest pesticide index

(Figure 2). Norway is particularly interesting because they started off with the highest pesticide index, and rapidly declined to have one of the lowest pesticide indices in 2018 (Figure 2).

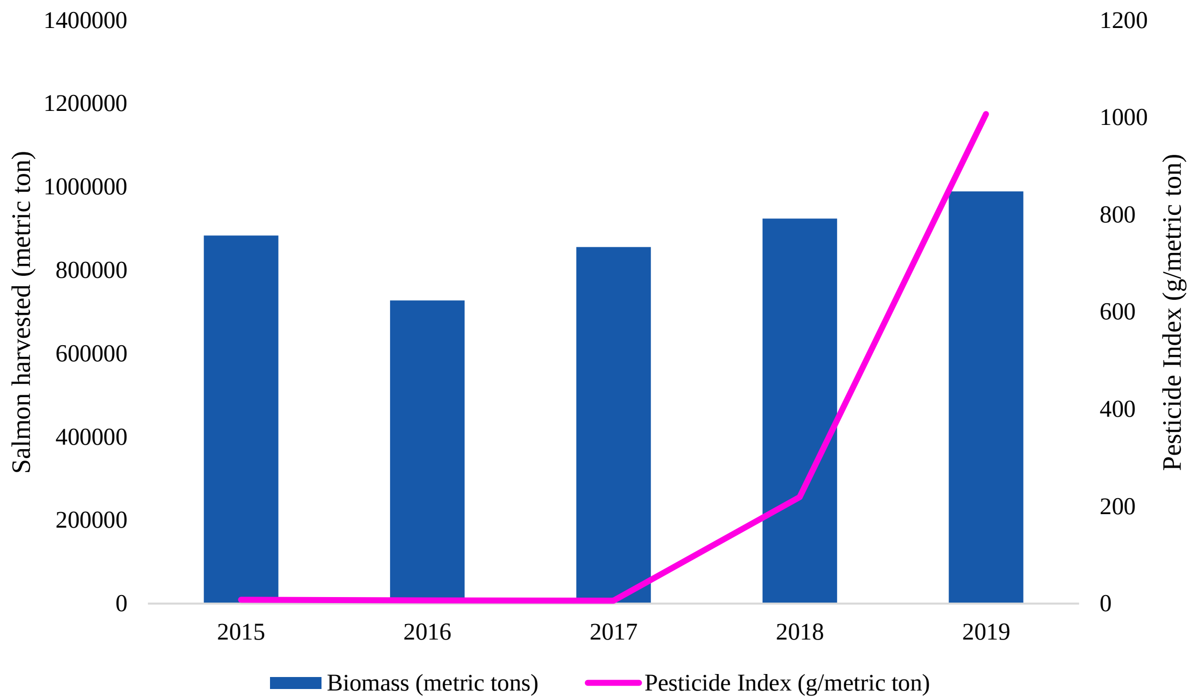

Figure 3. Pesticide indices (grams active ingredient / metric ton of salmon produced) of Chilean pesticide use from 2015 to 2019 (Servicio de Pesca y Acuicultura 2020a).

The quantity of salmon harvested in Chile has fluctuated only slightly since 2015, with the highest production quantity in 2019 and lowest production quantity in 2016 (Figure 3). Additionally, the ratio of pesticide applied to quantity of salmon produced remained low and stable from 2015 to 2017, and then began to exponentially increase in 2018 and 2019 (Figure 3). This trend is a result of the reintroduction of hydrogen peroxide as a treatment in 2017, which drastically increased the total quantity of pesticides applied in 2018 and 2019 (Figure 3). However, even excluding hydrogen peroxide, the ratio of pesticides applied to the biomass farmed has steadily increased from 2017 to 2018 and from 2018 to 2019 (Figure 2). This overall increase is reflective of a growing need for new treatment methods, because the sea louse species in Chile, *C. rogercresseyi*, has progressively become more resistant to other antiparasitics.

Overall, Norway, Canada and Chile have the largest ratios of pesticide use to farmed salmon (Figure 1, Figure 2). However, there is variation among these countries for why pesticide indices are high, and for why the pesticide index in Norway is decreasing while Chile's index is increasing (Figure 2). The following section will address the pesticide index fluctuations within, which will provide context for the recent decline in Norway's pesticide application, Chile's recent increase, Canada's relatively high index and Scotland's relatively low levels of pesticide application.

Antiparasitic management strategies in top salmonid producing countries

Norway

Historically, antiparasitics have been the preferred treatment method in Norway. However, sea lice resistance to medicines has increased exponentially over the past two decades and has forced farms to shift from traditional antiparasitics (predominantly azamethiphos, cypermethrin, deltamethrin and hydrogen peroxide) to non-medicinal treatments (Greaker, Vormedal, and Rosendal 2020; Overton et al. 2019). This includes the use of hydrolicers, which remove sea lice using high water pressure in a closed column and giving fish baths in fresh and warm water (Greaker, Vormedal, and Rosendal 2020). In fact, in 2017, over 74% of treatments were mechanical or thermal and by 2019, 59% of all treatments were thermal (Overton et al. 2019; Sommerset et al. 2020). However, thermal treatments have a much higher mortality rate than medical treatments (Sommerset et al. 2020).

According to BarentsWatch, an information portal launched by the Norwegian government, the percentage of medicinal treatment decreased from 44.35% in 2013 to only 12.18% in 2018 (BarentsWatch 2018). This was possible because of large increases in the number of cleaner fish, which are fish that eat sea lice off of the farmed species, and mechanical removal treatments (BarentsWatch 2018; Olaussen 2018). Overall, this has resulted in significant declines in the amount of pesticide used to treat sea lice, or *Lepeophtheirus salmonis*, in Norway. Even though antiparasitic treatment for sea lice has declined, as mentioned in the methods section, amoebic gill disease has become a large problem in Norwegian farms. This has resulted in large quantities of hydrogen peroxide being applied to treat the disease and is responsible for their high pesticide index in Figure 1 in recent years (Sommerset et al. 2020).

However, some of these non-medicinal treatments come at a cost to fish health, as thermal and mechanical treatments have much larger mortality rate (31% and 25%, respectively) compared to the mortality rate of azamethiphos, cypermethrin and deltamethrin, which are all less than 14% (Overton et al. 2019). Another alternative treatment, cleaner fish, also has some unforeseen downsides. The current levels of emaciation and skin ulcers on wrasse and lumpsucker cleaner fish, along with their high mortality rate, have raised major welfare concerns (Sommerset et al. 2020). Overall, in a survey by the Norwegian Veterinary Institute, they found that the majority of fish health personnel consider cleaner fish welfare in farms to be extremely poor (Sommerset et al. 2020).

Prior to the transition to non-therapeutant treatments, Norwegian salmon farms tried to address resistance by switching between different chemical therapeutics. However, multi-resistance, meaning sea lice are resistant to multiple treatments, has emerged, which poses a problem for this method (Olaussen 2018). Overall, resistance develops relatively quickly because sea lice are very adaptable (Olaussen 2018).

One major cause of the spread of resistance to azamethiphos, pyrethroids (deltamethrin and cypermethrin), emamectin benzoate and hydrogen peroxide was likely because there were not alternative treatments at the time when resistance began emerging, which resulted in increased application quantities (Hannisdal et al. 2020). Per Norwegian requirements, farms have to keep the number of adult female sea lice below 0.5 per fish, so when resistance began emerging, farms had to increase their treatment quantities to keep lice counts below that number (Hannisdal et al. 2020). This trend is also true for other countries and farms, which means that sea lice can be roughly tracked by the ratio of pesticide applied to fish farmed.

Overall, when considering fish escapes, antibiotics and pesticide use, Olaussen et al. believes current regulations in Norway do not provide enough incentive to shift industry practices to less environmentally harmful production practices (Olaussen 2018). They recommend that salmon farms used closed containment production systems that limit farming impacts on the surrounding ecosystems (Olaussen 2018).

Chile

Salmon is farmed in three regions in Chile, with the majority occurring in Region X (Los Lagos) followed by Region XI (Aysén) and then Region XII (Magallanes) (S. Bravo, Nuñez, and Silva 2013).

The first pesticide bath treatment used to treat sea lice infestations was metriphonate in 1981, followed by dichlorvos, ivermectin and then emamectin benzoate from 2000 to 2007 (Sandra Bravo et al. 2014). In 2007, emamectin benzoate was no longer able to effectively control sea lice populations, implying low sea louse sensitivity. This resulted in an increase in the quantity of emamectin benzoate applied and likely is the reason for the introduction of deltamethrin and hydrogen peroxide (S. Bravo, Nuñez, and Silva 2013; Sandra Bravo, Silva, and Monti 2012; Sandra Bravo et al. 2010).

SERNAPESCA is the governing body in Chile that regulates aquaculture. Some of their notable pesticide regulations include that any active ingredients in the same chemical family can only be applied a maximum of three consecutive times during a production cycle (Servicio Nacional de Pesca y Acuicultura 2015). They also prohibit the extra label use of antiparasitics and require that bath treatments not exceed seven days (Servicio Nacional de Pesca y Acuicultura 2015). These regulations are intended to limit excessive pesticide application and resulting sea louse resistance.

Chile is split into macro zones that determine the time frames when application is permitted, varying based on the oceanographic and seasonal conditions (Servicio Nacional de Pesca y Acuicultura 2015). This is also intended to coordinate treatments and limit sea louse spread from farm to farm. However, due to the high density of farms, even these measures are not enough to curb sea louse infestations.

SERNAPESCA also requires that companies report treatments at least three days prior to application along with the effectiveness of the treatment within two days (Servicio Nacional de Pesca y Acuicultura 2015). As of 2017, there has been increased surveillance in the Magallanes region because of an increase in the observed parasite loads (Servicio Nacional de Pesca y Acuicultura 2020b). This illustrates the push towards increased coordination and monitoring of sea lice on farms. However, information surrounding this monitoring is not readily accessible, like it is in Scotland and Norway, which makes it difficult for the public to hold companies or the Chilean government accountable (Scottish Salmon Producers Organization 2015; Sommerset 2020).

Scotland

Scotland has relatively low pesticide indices as a result of government regulations and industry-wide treatment plans. Their 1998 National Strategy was created to combat sea lice, with one of their explicit goals being to facilitate exchange of information between farmers, regulators, research scientists, pharmaceutical companies and any interest groups (Scottish Salmon Producers Organization 2015). Additionally, in 2013, the 2007 Aquaculture and

Fisheries (Scotland) Act was amended. This gave Scottish Ministers the legal power to do sea lice inspections on fish farms, look at sea lice records and assess the current measures in place to control sea lice (Marine Scotland 2019). As of June 10th, 2019, if the weekly average adult female sea lice count is above 2 per fish, the number must be reported to the Fish Health Inspectorate (FHI) within one week. FHI then increases monitoring of that site until the average adult female sea lice count per fish is below 2.

Cleaner fish (wrasse and lumpsucker) and physical removal are used to treat sea lice in addition to pesticides, which also helps to keep pesticide application low (Scottish Salmon Producers Organization 2014). However, even though the Scottish aquaculture industry has invested over 10 million euros in research on cleaner fish, they still face the same ethical issues as Norway (Scottish Salmon Producers Organization 2014).

Scottish farms also coordinate practices, including fallowing and treatments to reduce the likelihood of sea lice transmission between farms (Scottish Salmon Producers Organization 2014). Therapeutic treatments were found to be most effective when coordinating louse treatments in the early spring and early winter because it limits the number of female sea lice that are later able to breed (Scottish Salmon Producers Organization 2014). Scotland also advises farmers to administer treatments based on the build-up of pre-adults, which further limits the development of gravid (pregnant) females (Scottish Salmon Producers Organization 2014). All of these treatment strategies have allowed for Scotland to keep their pesticide use relatively low.

Canada

There are only three years of country level pesticide data available in Canada (Government of Canada 2020). This means that long term pesticide application trends are not visible in the above figures. As hydrogen peroxide was used during these three years, it is important to understand the history of pesticide use to understand if application has always been this high.

Hydrogen peroxide was granted full registration for its sale and use by Health Canada’s Pest Management Regulatory Agency (PMRA) under the *Pest Control Products Act* and Regulations in May of 2016 (“Registration Decision Hydrogen Peroxide” 2016). In the following years, between 2016 and 2018, hydrogen peroxide accounted for the majority of sea lice pesticides applied, and as hydrogen peroxide use only began in 2015, we can infer that pesticide use in Canada was significantly lower prior to 2015 (Government of Canada 2020). Therefore, while Figure 1 shows a very high pesticide index for the years 2016-2018, they likely had a much lower pesticide index prior to the introduction of hydrogen peroxide. Hydrogen peroxide is also used as an antifungal treatment for fish eggs, so it is not entirely reflective of the quantity of pesticide that is used to address sea lice. There is no distinction made between hydrogen peroxide used for sea lice or for antifungal purposes, so we cannot infer how much is actually used to treat sea lice.

Overall, sea lice management strategies vary between countries, with pesticide application being the favored treatment historically. However, in recent years, both Norway and Scotland have shifted towards non-chemical treatments, which have enabled them to drastically reduce their pesticide application.

Pesticide compounds applied in Chile

Mechanisms of action of pesticides used in Chile

The current mechanisms available for sea lice medication include acting on neurotransmission capabilities, molting processes and the detachment of sea lice from their fish hosts. Azamethiphos affects acetylcholinesterase (AChE) and emamectin benzoate effects glutamate-gated chloride channels, both of which inhibit neurotransmissions in sea lice (Aaen and Horsberg 2016). Deltamethrin and cypermethrin are chitin synthesis inhibitors and prevent sea lice from successfully molting (Aaen and Horsberg 2016). Finally, hydrogen peroxide treatment is able to treat fish with sea lice by inducing oxidative stress (Valenzuela-Muñoz et al. 2015). These pesticides are used to treat sea lice at different life cycle stages: organophosphates are only effective on pre-adults and adults (because AChE is less expressed in early life stages), chitin synthesis inhibitors are only able to impact sea lice that are still in molting stages of development and avermectins can be used for both juveniles and adults (Aaen and Horsberg 2016; San Martín et al. 2015).

Additionally, there are two methods for administering sea lice treatment: in feed or via immersive bath treatments. Avermectins and chitin synthesis inhibitors are usually given as an oral treatment (Aaen and Horsberg 2016). In-feed treatments require less physical labor, but fish that have low appetites at the treatment time may end up receiving a lower dose. This has the potential to increase sea louse resistance as some fish will not receive lethal doses, and therefore sea lice on those fish can reinfect farms (Aaen and Horsberg 2016). Organophosphates, pyrethroids and hydrogen peroxide are all applied as bath treatments (Aaen and Horsberg 2016). While bath treatments provide more even dispersal because they do not depend on fish appetite, some fish still may not receive full treatment (Aaen and Horsberg 2016).

Pesticide resistance in Chilean salmon farms and the ecological impacts of pesticides

The pesticides azamethiphos, emamectin benzoate, deltamethrin, lufenuron and hydrogen peroxide were applied in Chile in 2019. The following section will address the function of each pesticide, the development of resistance in *C. rogercresseyi* and the ecological impacts of each pesticide. These findings are summarized in the table below (Table 2).

Table 2. Summary of *C. rogercresseyi* resistance in Chile and ecological impacts of azamethiphos, emamectin benzoate, deltamethrin, lufenuron and hydrogen peroxide.

Compound	Resistance	Environmental Impact
Azamethiphos	• Over 90% efficacy in Region X and XI in 2014 (Agusti et al. 2016) • Resistance was developing in 2014 (Agusti et al. 2016) • Efficacy of azamethiphos declines each year (efficacy values, determined by the number of pre- and post-treatment adult sea lice, were 1.060 times higher in 2016 than 2017) (Arriagada et al. 2020)	• Lethal and sublethal impacts on American lobsters (*Homarus americanus*) (Dounia et al. 2016; Abgrall et al. 2000) • South American crab larvae (*Metacarcinus edwardsii*) were dying after exposure (Gebauer et al. 2017) • Benthic copepodid, *Tisbe battagliai,* impacted at low concentrations (Macken et al. 2015) • Sublethal impacts on blue mussels (*Mytilus edulis*) (Canty et al. 2007) • Stimulates primary productivity in the ocean, resulting in either nutrient limitation or deficiency (Rain-Franco et al. 2018)

Emamectin Benzoate	● Resistance detected in 2006 (Sandra Bravo et al. 2008) ● Treatments in 2008 in Region X did not to effectively control *C. rogercresseyi* populations (S. Bravo et al. 2013) ● *C. rogercresseyi* had lost sensitivity to emamectin benzoate in four Chilean farms in Region X and XI in 2014 (Agusti et al. 2016)	● Resulted in a decrease in photoautotrophic primary productivity during the spring, summer and winter seasons off Chiloé (Rain-Franco et al. 2018) ● Resulted in a decrease in chemoautotrophic primary production in the spring (Rain-Franco et al. 2018) ● Significant negative effect on crustacean abundance (Bloodworth et al. 2019) ● Negative effect on diversity and community structure of benthic ecology (Bloodworth et al. 2019) ● Sublethal effects in American juvenile lobsters (Daoud et al. 2018) ● Sublethal effects on the amphipod, *Monocorophium insidiosum*, in the Bay of Concepción (Tucca et al. 2014)
Deltamethrin	● Low sensitivity towards deltamethrin in the mid-west of Region X in 2014 (Agusti et al. 2016) ● Resistance present in Region X since 2008 (Kari Olli Helgesen et al. 2019; K. O. Helgesen et al. 2014) ● Resistance in 2008 in Region XI in the Las Guaitecas Archipelago (S. Bravo et al. 2013) ● Sensitivity decreased 3-12 times from 2007 to 2008 (Kari Olli Helgesen et al. 2019)	● Persists in sediment (Ernst et al. 2014) ● High lethality of *Gammarus pulex* and *Gammarus fossarum* (amphipod species) at low concentrations (Adam et al. 2010) ● Sublethal effects on the amphipod, *Monocorophium insidiosum*, in the Bay of Concepción (Tucca et al. 2014) ● Sublethal effects in *M. edwardsii* (Gebauer et al. 2017)
Lufenuron	● Currently high treatment efficacy (Poley et al. 2018) ● Resistance is already visible in the up and downregulation of genes (Poley et al. 2018) ● Low number of published studies	Published studies were not available for lufenuron, therefore studies on diflubenzuron were included instead as it has a similar mechanism of action. ● Decline in abundance of the Norwegian northern shrimp (*Pandalus borealis*) (Moe et al. 2019) ● Developmental effects in *Tisbe battagliai* (benthic copepod) at low concentrations (Macken et al. 2015) ● Higher mortality rate of Norwegian northern shrimp (*Pandalus borealis*) (Bechmann et al. 2017) ● Persistent in anoxic marine sediments (Selvik et al. 2002)
Hydrogen Peroxide	● Does not kill the majority of *C. rogercresseyi* (S. Bravo et al. 2010) ● *C. rogercresseyi* can strongly reattach 10 minutes after exposure (S. Bravo et al. 2010) ● Because of the geography and spacing of salmon farms, Bravo et al. (2010) thinks that hydrogen peroxide may not be a good treatment option for Chilean salmon farms	Hydrogen peroxide is generally considered the least toxic pesticide compared to other anti-louse treatments because it breaks down relatively quickly into water and oxygen (Schmidt et al. 2006). Although this breakdown means that there is a lower likelihood of the pesticide impacting non-target organisms, in cases of chronic exposure it can still have harmful effects. ● Much higher amounts are needed to treat the same biomass of fish, as 1 kg of hydrogen peroxide can treat 33 kg of fish while 1 kg of deltamethrin can treat up to 17 million kg of fish (Hannisdal et al. 2020) ● Lethal effects in the American lobster, the sand shrimp (*Crangon septemspinosa*) and two mysid species (*Praunus flexuosus* and *Mysis stenolepsis*) (Burridge et al. 2014) ● Sublethal effects in copepods and zooplankton (Van Geest et al. 2014) ● South American crab, *M. edwardsii*, is negatively impacted by exposure (Gebauer et al. 2017)

Azamethiphos

Azamethiphos is an organophosphate that was permitted in Chile by SERNAPESCA in 2013 (K. O. Helgesen et al. 2014a). It is able to kill sea lice by inhibiting acetylcholinesterase (AChE), which is an enzyme that is responsible for breaking down a neurotransmitter, acetylcholine (ACh), in the synapse. Without this enzyme, nerves in the sea louse will be continually stimulated, eventually leading to spastic paralysis and death (IRAC International MoA Working Group 2020). Azamethiphos also causes changes in the components of glutamatergic signaling, which affects intracellular pathways (Nunez-Acuna, Boltana, and Gallardo-Escarate 2016). These pathways are involved in neurotransmissions, like AChE, so changes here can affect the speed of transmissions in the synapse (Nunez-Acuna, Boltana, and Gallardo-Escarate 2016).

Sea louse resistance

In 2014, efficacy for azamethiphos on adult sea lice was above 90% in most Chilean farms (Agusti et al. 2016). In two farms in Region XI, sea lice had EC_{50} values (the concentration of drug that kills half of the lice) that were close to the *C. rogercresseyi* putative naïve level, which is the value *C. rogercresseyi* would have been prior to any pesticide exposure. However, in Region X, sea lice had EC_{50} values that were between eight and fifteen times higher than Region XI (Agusti et al. 2016). While sea lice in Region X still showed a high efficacy in 2014, these high EC_{50} values indicate that resistance is developing towards azamethiphos (Agusti et al. 2016). This is concerning given that azamethiphos was only introduced in 2013, so resistance has visibly developed in only one year. Between 2015 and 2017, one study calculated the efficacy of azamethiphos by taking into account the abundance of adult sea lice pre- and post-treatment. They found that efficacy was 1.114 times higher in 2015 than 2016 and 1.060 times higher in 2016 than 2017, showing an overall decline year to year treatment efficacy (Arriagada et al. 2020). Agusti et al. hypothesizes that these resistance levels were possible because of other organophosphates (metrifonate and dichlorvos), that were used between 1981 and 2001 (Agusti et al. 2016; Sandra Bravo et al. 2014). Sea lice were exposed to selective pressure from these pesticide exposures, which translated into faster resistance development to azamethiphos. This pesticide resistance also develops rapidly because of the short generation time of sea lice.

Another study found that even after only one azamethiphos treatment, sea lice have strong selective pressure to become pesticide resistant (Kari Olli Helgesen et al. 2019). The sea lice that survive application are the individuals that have alleles that reduce their sensitivity to the pesticide being applied (Kari Olli Helgesen et al. 2019). Then, those sea lice are the only ones breeding and producing the next generation, so the next generation will already be less sensitive to azamethiphos (Kari Olli Helgesen et al. 2019). Additionally, female sea lice are more resistant to azamethiphos than male sea lice. Female sea lice are responsible for the next generation, which means that female lice sensitivity is particularly important and therefore azamethiphos sensitivity monitoring should focus on females (Agusti et al. 2016).

When gravid, or pregnant, female sea lice were exposed to 0.4 and 2 ppb concentrations, 44% and 50% of their egg strings hatched after being placed into fresh filtered seawater (Sandra Bravo et al. 2015). While these values are significantly below the recommended application at 100 ppb, these concentrations were used because they have been found to separate sea lice with full sensitivity from those with reduced sensitivity (Sandra Bravo et al. 2015). Monitoring the hatching ability after pesticide exposure is crucial because resistance is hereditary and killing the offspring and adults is equally important when managing sea lice.

There are a few mechanisms by which sea lice can develop resistance to azamethiphos, with the primary method being due to mutations in the AChE (Agusti-Ridaura et al. 2018). Specifically, AChE1a is most likely the main synaptic AChE in *C. rogercresseyi*. Agusti-Ridaura et al. found that resistant lice had a DNA mutation that coded for a change from the amino acid phenylalanine to valine at codon 318 (F/V318) in AChE1 (Agusti-Ridaura et al. 2018). This indicates that there is a link between resistance and the F/V318 variant. Another mutation (Phe362Tyr) that exists in the gene for AChE protects sea lice from dying during azamethiphos bath exposure (Kari Olli Helgesen et al. 2019).

In addition to mutations that affect neurotransmissions, resistant sea lice show inhibited NOTCH signaling pathways after exposure (Boltana et al. 2016). This is important because exposure to azamethiphos results in the activation of the NOTCH signaling pathway, so if sea lice are able to inhibit NOTCH signaling pathways, they can counteract the effects of the pesticide (Boltana et al. 2016).

An upregulation in genes that were previously linked to resistance to avermectins (emamectin benzoate) and pyrethroids (deltamethrin and cypermethrin) were also upregulated in response to azamethiphos exposure (Valenzuela-Muñoz et al. 2015). This indicates that *C. rogercresseyi* may have a similar response to organophosphates as to avermectins and pyrethroids. Therefore, switching between pesticides will not necessarily result in effective treatments if resistance is applicable to multiple pesticides. This type of transferrable resistance is supported by a study in Norway that found sea lice with multi-resistance (Olaussen 2018).

Environmental Impact

In aqueous environments, most azamethiphos remains in the aqueous phase, which means that exposure for marine organisms will primarily occur in the water column (Ernst et al. 2014). This, coupled with recent studies done in Chile, indicate that azamethiphos exposure has negative effects on a variety of organisms.

In a study on adult male American lobsters (*Homarus americanus*), after five, one-hour exposures to 5 µg per liter of azamethiphos, they had an acute mortality rate of 93% because of its effect on hemolymph plasma, electron transport systems and metabolic rates (Dounia et al. 2016). This is especially concerning given that the manufacturers recommendation for application is around 100 µg / L, or 100 ppb, for between 30 and 60 minutes, which is significantly higher than the tested concentration (Arriagada et al. 2020; Agusti et al. 2016). Even at lower exposures, adult male lobsters still experienced hemolymph electrolyte and water fluxes, which means that regardless of concentration, azamethiphos will have a negative impact on lobsters (Dounia et al. 2016). Additionally, chronic exposure, which would be similar to exposure near salmon farms, resulted in sublethal effects in male American lobsters (Couillard and Burridge 2015). Sublethal effects are dangerous for a variety of reasons. Primarily, changes in energy allocation, due to increased stress, may result in delayed gonad maturation and impaired reproduction. Second, azamethiphos persisted in the lobsters after 24 hours in clean running seawater, which means that the addition of other pesticides or stressors could result in cumulative impacts and result in more severe responses (Couillard and Burridge 2015).

High levels of azamethiphos exposure also impact juvenile American lobsters by forcing them to leave their shelters (Abgrall et al. 2000). This drastically decreases the chances of survival into adulthood because juveniles rely on shelter to avoid predation. At concentrations of

100 μg per liter and short exposure times, lobster shelter use wasn't affected. However, if exposure amount or time increased (as it likely would around salmon pens), the juvenile lobsters will die either from pesticide exposure or indirectly because the lobster left its shelter (Abgrall et al. 2000). In combination with the fact that adult lobsters can be negatively impacted, azamethiphos may have an increased ability to harm lobster populations as it can keep juveniles from ever maturing and reproducing. While this specific lobster species is not found in Chile, according to SERNAPESCA, there are seven lobster species and a variety of crustaceans important for Chilean fisheries (Servicio Nacional de Pesca y Acuicultura 2019). Azamethiphos will likely affect these crustaceans in similar ways to the American lobster, so these studies provide insight for potential ecological impacts in Chile

Metacarcinus edwardsii is another crustacean that is negatively impacted by azamethiphos exposure. This is a South American crab species important for artisanal fisheries in Chile and its distribution largely overlaps with the distribution of the salmon farming industry (Gebauer et al. 2017). Therefore, it is important to assess the potential effect of azamethiphos on their populations. *M. edwardsii* larvae that were exposed to low levels (10 μg per liter) and high levels (up to 500 μg per liter) of azamethiphos were all dying after 30 minutes of exposure (Gebauer et al. 2017). Additionally, chronic exposure of less than 0.5 μg per liter still resulted in a 24% increase in mortality, which is likely how organisms would be exposed near salmon farms (Gebauer et al. 2017). Even at extremely low concentrations, exposure may have detrimental impacts on populations. Overall, as Gebauer et al. noted, anti-parasite chemicals may have a much greater impact on non-target species than been previously thought (Gebauer et al. 2017).

The benthic copepodid, *Tisbe battagliai*, is an important food source for many macroinvertebrates and fish. More importantly, it is a species that is reflective of non-target species that may be found near fish farms, and therefore exposed to azamethiphos. While azamethiphos did no effect the copepodid at low concentrations, it was acutely toxic at higher concentrations (Macken et al. 2015). This result implies that azamethiphos could have impacts on the bottom of marine food chains, therefore impacting the entire ecosystem.

One study explicitly utilized recommended aquaculture concentrations of azamethiphos and found that it can rapidly impact AChE activity in blue mussels (*Mytilus edulis*), which is the same mechanism by which azamethiphos kills sea lice (Canty et al. 2007). Azamethiphos can also have sublethal cytological and immunology effects, by impacting hemocyte viability and immune function of *M. edulis* (Canty et al. 2007). This illustrates that azamethiphos may have an effect on non-target mussel species, and even mussel species that are being farmed in nearby aquaculture facilities. The Chilean mussel, *Mytilus chilensis*, is one of the most economically important species in Chilean aquaculture and this study suggests that azamethiphos may have an impact on their production (FAO 2020a).

Separate from organism impacts, azamethiphos can have impacts that affect an entire ecosystem. Primary productivity is crucial for fisheries in Chile, as it provides a source of energy for marine fish and other organism populations. However, too much primary productivity can use up all of the nutrients in a given area, creating a nutrient deficiency. In some cases, azamethiphos can actually stimulate primary productivity in the ocean, resulting in either nutrient deficiency in ecosystems (Rain-Franco, Rojas, and Fernandez 2018). This would have cascading impacts on the fisheries in the area and may negatively impact the economy.

Emamectin Benzoate

Emamectin benzoate is an avermectin that was first introduced in Chile at the end of 1999 and interferes with nerve transmission in sea lice (Sandra Bravo et al. 2010). Specifically, it binds to the glutamate-gated chloride channels in the nerve cells of sea lice and allows for more chloride ions to enter the nerve cell. If more chloride is entering nerve cells, the neurons cannot communicate with each other and the sea louse becomes paralyzed and dies. Emamectin benzoate is a treatment that is usually given through feed and has been utilized over 14 years in Chile, with a decline in its use starting in 2008 (Agusti et al. 2016). Feed pellets are usually coated in emamectin benzoate, so when the fish eat, the pesticide is absorbed in the gut and distributed into fish tissue, including skin and mucus (MSD Animal Health 2012). Then, when sea lice feed on the host, emamectin benzoate is also consumed and paralyzes the louse (MSD Animal Health 2012).

Sea louse resistance

Resistance to emamectin benzoate is inevitable in countries with large farming areas with extensive emamectin benzoate use, like Chile. This is because there is greater exposure of fish, and therefore sea lice, to low concentrations, which may be a potential driver for treatment resistance (Lam et al. 2020). Emamectin benzoate resistance was first detected in 2006 in Chile, six years after its use began (Sandra Bravo, Sevatdal, and Horsberg 2008). The loss of sea louse sensitivity in Region X was not correlated with the geographical location or the number of years a given farm was in operation, which means that the main cause in the loss of sensitivity is the almost exclusive use of emamectin benzoate for over seven years in the region (Sandra Bravo, Sevatdal, and Horsberg 2008). Ivermectin (another avermectin) was also used for ten years during the 1990's, which likely resulted in selective pressure for lice that were resistant towards the mechanisms that avermectins utilize to control lice populations (Sandra Bravo, Sevatdal, and Horsberg 2008). This means that, in total, *C. rogercresseyi* had been under selective pressure to develop resistance for 15 years (as of 2006) (Sandra Bravo, Sevatdal, and Horsberg 2008).

Emamectin benzoate exposure to *C. rogercresseyi* gravid females decreases the ability of eggs to hatch (Sandra Bravo et al. 2015). However, at 100 ppb and 500 ppb, 43% and 42% of egg strings still hatched after being incubated in a pesticide free environment (Sandra Bravo et al. 2015). Per manufacturer instructions, doses are recommended to be between 50 and 100 μg per kilogram of fish per day for 7 to 14 days, which is less than these tested concentrations (Sandra Bravo, Silva, and Monti 2012; Agusti et al. 2016). Therefore, similar to azamethiphos, even after treatment, there is still a significant amount of sea louse eggs that survive and are able to become another generation of more resistant lice.

After a year of monitoring from September 2007 to August of 2008 in Region X on a farm in the Las Guaitecas Archipelago, emamectin benzoate did not effectively control *C. rogercresseyi* populations (S. Bravo, Nuñez, and Silva 2013). Even after treatment, the prevalence of adult sea lice was over 80% and sea louse abundance only slightly decreased after a second treatment (S. Bravo, Nuñez, and Silva 2013). During the time period when treatment efficacy was very low (2007), there was also a large increase in the amount of emamectin benzoate applied, which is likely explained by this decline in treatment efficacy (Sandra Bravo, Silva, and Monti 2012). As noted in the country pesticide comparison, this means that tracking the amount of pesticide applied can also be a measurement of treatment efficacy, and therefore sea lice resistance.

Throughout 16 farms in in Puerto Montt, Hornopiren, Castro and Quellón, *C. rogercresseyi* showed low sensitivity levels to emamectin benzoate even when the concentration went from 50 µg per kg of fish to 100 µg (Sandra Bravo, Silva, and Monti 2012). The abundance of *C. rogercresseyi* did not decline even after emamectin benzoate treatment in some farms in Chile and even if it did, the reduction in lice was only for a short period of time, with a fast return to pre-treatment abundance levels (Sandra Bravo, Silva, and Monti 2012). This is supported by another study done in 2014, which found that *C. rogercresseyi* had lost sensitivity to emamectin benzoate in four Chilean farms in Region X and XI (Agusti et al. 2016). In fact, at this time EC_{50} values were at least ten times higher than the naive sensitivity of *C. rogercresseyi*, which indicates a high level of resistance (Agusti et al. 2016).

An additional hurdle to emamectin benzoate use is that reduced sensitivity can persist in up to seven generations of *C. rogercresseyi* (Sandra Bravo, Sevatdal, and Horsberg 2010). This means that sea louse populations in Chile will likely not become sensitive again due to the close proximity of farms, which allows for the movement of resistant genes from farm to farm unless all application stops. Finally, as organophosphate, pyrethroid and avermectin resistance may be linked, this seven-generation persistence may not even go away if emamectin benzoate application stops because of multi-resistance (Valenzuela-Muñoz et al. 2015).

Environmental Impact

Emamectin benzoate has detrimental impacts on non-target organisms and marine environments. In Llico Bay on Chiloé, emamectin benzoate concentrations equivalent to doses used in salmon farms resulted in a 60% to 90% decrease in photoautotrophic primary productivity during the spring, summer and winter seasons (Rain-Franco, Rojas, and Fernandez 2018). Chemoautotrophic primary production also declined between 70 and 80% in the spring (Rain-Franco, Rojas, and Fernandez 2018). This can be dangerous for ecosystems because if primary productivity decreases, the ecosystem cannot support primary consumers or organisms farther up in the food chain. If ecosystems, especially in Chiloé, experience declines in fishery productivity, this would have large impacts on artisanal fishermen and any communities that depend upon marine resources. Additionally, emamectin benzoate can potentially act as a depressor of carbon fixation, which would result in areas where emamectin benzoate decreases the ecosystems ability to act as a carbon sink, because organisms are not intaking carbon dioxide from the atmosphere (Rain-Franco, Rojas, and Fernandez 2018).

In Scotland, a model was created using data collected near eight salmon farms and found that emamectin benzoate had a significant negative effect on overall crustacean abundance as well as the diversity and community structure of the benthic ecology (Bloodworth et al. 2019). Additionally, emamectin benzoate was found in 97% of the sampled locations taken near the eight farms, which shows that emamectin benzoate is more widespread in Scotland than previously thought (Bloodworth et al. 2019). This means that the presence of emamectin benzoate in other countries, like Chile, may also be more widespread than previously thought.

In addition to azamethiphos, emamectin benzoate also has a negative impact on crustaceans. In one study, American juvenile lobsters experienced sublethal effects after being in sedimentary conditions similar to those under an Atlantic salmon net pen after in-feed treatment (Daoud et al. 2018). Impacts included delayed molting and growth, which can have population impacts if offspring are not able to mature. They also found that increased exposures and higher doses resulted in increased mortality and toxicological effects (Daoud et al. 2018). Again, crustaceans are an important part of the Chilean economy, particularly in artisanal fisheries, so declines in lobster populations may have a negative impact on the Chilean economy.

In the intertidal zone of Cocholgüe Beach of the Bay of Concepción, short term emamectin benzoate exposure caused sublethal effects on the amphipod, *Monocorophium insidiosum* (Tucca et al. 2014). Glutathione S-transferase enzyme (GST) activity and the amount of thiobarbituric acid reactive substances (TBARS) increased with exposure, which is an indication that the amphipods were under oxidative stress (Tucca et al. 2014). Emamectin benzoate also has the potential to persist and accumulate in sediment, which is amplified by the consecutive periods of treatment in salmon pens (Tucca et al. 2014). This can result in greater levels of the pesticide accumulating and result in toxic side effects for amphipods and crustaceans, which are important for marine ecosystems and fisheries.

Deltamethrin

Deltamethrin was introduced to Chilean salmon farms in 2007 (K. O. Helgesen et al. 2014b). It is usually applied as a bath treatment and alters the voltage-gated sodium channels in sea louse nerve cells. This means that sea lice experience uncontrolled action potentials that lead to the exhaustion of nerve cells and eventually, death. Deltamethrin is also classified as a xenobiotic drug, meaning that its application leads to changes in the glutamatergic synapse receptors of *C. rogercresseyi*, which results in the inhibition of neurotransmissions and can lead to death (Nunez-Acuna, Boltana, and Gallardo-Escarate 2016).

Sea louse resistance

One of the mechanisms for deltamethrin resistance is through the Notch signaling pathway. Deltamethrin exposure inhibits *C. rogercresseyi* Notch signaling pathways in the same way that azamethiphos does, and sea lice develop resistance by preventing this Notch pathway inhibition (Boltana et al. 2016).

In a study running from 2007 to 2008, deltamethrin treatment did not give the expected control of *C. rogercresseyi* populations in the Las Guaitecas Archipelago of Region XI (S. Bravo, Nuñez, and Silva 2013). In a more recent study, they found farms in Region X were applying a high number of treatments and there was a high re-infestation rate, which also indicates a severe resistance to deltamethrin (Agusti et al. 2016). Both of these studies are evidence that deltamethrin resistance is present and has been in Region X since 2008 (K. O. Helgesen et al. 2014a).

Bioassay results have found that EC_{50} values decreased between 3 and 12 times from 2007 levels to 2008 levels (Kari Olli Helgesen et al. 2019). This is a drastic change when considering that the development of resistance occurred in one year. Compared to Norway, Chile uses a greater percentage of pyrethroids for sea lice treatments and also has a more intense treatment regime (Kari Olli Helgesen et al. 2019). This has likely contributed to the rapid development of deltamethrin, and other pyrethroid resistance in Chile (Placencia et al. 2018).

The majority of eggs are not killed upon application, which means that even after treatments, if there are viable egg strings, they will hatch and reinfect the farm. After exposure to 0.2 ppb and 1 ppb of deltamethrin for 24 hours, 67% and 61% of egg strings were still able to hatch (Sandra Bravo et al. 2015). This means that deltamethrin treatments will not be able to completely remove infestations and will allow resistance to develop quickly. Females are also more resistant than males to deltamethrin, which should be noted because female lice are responsible for the next generation of lice (Agusti et al. 2016; Kari Olli Helgesen et al. 2019). Therefore, sensitivity monitoring should focus on females, similar to azamethiphos.

Interestingly, one author also hypothesized that more efficient bath treatments (including the synchronization of treatments between neighboring farms), may actually accelerate resistance development (Kari Olli Helgesen et al. 2019). This is because if treatment is more effective, only the most resistant sea lice will survive and be able to reproduce. While they state that this has not been documented, it is an interesting hypothesis that may be important to understand to develop effective treatment strategies (Kari Olli Helgesen et al. 2019).

Environmental Impact

Similar to emamectin benzoate, deltamethrin also persists in sediment and is primarily found in the particle phase (Ernst et al. 2014). In the Reloncaví Fjord and the Chiloé Inner-Sea, deltamethrin was found in all samples that were several orders of magnitude higher than in salmon farming areas in Norwegian fjords (Placencia et al. 2018). This shows that the increased use of pyrethroids during the past few decades has and continues to directly impact the sediment surrounding salmon farms (Placencia et al. 2018).

Amphipods play an important role in nutrient cycling and are a food source for many fish species (Welton 1979; Maitland 1966). Many of these organisms are found in sediment and are highly sensitive to deltamethrin. The amphipod species *Gammarus pulex* and *Gammarus fossarum* show a high lethality of deltamethrin in the youngest segments of their populations even at the lowest tested concentration (Adam et al. 2010). The offspring of *G. pulex* and *G. fossarum* make up the largest portions of their populations and are essential for future generations success, which means that deltamethrin could put amphipod species at risk (Adam et al. 2010). Additionally, the amphipod *M. insidiosum*, which is also important for marine food webs, was found in sediment from the intertidal zone of the Bay of Concepción and experienced sublethal effects from deltamethrin exposure (Tucca et al. 2014).

In addition to the impact of azamethiphos on *M. edwardsii*, deltamethrin can also have detrimental impacts on the crustacean. After exposure to deltamethrin at multiple concentrations (0.1, 0.25, 0.5 and 1 μg per liter), 100% of *M. edwardsii* larvae were classified as dying (Gebauer et al. 2017). The concentration recommended by the manufacturer is between 2 and 3 μg per liter for 40 mins, which is well above the concentrations tested (Gebauer et al. 2017; Agusti et al. 2016). Again, this shows that the use of pesticides, in this case deltamethrin, may have negative impacts on the artisanal fishing community that relies on *M. edwardsii* populations.

SERNAPESCA facilitates the application timetable of deltamethrin and azamethiphos bath treatment (Gebauer et al. 2017). This usually entails eight days of application followed by eight days without any application. However, this timetable means that non-target organisms may be exposed to deltamethrin for long periods of time (Gebauer et al. 2017). In particular, when *M. edwardsii* larvae exposed to azamethiphos concentrations that were less than 0.5 μg per liter, they experienced a 24% increase in mortality, which means that even low levels of parasite control may impact non-target species (Gebauer et al. 2017).

Lufenuron

Lufenuron is an anti-parasitic, along with diflubenzuron, that inhibits chitin synthesis in sea lice and is usually administered as an oral treatment. Specifically, one study found that the primary target of lufenuron is the last chitin synthase (CHS) enzyme in the chitin synthesis pathway (Harðardóttir et al. 2019).

Lufenuron was only registered for aquaculture use in Chile in 2016, so there is currently little literature on *C. rogercresseyi* resistance and its environmental impacts (Rath, Erdely, and Rainer 2017). However, diflubenzuron has been on the Chilean market since 2010 and is also a chitin synthesis inhibitor, meaning that lufenuron and diflubenzuron would likely impact sea lice and non-target organisms in the same way (Agusti et al. 2016). Therefore, the section on lufenuron's environmental impacts will include studies that were done with diflubenzuron.

Sea louse resistance

Lufenuron impacts the ability of sea lice to metabolize their old cuticle as well as the function of their cuticle development proteins and solute transport (Poley et al. 2018). In a study of the effect of lufenuron on *L. salmonis*, treatment efficacy was around 90% (Poley et al. 2018). However, even though efficacy appears to be high, it can take a few years from the start of a new chemical treatment for this resistance to appear, even if there is already some level of resistance present (Olaussen 2018). Additionally, while lufenuron was found to impact larvae molting, exposure to *L. salmonis* egg strings for 24-72 hours at 500 ppb still had a hatching success rate of over 90%, which means that lufenuron does not prevent any existing eggs from hatching (Poley et al. 2018).

Even though efficacy was high, *L. salmonis* experienced the downregulation of 1045 expressed transcripts after exposure, 50 of those being transport-related transcripts, along with the upregulation of three transcripts related to chitin synthesis (Poley et al. 2018). This illustrates the rapid response that sea lice can have to pesticide application. Additionally, this study was not done on *C. rogercresseyi*, which means that the efficacy levels may not be correct because of potential multi-resistance present in Chile.

Environmental Impact

While there are limited studies on the impact of lufenuron on aquatic environments, diflubenzuron is also a chitin synthesis inhibitor and therefore the environmental effects on organisms that utilize chitin will be similar to the effects from lufenuron.

Diflubenzuron is persistent in anoxic marine sediments, meaning that it does not readily degrade in sediment (Selvik et al. 2002). Diflubenzuron is also not readily dissolved in water, so treatment usually remains first in feed pellets, and then later in fecal pellets, which then sink and become deposited on the seafloor as sediment. As such, diflubenzuron is then able to persist in the sediment below salmon farms and may lead to oxygen deficiencies in the sediment (Selvik et al. 2002). This diflubenzuron persistence means that benthic organisms will be exposed to diflubenzuron.

Additionally, the mussel species, *Mytilus chilensis*, is an important source of production in the Los Lagos Region, and shares bodies of water with the salmon industry (Norambuena-Subiabre, González, and Contreras-Lynch 2016). In a study funded by the Fisheries Undersecretary of the Chilean government, these mussels were found to uptake diflubenzuron concentrations that would be considered unacceptable for human consumption. However, these mussels were able to remove the anti-parasitic from their system within a few days and the concentrations the mussels were exposed to was higher than they would be in farm conditions. Overall, diflubenzuron likely does not have an impact on the international quality parameters required for mussels (Norambuena-Subiabre, González, and Contreras-Lynch 2016).

When exposed to diflubenzuron medicated feed, the northern shrimp, *Pandalus borealis*, had significantly higher rates of mortality (Bechmann et al. 2017). Potentially more important is the fact that diflubenzuron exposure also resulted in a decreased number of successful molts, which has population level implications (Bechmann et al. 2017). Overall, the abundance this shrimp has declined in Norwegian fjords as a result of diflubenzuron treatment and poses a danger to shrimp populations (Moe et al. 2019). While this particular species is not found in Chile, it illustrates the effect that diflubenzuron, and therefore lufenuron, may have on other crustacean populations near salmon farms.

One benthic organism, *T. battagliai*, is a harpacticoid copepod that is an important food source for many macroinvertebrates and fish. More importantly, it is a species that is reflective of non-target species that may be found near fish farms, and therefore exposed to diflubenzuron. At concentrations well below the manufacturers recommended dosage of 0.1 to 0.3 milligrams per liter, developmental effects were observed in this copepod (Rafaela Leão Soares et al. 2016; Macken et al. 2015). This means that diflubenzuron may have adverse effects on non-target organisms.

Hydrogen Peroxide

Hydrogen peroxide is another bath treatment that is utilized to remove sea lice from salmon hosts. While its mechanism for detaching sea lice is not entirely understood, according to Chavez-Mardones et al., hydrogen peroxide affects some of the enzymes in sea louse antioxidant systems and induces oxidative stress (Valenzuela-Muñoz et al. 2015). Hydrogen peroxide is also an oxidizing agent and generates gaseous oxygen, which becomes trapped inside the cuticle of the sea lice (Gebauer et al. 2017). Gas bubbles have also been found in the louse gut and hemolymph, which immobilizes, or paralyzes the louse (Bruno and Raynard 1994).

While hydrogen peroxide has been used as early as 1994 in Chile, it was officially reintroduced into farms in February of 2007 as an alternative to emamectin benzoate (Sandra Bravo et al. 2010).

Sea louse resistance

The majority of *C. rogercresseyi* are not killed at the manufacturer's recommended treatment concentration of 1.5 grams per liter (Sandra Bravo et al. 2010; Gebauer et al. 2017). This, along with the fact that *C. rogercresseyi* can strongly reattach 10 minutes after exposure, has brought the overall effectiveness of hydrogen peroxide into question (Sandra Bravo et al. 2010). This ability to recover and find a host means that there is a high risk of reinfestation after application (Sandra Bravo et al. 2010). Additionally, cross infection between farms is highly likely because *C. rogercresseyi* copepodids frequently disseminate into the water column and into nearby farms. However, one study did find that as hydrogen peroxide concentration increased, the number of sea lice that detached from fish also increased (Valenzuela-Muñoz et al. 2020).

While the impact of hydrogen peroxide on adult sea lice is relatively minimal, hydrogen peroxide has a larger impact on copepodids. They are more impacted by hydrogen peroxide than adult sea lice because while adult sea lice are immobile, and therefore vulnerable for approximately 2 hours after treatment, they do not actually die, while copepodids have reduced survival after treatment (Marín et al. 2018). Overall, hydrogen peroxide treatments can have an impact at the population level because of its effect on sea lice in the "infective stage" of development but does not limit cross contamination and the reattachment of adult sea lice.

As with azamethiphos and deltamethrin, female sea lice are more resistant to hydrogen peroxide than males (Chávez-Mardones et al. 2017). In fact, at 1000 mg per liter concentrations, female sea lice accounted for 75% of surviving lice (Chávez-Mardones et al. 2017). Finally, at 2000 mg per liter, bioassay results found that 100% of the surviving lice were female (Chávez-Mardones et al. 2017).

A recent study found that hydrogen peroxide treatment induced changes in genes that are related to drug-responses and oxidative stress in female sea lice (Valenzuela-Muñoz et al. 2020). Additionally, exposure upregulates the catalase gene and affects molecular pathways that are involved in the detoxification of free radicals, oxidative stress and reproduction (Valenzuela-Muñoz et al. 2020).

Catalase (CAT), glutathione peroxidase (GPX) and peroxiredoxin (PRX), are enzymes that are involved in the antioxidant systems of *C. rogercresseyi* and were found to be more active after hydrogen peroxide application (Chávez-Mardones et al. 2017). Catalase expression has also been specifically found to be upregulated in resistant sea lice, in comparison to sensitive lice (Agusti-Ridaura et al. 2020). However, this expression is only induced by hydrogen peroxide exposure, which means that it cannot be used as a resistance marker because it does not appear in unexposed lice that may be resistant (Agusti-Ridaura et al. 2020). Instead, Agust-Ridaura et al. found that Glp1_v2, an aquaglyceroporin, may be a channel for hydrogen peroxide, which means that its downregulation limits the amount of hydrogen peroxide that can enter sea louse cells and is promising as a resistance marker (Agusti-Ridaura et al. 2020).

Overall, because of the geography in Chile and density of salmon farms, Bravo et al. (2010) suggests that hydrogen peroxide may not be a good treatment option for Chilean salmon farms. However, they do indicate that it could potentially be effective if salmon were treated in well boats and water was filtered to remove the detached parasites, which would avoid any lice dispersal to nearby farms (Sandra Bravo et al. 2010).

Environmental Impact

Of all the anti-louse pesticides, hydrogen peroxide has the smallest environmental impact because it degrades into water and oxygen via chemical reduction, decomposition by algae, zooplankton and heterotrophic bacteria (Schmidt et al. 2006).

However, while hydrogen peroxide is one of the least toxic pesticides for sea louse management, this is only in comparison to other antiparasitics: it still has some negative ecological effects (Burridge et al. 2014). At concentrations close to recommended treatment concentrations, lethal effects have been observed in the American lobster, the sand shrimp (*Crangon septemspinosa*) and two mysid species (*Praunus flexuosus* and *Mysis stenolepsis*) (Burridge et al. 2014). Additionally, copepods and zooplankton experienced sublethal effects at 120 to 460-fold dilution doses compared to recommended treatment concentrations (Van Geest et al. 2014). Specifically, copepod feeding was inhibited and zooplankton experienced inhibition in feeding and mobility (Van Geest et al. 2014).

Depending on the concentration, some bacterial, algal, zooplankton and invertebrate populations may also be impacted by hydrogen peroxide (Schmidt et al. 2006). However, in this study the majority of hydrogen peroxide was rapidly reduced to concentrations that were low enough that it was not likely to cause detrimental effects for most aquatic organisms (Schmidt et al. 2006).

The South American crab, *M. edwardsii*, is also negatively impacted by hydrogen peroxide exposure (Gebauer et al. 2017). Exposure exceeding 1500 milligrams per liter (the recommended treatment concentration) resulted in approximately 67% mortality of larvae and had sublethal effects, including delayed molting, on the remaining 38% of larvae (Gebauer et al.

2017). Additionally, chronic exposure of hydrogen peroxide, similar to the exposure larvae may experience near a salmon farm, resulted in a high mortality, and at the recommended treatment concentration, 100% of larvae were affected (Gebauer et al. 2017).

Potential anti-louse treatments

Historically, pesticides have been the main treatment strategy for managing sea lice in open-net salmon farms. However, declining lice sensitivity has resulted in increases in pesticide application and a constant search for new pesticide compounds.

While companies are working to develop new pesticides, their potentially toxic effects on surrounding ecosystems and non-target species are not yet known. Additionally, multi-resistance has been documented in Norway and is likely present in Chile. This can be inferred because *C. rogercresseyi* responds to avermectins, pyrethroids and organophosphates in a similar way, indicating resistance to one pesticide can be applicable to other pesticides (Olaussen 2018; Valenzuela-Muñoz et al. 2020). As a result of previous applications, sea lice may adapt more quickly to new pesticides, even if the new compound has never been used.

One of the potential mechanisms of action for treating sea lice is the nicotinic acetylcholine receptor (nAChR). Neonicotinoids are a group of insecticides that bind to the nACh receptor in nerve cells and cause continuous stimulation, eventually leading to parasite death. One of these compounds, imidacloprid, is currently in development and is effective at treating sea lice (Aaen and Horsberg 2016). Benchmark, a company based in the UK, is currently working on releasing their imidacloprid product called BMK08. However, based on an analysis of 214 toxicity tests of 48 species, both short- and long-term exposure levels of neonicotinoids, like neonicotinoids can have negative impacts on survival, growth and mobility of aquatic insects and crustaceans (Morrissey et al. 2015). Of particular importance is the potential impact on mayfly (*Ephemeroptera*), caddisfly (*Trichoptera*) and midge (*Diptera*) species, which are a crucial part of aquatic food chains and are highly sensitive to neonicotinoids (Morrissey et al. 2015). Additionally, imidacloprid has sublethal impacts on the adult black tiger shrimp (*Penaeus monodon*), which illustrates that it may impact other non-target crustaceans (Butcherine et al. 2020).

Other potential pesticide compounds include cartap hydrochloride, which blocks nAChR, and spinetoram, which modulates nAChR, and are highly effective against sea lice. However, spinetoram was difficult to dissolve in seawater, which is crucial for pesticides used in aquaculture (Aaen and Horsberg 2016). Overall, many molecules are not able to fully dissolve in sea water, which limits the potential available pesticides (Aaen and Horsberg 2016). Another pesticide that has been assessed for use is pyriprole, which is an antagonist to GABA-gated chloride channels in sea louse nerve cells. It dissolves successfully in sea water and induces mortality in sea lice even at relatively low concentrations (Aaen and Horsberg 2016). However, pyriprole is a type of phenylpyrazoles, which is harmful to terrestrial ecosystems and therefore may have negative impacts on organisms near fish farms (Konwick et al. 2006). This overview of some of the potential pesticides illustrate that it is difficult to find new antiparasitics that fit all of the requirements for aquaculture and that are safe for use.

As seen in Norway and Scotland, other methods of managing sea lice include thermal, freshwater and mechanical treatments. Another non-chemical treatment is ‘depth-based’ prevention. This involves increasing the depth of net pens to separate the salmon from the infective copepodids, which live in surface waters (Coates et al. 2020). However, because swimming depth may be a heritable trait, sea lice that are able to swim at greater depths may be selected for, thereby adapting to depth-based prevention in the same way as chemical treatments (Coates et al. 2020). This has major implications for other non-chemical treatments. If there is any genetic component that allows for sea lice to survive thermal, freshwater or mechanical treatments, lice will be able to reduce their sensitivity. This would then reduce the effectiveness of non-chemical treatments. Therefore, regardless of the treatment, sea lice resistance may develop, indicating that the only way to combat infestations in the long term is to increase research specific to Chile that is able to determine the most effective treatment timing, coordination and geographic distribution of farms.

There are a limited number of pesticide compounds that are viable for sea lice treatment, which means that if sea lice develop resistance to all available antiparasitics, there are not any other compounds that can be readily applied. Development of new sea louse pesticides is limited because of issues with the ability of compounds to dissolve in seawater and their safety for use in marine environments. This means that companies need to be careful with application, as increased frequency and application quantity can lead to increased resistance. In order to support these companies, researchers need access to information about the quantity and timing of pesticide application to study resistance patterns at a national and regional level. In Chile, this is vital because of the close proximity of farms in addition to the limited flow of water in the fjords, which enable lice to easily travel from one farm to the next, resulting in widespread resistance.

Conclusion: the future of Chilean salmon farming

Overall, transparency would benefit Chile for a multitude of reasons. First, increased transparency would provide the opportunity for more scientific research. Second, with this research, Chile has the opportunity to become a leader in pest management strategy and three, Chile risks losing key consumer markets if they refuse to increase company level transparency.

The current population growth rate and demand for salmon means that there is potential for Chile to surpass Norway in sea-louse management strategies and overall financial and environmental sustainability, given proper industry transparency. While this has not been possible in the past because of industry-wide setbacks due to disease outbreaks and consumer perception of Chilean salmon, access to company data could mitigate setbacks in the future (Poblete et al. 2019). This is because in the past, a lack of access to data prevented government regulation and scientific research had kept up with industry growth, which has the potential to be changed (Poblete et al. 2019). Most notably, the outbreak of infectious salmon anemia (ISA) in 2007 led to widespread industry setbacks (Poblete et al. 2019). Additionally, other salmon-producing nations are still grappling with sea lice infestations, as even non-chemical treatments in Norway and Scotland still have drawbacks. This means that as one of the top salmon producers, Chile has an opportunity to take the lead in sea-lice management and sustainability.

Research specific to Chilean farming is also necessary to combat disease and pest infestations because effective solutions vary depending location (Barzman et al. 2015). Therefore, even if other countries are successful in their search for solutions, those solutions may not be best treatment strategies for Chilean geography and conditions.

In terms of public information access, a study by Overton et al. in Norway found that national databases are extremely important as they allow for an in-depth analysis of industry-wide processes (Overton et al. 2019). They also note that Scottish databases on salmon mortality were recently made public, which allowed for a more comprehensive analysis that helped farmers and researchers understand the underlying mechanisms of fish death (Overton et al. 2019). Data on pesticide application and quantities is publicly available data in the other major salmon producing countries (Norway, Canada, Scotland) and their continued global success illustrates that publishing this data has not harmed these companies (Sapag 2020). Overall, a lack of publicly available information on what pesticides are being used and their application makes it difficult for researchers to conduct scientific studies that could benefit companies in the long run. Research may be able to provide insight into new treatments that are more efficient and mitigate the impact to farmed fish and non-target organisms.

In recent years, transparency has also become a greater concern for consumers when deciding where to purchase a product. This means that consumers in the United States, Japan and the European Union may be less likely to purchase salmon from Chile because of the low transparency in regard to farming practices. As consumer concern grows, so does the need for salmon companies that operate in Chile to make their practices public. Additionally, many international and national publications have been critical about the state of the Chilean farming industry, which does not reflect well on Chilean companies (Sapag 2020). Separate from consumer demand, many of the pesticides currently used in Chile have negative impacts on the environment, and potentially on human beings. However, due to low levels of transparency, the Chilean public is not necessarily aware of these risks. This has also contributed to growing distrust between the salmon industry and the Chilean public, which is in the best interest of the salmon companies to resolve. The public is also not currently able to keep companies accountable for their farming practices, which means that there is an added layer of public distrust towards Chilean regulatory agencies and whether or not they are effectively keeping companies accountable.

As long as open-net salmonid farming occurs, sea lice will pose a problem (Scottish Salmon Producers Organization 2015). Therefore, it is crucial for Chile to increase the free flow of information between all stakeholders to collaboratively work towards effective sea lice management strategies. As seen in this report, Chile is grappling with decreasing sea louse sensitivity and limited opportunity to use other pesticide treatments. While Norway and Scotland have shifted to non-chemical treatment options, many obstacles around fish health still remain. As the second largest producer of salmon, Chile has an opportunity to take the lead in research and development of future management strategies.

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