Policies and Technologies for a 'fish out of place'

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Abstract

In a world where the race to feed a growing population intensifies, the oceans have become the new frontier for food production. Aquaculture, particularly salmon farming, has risen as a beacon of hope, promising to deliver protein-rich food to millions. Yet, beneath the surface of this industry's success, complex environmental challenges persist—most notably, the escape of farmed salmon, which casts long shadows over wild salmon populations and fragile marine ecosystems.

This thesis evaluates the effectiveness of existing policies and technologies in mitigating the ecological risks associated with farmed salmon escapes. Through a detailed analysis of 14 global salmon production regions, the research assesses the strengths and weaknesses of these policy frameworks, revealing that while regulatory measures have evolved, their effectiveness is often constrained by weak enforcement and the inherent challenges of open-net pen aquaculture. Additionally, the thesis explores the role of triploid (sterile) salmon in addressing the environmental challenge of escapes, with a particular focus on aquaculture production in Newfoundland, Norway, and Tasmania. By situating these findings within the broader context of environmental policy and the global aquaculture industry, the thesis reveals the complexities of aligning production goals with environmental sustainability in food production.

Keywords: salmon aquaculture, escapes, introgression, policy, technology, sustainable intensification

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List of Abbreviations

ACFFA - Atlantic Canada Fish Farmers Association

ASF - Atlantic Salmon Federation

BIM - Irish Sea Fisheries Board

CBC - Canadian Broadcasting Corporation

CMS - Containment Management System

DFO - Department of Fisheries and Oceans

ECOPACT - Environmental Code of Practice for Aquaculture Companies and Traders

EIA - Environmental Impacts Assessment

EPA - Environmental Protection Agency

FAO - Food and Agriculture Organization

HSMB - Heart and Skeletal Muscle Inflammation

ICRA - Icelandic Code of Regulations for Aquaculture

ICES - International Council for the Exploration of the Sea

IMAS - Institute for Marine and Antarctic Studies

ISGA - Irish Salmon Growers' Associations

MAST - Icelandic Food and Veterinary Authority

NASCO - North Atlantic Salmon Conservation Organization

NINA - Norwegian Institute for Nature Research

NRS - Norway Royal Salmon

NRCan - Natural Resources of Canada

NYTEK - Norwegian Technical Standard for Aquaculture Equipment (NS 9415)

OECD - Organisation for Economic Co-operation and Development

RSPCA - Royal Society for the Prevention of Cruelty to Animals

SALTAS - Salmon Enterprises of Tasmania

TAMP - Tasmanian Alliance for Marine Protection

TFDA - Tasmanian Fisheries Development Authority

The Code - Code of Containment for the Culture of Salmonids

WAC - Washington Administrative Code

NOAA - National Oceanic and Atmospheric Administration

Co-Authorship statements

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Narges Jalili Kolavani and Charlie Mather conceived the study. Narges Jalili Kolavani conducted the initial literature review and identified the top salmon-producing regions. Data collection was primarily handled by Narges Jalili Kolavani, with Charlie Mather providing supplementary data and reviewing the gathered information. Narges Jalili Kolavani performed the primary data analysis, with input and guidance from Charlie Mather. The thematic analysis and comparison of policy frameworks were jointly developed by both authors.

Narges Jalili Kolavani wrote the first draft of the manuscript, which was then critically revised by Charlie Mather. Both authors contributed to the final manuscript by refining the arguments, revising the text, and ensuring the overall coherence of the paper.

Chapter one: Introduction and Overview

1.1 Research Context

The State of World Fisheries and Aquaculture 2024 showcases FAO's "Blue Transformation," focusing on advancing sustainable aquaculture intensification, improving fisheries management, and strengthening aquatic food value chains with updated data [1]. It highlights the significant potential of aquaculture to deliver nutritious diets and address the increasing global demand for food fueled by population growth (Figure 1.1) [1]. This promise has materialized in one of the most successful forms of animal agriculture, an industry that is built on a sophisticated infrastructure that includes nets and cages in nearshore environments, primarily focused on the cultivation of Atlantic salmon, and supported by commercial feed [2,3]. This sector has rapidly expanded from its origins in Norway to become a global enterprise [1]. Norway, the world's largest producer, continues to dominate the market, accounting for over half of the global supply. In 2022 alone, at just under 1.6 million metric tons, Norway accounted for nearly 39 percent of the global production of all salmonid species [4] (Figure 1.2).

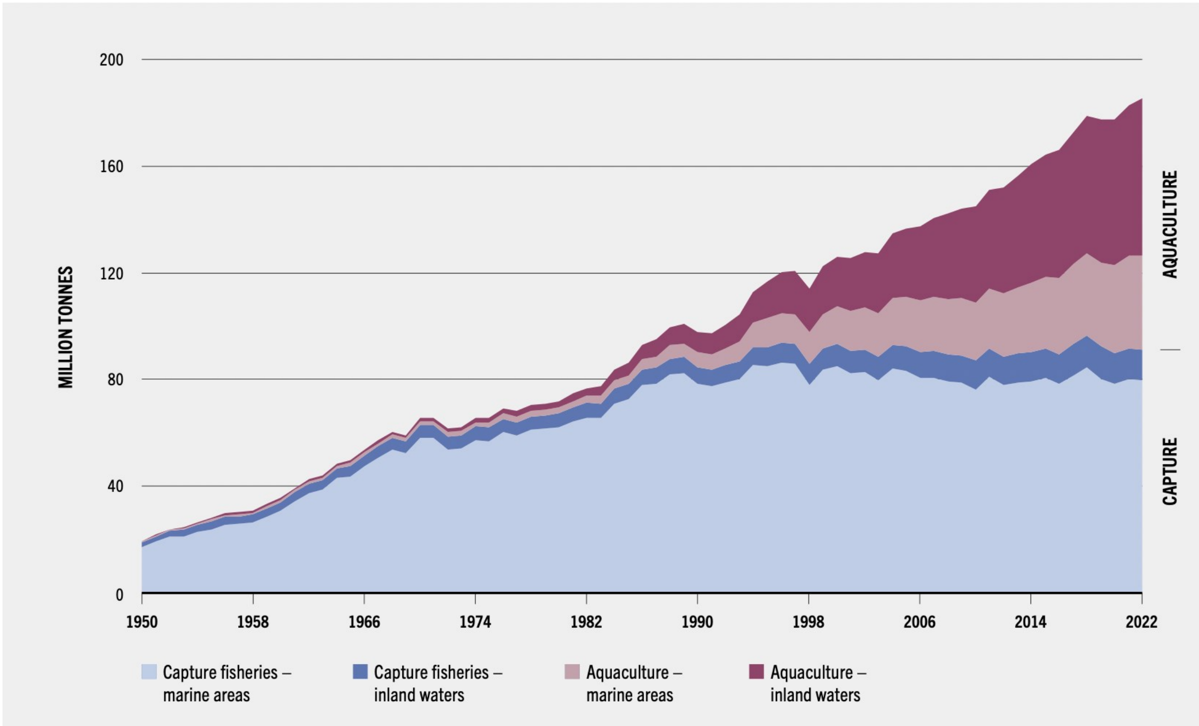

Figure 1.1: World fisheries and aquaculture production of aquatic animals [1][1].

[1] NOTES: Aquatic animals excluding aquatic mammals, crocodiles, alligators, caimans, aquatic products (corals, pearls, shells and sponges) and algae. Data expressed in live weight equivalent.
SOURCE: FAO. 2024. FishStat: Global production by production source 1950-2022. [Accessed on 29 March 2024].

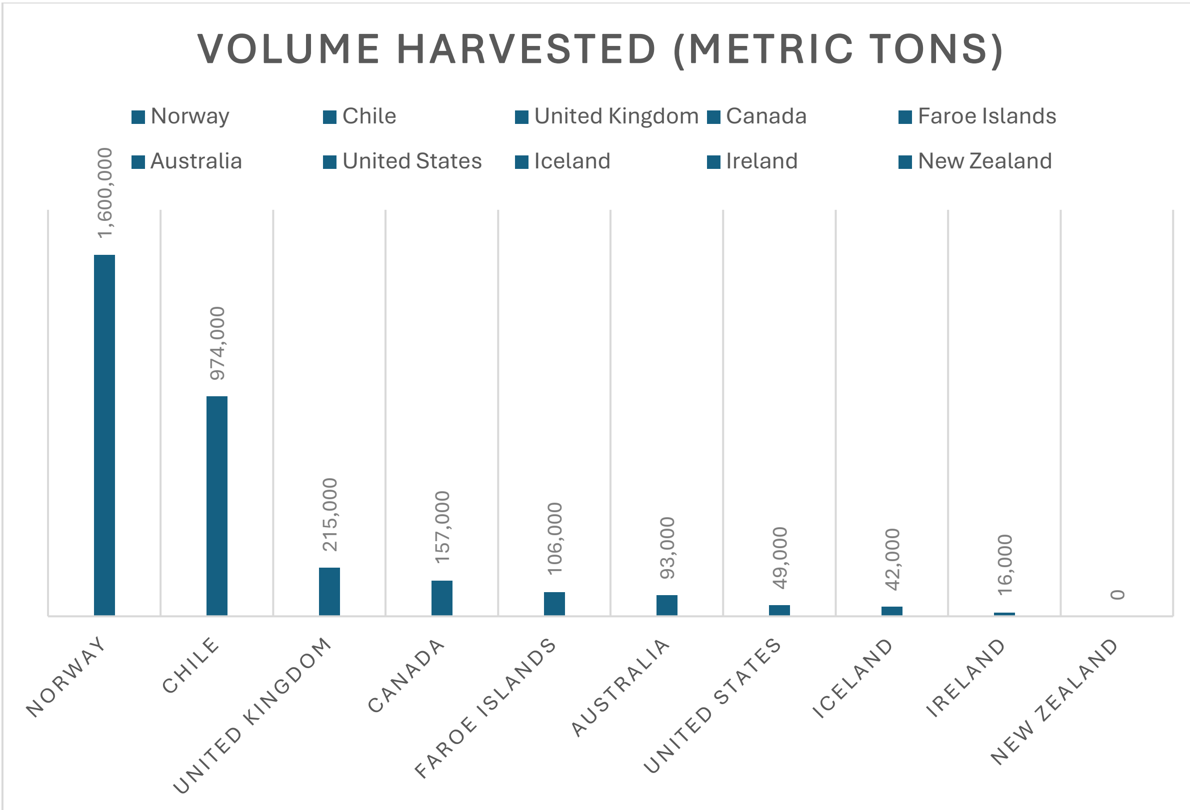

Figure 1.2: Leading Global Salmon Producing Nations in 2022 [4].

Salmon aquaculture has spread globally from Norway to countries such as Chile, Canada, Scotland, and the Faroe Islands, transforming the industry into a global powerhouse [5]. Leading companies such as Mowi, Cermaq Group, Leroy Seafood Group, SalMar, and AquaChile have played significant roles in the global expansion of salmon aquaculture. According to a recent ranking by IntraFish, the world's 15 largest farmed salmon producers also include Cooke Aquaculture, Bakkafrost, Multi-X, NTS, Australis Seafood, Grieg Seafood, Salmones Blumar, Nova Sea, Scottish Sea Farms, and Tassal. Together, these companies dominate the industry and contribute significantly to its vast scale, as illustrated in (Figure 1.3) [4].

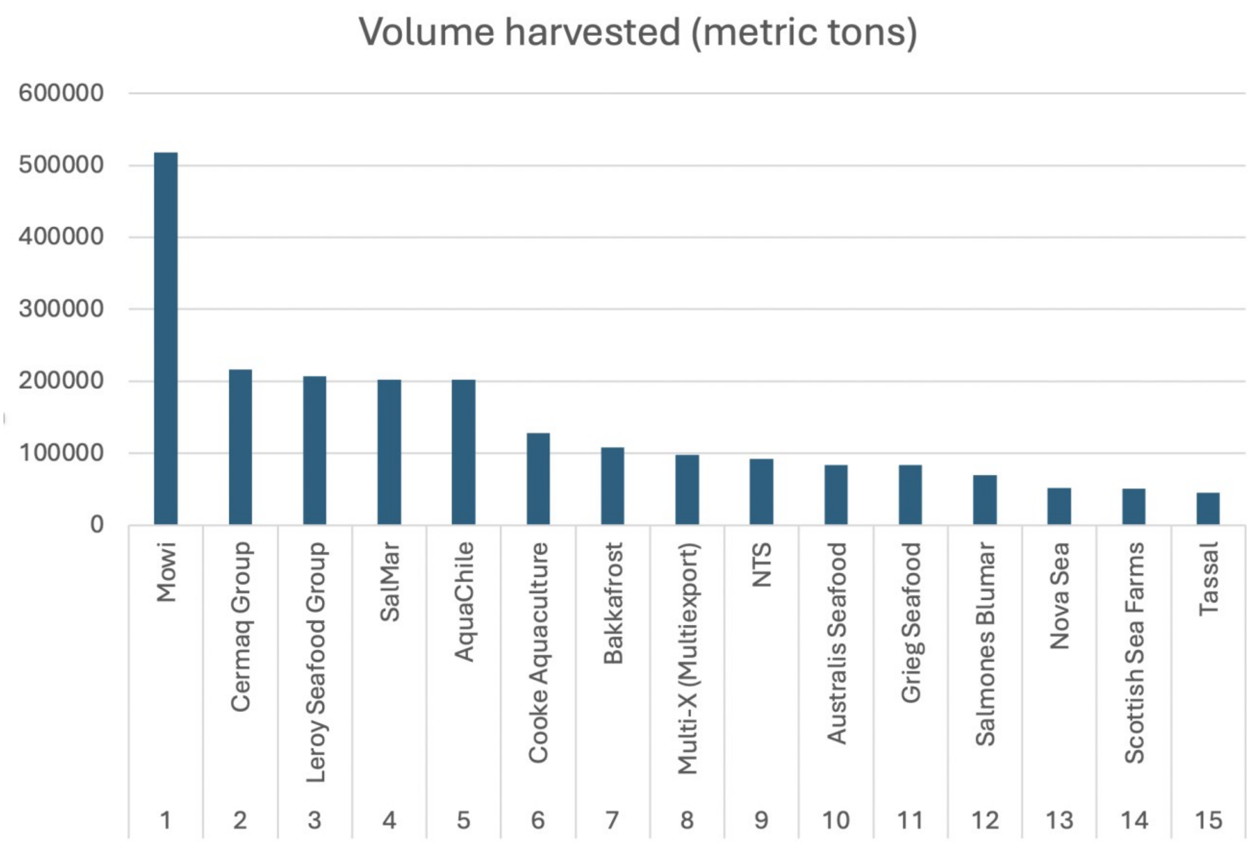

Figure 1.3: Leading Global Salmon Producing Companies in 2022, Intrafish, 2023 [4].

However, the rapid expansion and industrialization of salmon farming have not come without significant environmental costs. The industry has faced criticism for its environmental record, with key issues including pollution from waste discharge, the spread of diseases and parasites, the use of antibiotics, as well as the release of pathogens, chemicals, and soluble nutrients into the water [6]. Additional concerns include escapes of farmed fish, mooring impacts, biofouling detritus from in-water cleaning, and the accumulation of fish feces and uneaten food on the seabed [7]. Among these, the escape of farmed salmon has emerged as a critical matter of concern [8]. The escape of farmed fish not only threaten marine ecosystems and wild salmon populations but also pose substantial risks to the long-term sustainability of the aquaculture industry itself [9] (Figure 1.4).

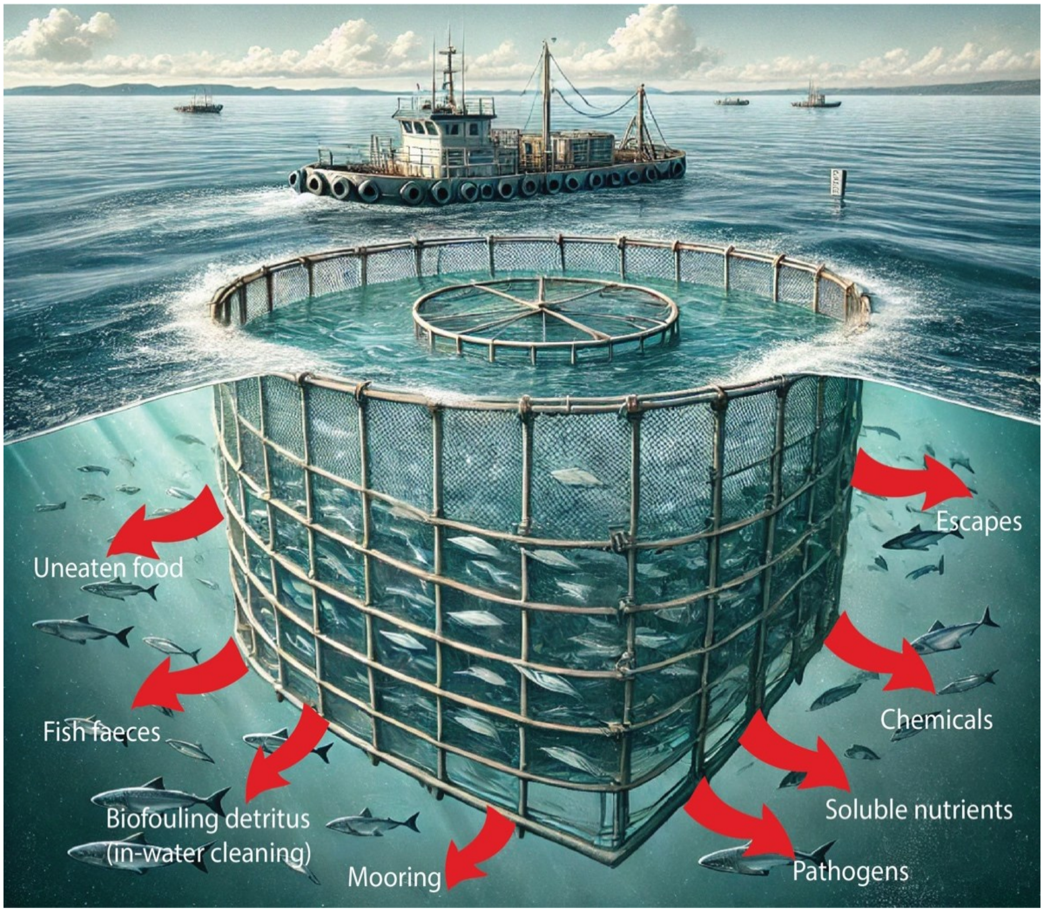

Figure 1.4: Diagram of the main interactions cage-environment-cage. Adapted and reproduced from the original image in the source [10]. The image was recreated using AI tools based on the original content provided by FAO.

1.2 Escape Incidents and their Challenges

Reports of farmed salmon escapes are newsworthy events and industry magazines like *Intrafish* regularly cover escape incidents around the world. In 2019 they compiled data on the number of escapes of more than 100,000 fish over the previous 20 years and came up with a figure of more than 5 million escapes globally [11]. The largest escapes have happened in Chile while other significant escape events were recorded for all the major producing countries, including in the 14 production regions covered in this study [11]. Establishing accurate figures on the number of escapes globally or even within countries is, however, a significant challenge [12]. In the *Intrafish* article, for example, the figure of 5 million escapes is only for escapes of more than 100,000 fish, and they acknowledge that "salmon escapes below 100,000 fish are even more common and frequent in all farming areas" [11]. An additional problem in producing accurate figures is that not all salmon producers are required to record the number of escapes as part of their licence conditions. In other cases, companies have been unwilling to disclose escape numbers for fear of criticism from environmental groups or investors. The *Intrafish* article noted that Huon Aquaculture in Tasmania was unwilling to declare whether a large escape in 2018 involved more than 100,000 fish [11]. A final problem is that escapes are often associated with what industry and regulators call 'trickle escapes' [13]. Assessing the number of these 'slow leaks' of fish from cages is almost impossible to determine [14].

These uncertainties combined with the difficulty of accurately knowing the number of escapes has not deterred policy makers from developing frameworks and policies to manage and prevent escapes from happening. This is in part because of the potential impact of even relatively small escapes on ocean ecologies [15]. While large escapes over 100,000 fish are obviously of great concern for local ocean environments, smaller escapes can have significant impacts especially when these numbers are considered relative to wild populations [14]. In Newfoundland and Labrador, for example, the impact of 20,000 farmed salmon escaping in 2013 was assessed in the context of the region's wild salmon populations, estimated at only around 12,000 fish [16]. In other words, even relatively small escapes from the perspective of aquaculture production have the potential to overwhelm wild populations with associated environmental problems, including extensive introgression into wild salmon populations as has been documented in the Newfoundland and Labrador case [14].

1.3 Ecological and Genetic Impacts of Escaped Farmed Salmon

The ecological impact of escaped farmed salmon on wild salmon and the surrounding ecosystem has been a subject of increasing concern, particularly due to the potential for genetic introgression, competition, and ecosystem alteration. Escaped farmed salmon, especially from aquaculture facilities, pose significant risks to wild salmon populations through direct competition for resources, potential for disease transmission, and hybridization [17,18]. For example, research has shown that the abundance of escaped farmed Atlantic salmon in rivers is strongly correlated with the intensity of aquaculture activities in nearby areas [19]. These escapes can lead to long-term genetic changes in wild populations, compromising their genetic integrity and fitness [19]. In Norway, extensive studies have shown that this genetic mixing results in decreased survival rates and lower reproductive success in subsequent generations [20]. Similarly, in New Brunswick, Canada, escaped juvenile farmed salmon have been observed to outnumber wild salmon in freshwater streams, creating direct competition for resources and further stressing wild populations [21].

In regions where Atlantic salmon is an exotic species, such as the Pacific coasts of North America and Chile, escaped farmed salmon pose different risks [22]. The potential for escaped salmon to establish self-sustaining populations in these areas is a significant concern Although historical attempts to introduce anadromous populations of Atlantic salmon in these regions have largely failed, the possibility of establishment, particularly in areas where native salmonid populations are depressed, cannot be ruled out [23]. Moreover, the ecological effects of escaped Atlantic salmon in these regions include potential competition with native Pacific salmonids [24]. Although Atlantic salmon are generally competitively inferior to Pacific salmonids, the outcome of such interactions can be context-dependent, with factors like body size and prior residency playing crucial roles [23].

1.4 Controversies Surrounding Farmed Salmon Escape

Incidents of farmed fish escaping into the wild have become a significant environmental concern in recent years, with each incident revealing different facets of the ongoing challenges faced by the aquaculture industry. The phenomenon of farmed salmon escaping from containment systems is not merely a series of isolated events; rather, it underscores a persistent and complex issue with profound ecological, genetic, and socio-political implications. These escapes highlight the vulnerability of both the environment and the industry to unforeseen failures, and they provoke critical questions about the sustainability of current aquaculture practices. By examining several notable examples, we can glean different lessons about the nature of these escapes and the controversies they spark.

First, escape incidents can have socio-political effects that extend beyond ecological disruption, as demonstrated by the Puget Sound incident in August 2017 [25]. In this case, the collapse of a net enclosure near Washington's Cypress Island led to the release of tens of thousands of non-native Atlantic salmon into the local ecosystem. The strong response from the Lummi Nation, who declared a state of emergency and recaptured many of the escapees, illustrates how these events extend beyond environmental concerns, deeply impacting political and community values. In response to the incident, Cooke Aquaculture offered the Lummi Nation increased payment for the recaptured salmon in exchange for not advocating against net-pen aquaculture—a proposal the tribe rejected as "insulting" [25]. This incident not only underscores the environmental consequences of farmed fish escapes but also highlights the significant social and political tensions they can ignite.

For my second example, I use the case of Newfoundland's Conne River, where the genetic implications of farmed salmon escaping are starkly illustrated. In this instance, interbreeding between escaped farmed salmon and wild salmon has been identified as a critical factor in the decline of wild populations [26]. This event underscores the genetic risks associated with such escapes, particularly the introduction of non-native alleles into wild populations, which can undermine the genetic integrity of wild salmon [8]. The ensuing controversy, with the Atlantic Canada Fish Farmers Association (ACFFA) challenging the findings of the Department of Fisheries and Oceans (DFO), highlights the contentious nature of farmed fish escape [27].

This conflict is part of a broader debate about the sustainability of open-net pen aquaculture systems [28]. While the industry emphasizes technological advancements, stricter regulations, and containment measures as solutions, the fundamental issue of farming in open marine environments, where escapes are inevitable, remains unresolved [29]. The long-term ecological consequences of these escapes could be far-reaching, potentially leading to the further decline of wild salmon populations.

The escape of salmon fry from Samherji's land-based farm in Oxarfjordur, Iceland, in May 2024, challenges the perception that land-based systems are immune to escape-related issues, and provides a third example of the lessons that we can learn from escape events [30]. In this incident, over 5,000 salmon fry, each weighing approximately 70-80 grams, were accidentally released due to a system failure when the water level in a fry tank rose, causing the fish to be sucked through an overflow opening and into the drainage system. This event highlights a critical oversight in the hatchery's design, as it lacked the necessary equipment to prevent such an occurrence, as noted by the Icelandic

Food and Veterinary Authority (MAST) in their investigation. Although the fry had not yet undergone smoltification—the process that prepares juvenile salmon for marine environments—there remains a concern that some may have smolted in the settling pond and subsequently escaped into the sea. While many view the shift to land-based systems as a solution to the challenges posed by traditional marine open-net farming, this example demonstrates that it might not be a foolproof or permanent approach. This incident underscores that even in controlled, land-based environments, where the risk of escape is generally perceived to be minimal, significant vulnerabilities still exist [30].

In the fourth example, a similar concern arises from SalMar's offshore aquaculture operation near Frøya, Norway, where a significant number of salmon escaped under unclear circumstances [31]. The exact number of escaped fish remains unknown, highlighting a critical issue in the industry's ability to monitor and report such events accurately. Moreover, many of these escaped salmon were infected with Heart and Skeletal Muscle Inflammation (HSMB), a common viral disease in the Norwegian salmon industry. This incident not only underscores the potential for disease spread following an escape but also questions the industry's transparency and its ability to manage such risks effectively [31]. Together, these examples challenge the reliability of technological solutions, including land-based and offshore systems, which are often touted as safer and more sustainable alternatives to marine open-net farms, yet still remain vulnerable to the risk of fish escapes.

Finally, the continuous pattern of farmed salmon escapes, particularly in Norway, highlights the scale of the issue, with over 2 million salmon escaping in the last decade alone [14]. These repeated incidents underscore significant gaps in the industry’s management practices. The problem is further exacerbated by the underreporting of escapes and the inherent difficulties in tracking and quantifying them, making the issue both widespread and persistent. The actual number of escaped farmed salmon in Norway is estimated to be significantly higher than the officially reported figures. This discrepancy arises because the reported numbers (blue line) represent only known and confirmed escapes, while the estimated figures (red line) suggest that the true escape rates are approximately four times higher [14] (Figure 1.5).

Collectively, these examples tell a broader story: the escape of farmed salmon is a persistent and significant environmental issue with diverse consequences. These incidents underscore the need to re-evaluate the commonly proposed solutions for managing the environmental challenges posed by farmed fish escapes. This thesis will critically assess the effectiveness of existing policies and technologies in addressing these issues, with a particular focus on farmed fish escapes and the potential of triploid salmon as a solution, aiming to determine their role in mitigating the environmental impacts of aquaculture.

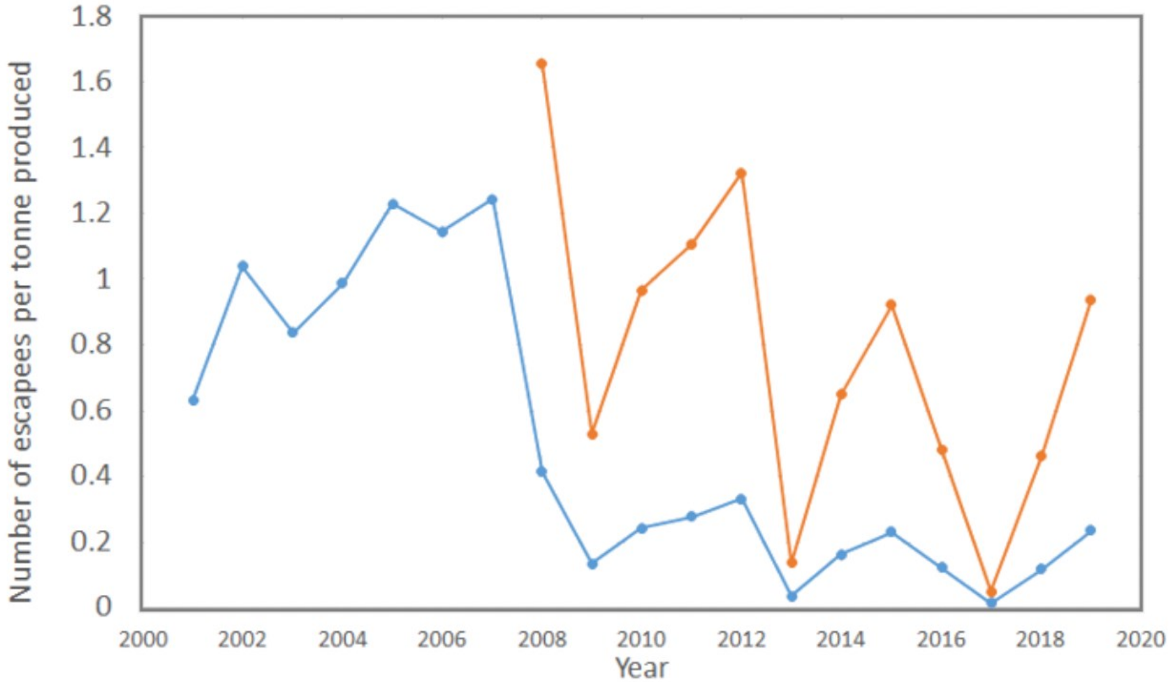

Figure 1.5: Number of escaped salmon in Norway - the number of individuals per tonne produced. The blue line shows reported releases and the red line shows the estimated total number of escapees (multiplication by a factor of 4) [14].

1.5 Research Objective

This thesis critically evaluates the effectiveness of policies and technologies designed to mitigate the environmental challenges associated with escaped farmed salmon. It focuses particularly on farmed fish escapes and the potential of triploid (infertile) salmon as a solution. By examining the development and implementation of these strategies, the study assesses their strengths and weaknesses in addressing the environmental impacts of aquaculture.

1.5.1 Research Questions

To achieve this objective, the research is guided by the following questions:

- How effective are the current global policies and technological innovations in mitigating the ecological and genetic impacts of escaped farmed salmon on wild salmon populations and marine ecosystems?
- What are the strengths, weaknesses, and enforcement challenges of existing policy frameworks aimed at regulating farmed salmon escapes in major aquaculture regions?
- What potential does the use of triploid (sterile) salmon have in addressing the environmental and genetic risks of escaped farmed fish, and how does this align with sustainable intensification goals?

1.6 Chapters Overview

The thesis is presented in manuscript format and is organized into four main chapters. The first chapter serves as the introduction, outlining the significance of the topic and the research objectives. The second chapter explores the global landscape of aquaculture regulations, focusing on the evolution and implementation of policies aimed at preventing the escape of farmed salmon across fourteen major salmon-producing regions, including Norway, the Faroe Islands, Iceland, Scotland, Ireland, Canada (Newfoundland, New Brunswick, Nova Scotia), the USA (Washington State, State of Maine), New Zealand, Australia (Tasmania), and Chile. This chapter builds on the foundational work of Naylor et al., published nearly two decades ago, by providing a detailed review and critical assessment of escape policies across 14 major salmon production regions worldwide. Following the analytical approach established by Naylor et al. (2005) [29], I update the policy landscape in regions that have since developed escape policies, such as New Brunswick, Chile, the Faroe Islands, and

Tasmania. I also include an assessment of new policies in regions that have recently entered salmon production, including Newfoundland and Labrador, Nova Scotia, and New Zealand.

Through a systematic review of government documents, academic literature, and industry reports, I analyzed the regulatory frameworks in place to manage farmed salmon escapes. The findings reveal that while all 14 regions have measures to address escapes, the effectiveness of these policies varies significantly. I categorized these regulations into five key themes: regulatory framework, production requirements, reporting and recapture regulations, monitoring requirements, and sanctions, allowing for comparative analysis across regions. This chapter provides a comprehensive update on the development of escape policies and assesses the strengths and weaknesses of these frameworks, as well as new technologies aimed at preventing escapes. Despite the rapid evolution of policies, my findings suggest that their effectiveness is often constrained by weak enforcement, limited sanctions, and the inherent challenges posed by open net pen aquaculture, where escapes are deemed inevitable.

The third chapter examines the use of triploid Atlantic salmon in aquaculture as a technology that addresses both the environmental problems associated with escaped farmed salmon and the production challenges of early maturity. Triploid salmon, genetically modified to be sterile, are explored as a potential solution to prevent the genetic impact of escaped farmed salmon on wild populations while enhancing production efficiency. The chapter critically analyzes the implementation and impact of triploid salmon through three case studies: Newfoundland, Norway, and Tasmania.

In Newfoundland, triploid salmon were introduced to balance production benefits with ecological considerations, particularly due to early maturation issues with local salmon stocks. In Tasmania, where there are no wild Atlantic salmon, triploid salmon have been primarily used to enhance production. In Norway, triploid salmon were initially adopted but later discontinued due to production inefficiencies rather than environmental or welfare concerns.

Through a qualitative analysis of literature and environmental implications, I examine whether this technological solution can effectively balance environmental concerns with production goals. This chapter highlights the complex interplay between production goals and environmental safeguards. The findings reveal that while triploid salmon are promoted for their environmental benefits, production priorities often take precedence, especially when challenges arise. This chapter underscores the difficulty in separating production and environmental objectives in aquaculture. The final chapter concludes the thesis by summarizing the findings and discussing the implications for the future of the salmon aquaculture industry.

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Chapter Two: Regulating a ‘fish out of place’: a global assessment of farmed salmon escape policies and frameworks

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Abstract

Our paper aims to contribute to scholarship on the role of policy in regulating aquaculture development globally. We focus on the rapid rise in regulatory frameworks for farmed salmon escapes across 14 global production regions. Escape policies and frameworks aim to address a critical area of environmental concern for salmon aquaculture: the environmental, ecological and social impact of farmed salmon escapes into the wild. Building on previous research, we provide an updated global assessment of farmed salmon escape policies. Our findings reveal a rapid rise in the spread and implementation of escape regulations globally and the development of new technologies that aim to address this problem. We assess the strength and weaknesses of the various policy mechanisms designed to respond to the problem of escapes. While policies for escaped fish are in place in all production regions, we argue that their effectiveness is constrained by their various weaknesses and by the inevitability of farmed salmon escapes in open net pen aquaculture.

Keywords: farmed salmon, escapes, policies and frameworks, aquaculture, blue economy

2.1 Introduction

A critical challenge facing aquaculture policy is how to realise this sector's potential in providing food and economic opportunities while minimizing the environmental impacts of farming fish in the ocean [1–3]. The problem of aquaculture's environmental impact is gaining prominence in the context of blue economy strategies where aquaculture is positioned to play a key role in realising the economic potential of the ocean [4]. How to mitigate aquaculture's environmental impact is also an issue for groups and organizations who see the potential for aquaculture sourced 'blue foods' in addressing food insecurity and the global demand for nutritious sources of protein [5]. The Blue Economy (BE) emphasizes the sustainable use of ocean resources, aiming to balance economic growth, environmental sustainability, and social equity. As a broad framework, BE advocates for solutions that address ocean-related challenges while fostering long-term development [6]. In the context of aquaculture, however, current framings of BE can sometimes misapply its principles, particularly with regard to farmed or escaped salmon. Countries are increasingly developing BE strategies, with aquaculture positioned as a key driver of ocean-based economic growth. While aquaculture offers undeniable advantages, such as supporting the Blue Economy and addressing food security concerns, it is not without global criticism, particularly due to the observed and potential environmental impacts associated with the industry [7,8]. In this context, effective policy is widely regarded as crucial foundation for achieving aquaculture's potential as a key part of a sustainable ocean economy [2,9].

The environmental challenges of aquaculture production vary across sectors and by species. For the global salmon aquaculture sector, one of the more intractable environmental problems is the escape of farmed fish from open net pens into the marine environment [9–11]. Farmed salmon escape their ocean based cages through continuous low-level leakage and in much large numbers often associated with the collapse of open net pens [12]. Infrastructural issues such as net damage are also primary causes while adverse weather, improper handling, and human factors contribute to escape events [13]. Escaped salmon can negatively affect wild fish, leading to competition, predation, disease transmission, and interbreeding [14,15]. Escaped Atlantic farmed salmon, notably in North American and northern European rivers, may pose a significant threat to wild Atlantic salmon populations through genetic introgression [16], even though there is little evidence for the establishment of farmed salmon populations in the wild. Genetic introgression has been found in Canada, Norway, and Scotland and may impact the fitness of wild salmon populations [17–19]. A risk assessment by the Institute of Marine Research in Norway revealed that 21 out of 34 wild salmon populations are moderately to highly vulnerable to genetic introgression from escaped Atlantic farmed salmon [20]. Besides the environmental issues, there are also socio-ecological conflicts that may result from farmed salmon escapes. A source of these socio-ecological problems in Chile and elsewhere is that escaped salmon remain the property of the aquaculture company, which can lead to conflicts between small scale fishers harvesting salmon and the companies involved in farming salmon [21].

In the mid-2000s Naylor and her colleagues summarised and assessed the wide range of ecological and social risks associated with farmed salmon escapes – ‘fugitive fish’ in their words [22]. For us, and in this paper, escaped salmon are best understood as "fish out of place." This framing captures their unnatural existence outside controlled farming environments; they have been bred to live in cages and consume commercially produced feed. Naylor and her colleagues also examined the policies and frameworks aimed at mitigating the problem of salmon escapes. Their analysis found gaps in policies for several production regions that had no escape regulations whatsoever including New Brunswick in Canada, Chile, the Faroe Islands and Tasmania. They also concluded that the "policy initiatives to prevent or mitigate escapes remain relatively weak in most major salmon-farming regions" [22]. Of considerable concern was their finding that policies and frameworks were not commensurate with the wide range of risks caused by farmed salmon escapes into the wild. In their conclusion, Naylor and colleagues called for an aquaculture policy based "not on development alone, but on precautionary, sustainable development" [22].

The purpose of our paper is to build on the Naylor et al. contribution published almost two decades ago through a detailed review and critical assessment of escape policies in 14 salmon production regions around the world. Our research aims to build on their contribution by following their analytical approach to policies and frameworks and by providing policy updates on regions that have established escape policies since their contribution (New Brunswick, Chile, Faroe Islands and Tasmania). We also review policies in 3 regions that are new to salmon production since the mid-2000s. These include the Canadian provinces of Newfoundland and Labrador and Nova Scotia, and New Zealand. Second, we provide a thorough assessment of these policies and frameworks, and we assess new technologies aimed at preventing escapes. Overall, our aim is to provide a timely and long overdue update to the Naylor et al. paper by critically assessing policy for salmon escapes in the context of its environmental and social risks. Our findings reveal the rapid development of escape policies across these 14 regions. While these policies and frameworks aim to address the problem of farmed salmon escapes, we argue that their effectiveness is constrained by their various weaknesses and by the inevitability of farmed salmon escapes from open net pen aquaculture.

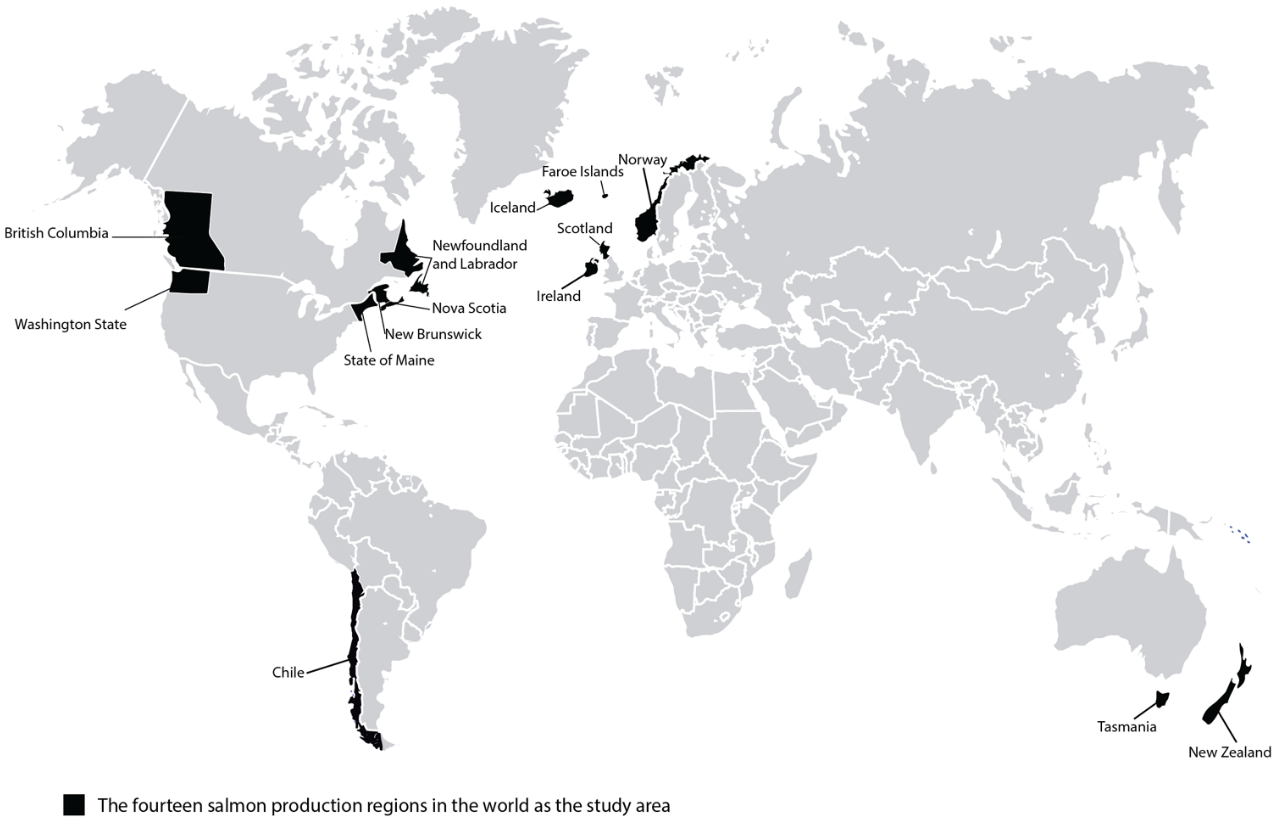

Figure 2.1: The top 14 global salmon producing regions, (FAO) FishStat database [23].

2.2 Methods

Our analysis of the policies and regulatory frameworks for farmed fish escapes is based on a range of different sources including official government policy documents and government reports, reports by multilateral institutions and by non-governmental organisations, websites of industry associations, academic peer reviewed papers, and industry news articles. Our methodological approach began with a detailed academic literature search using Google Scholar and Web of Science on research related to farmed salmon escapes including their environmental impact and policy responses. We draw on academic papers and reports that examine the environmental impact of escapes and research that examines aquaculture policy and its role in minimizing fish escape impact and incidence. This provided the context for our subsequent empirical analysis of the regional cases.

We then identified the top salmon producers by volume using the Food and Agriculture Organisations' (FAO) FishStat database [23]. Using this database we identified the top 14 production regions for farmed salmon and their associated regulatory systems in 10 countries[2] (Figure 2.1). For each of the 14 production regions we conducted a systematic analysis of their regulations for farmed salmon escapes. We sourced this information from official government websites (national and regional) and the departments responsible for aquaculture regulation and fish escape policy. We included formal legislation as well as codes of containment that are used in some production regions. Our analysis assessed legislation and regulations specific to aquaculture and farmed salmon escapes and legislation that may be used to indirectly manage escape incidents (e.g. Environmental Impact Assessment System in Chile or the Clean Water Act in Washington State). We also included data from regional or multilateral organisations that are involved in Atlantic salmon conservation including the Atlantic Salmon Federation (ASF) and the North Atlantic Salmon Conservation Organisation (NASCO). A detailed description of the sources we use is available in Appendix 1.

The policies and regulations were analysed and organized across five key themes: regulatory framework (the structure and comprehensiveness of regulations governing farmed fish escapes); production requirements (standards and guidelines for aquaculture production to minimize escape incidents); reporting and recapture regulations (mandates for reporting escape incidents and procedures for recapturing escaped fish); monitoring requirements (obligations for monitoring and surveillance of aquaculture operations to detect and prevent escapes); and sanctions (penalties and enforcement mechanisms in place for non-compliance or escape incidents). These themes are broadly consistent with Naylor et al's (2005) assessment of escape policies in salmon producing

[2] We use the term 'production region' rather than country since 2 countries in our analysis – Canada and the United States – include more than one production region with a corresponding regulatory authority.

regions [22]. We present these themes in table format in way that allows for comparisons across production regions and we describe variations and commonalities across these regions. Our thematic approach to the policies and regulations allowed us to compare and contrast the specific differences in policies across the 14 production regions.

Our analysis of the strengths and weaknesses of these policies is based on a detailed assessment of the policies across the five themes. We argue that policies and regulations are relatively weaker when they are likely to have a limited impact on reducing escapes. Monitoring, for example, is an important tool for regulators to assess the number of escapes that happen but on its own it does not limit escapes from happening. In contrast, there are several other initiatives that are stronger as they have a more tangible impact on escapes and their environmental impact including the use of escape proof nets, the use of triploid fish, and imposing heavy financial sanctions or withdrawing aquaculture licences. In spite of these various regulatory systems, eliminating escapes entirely in the context of open net pen aquaculture seems unlikely given the consensus that escapes are inevitable with the production infrastructure that supports salmon aquaculture [22,24].

Table 2.1: Analysis of aquaculture policies and frameworks for escapes in 14 production regions.

Regulatory framework / Regions	USA		Canada				Australia							
	Washington	Maine	BC	Newfoundland and Labrador	Nova Scotia	New Brunswick	Tasmania	Iceland	Scotland	Norway	Chile	Faroe Islands	New Zealand	Ireland
Regulatory framework	US Clean Water Act [50]. Washington Administrative Code [51].	Containment Management System (CMS) [52]. Maine Marine Finfish Aquaculture Act (2023) [53]. Code of Containment [54].2024-07-17 12:18:00 PM	The Pacific Aquaculture Regulations (PAR) [55].	NL's Code of Containment [56]. Aquaculture Policy and Procedures Manual[57]. Newfoundland and Labrador Aquaculture Act [58].	Code of Containment [59]. Fisheries and Coastal Resources Act [54].	Code of Containment for Finfish Aquaculture [60,61]. New Brunswick Aquaculture Act [62].	Marine Farming Development Plans under Marine Farming Planning Act 1995 [62,63].	Icelandic regulation on aquaculture [64].	Aquaculture code of practice[65]. Aquatic Animal Health Regulations 2009 [66]. Fisheries Management Scotland [67].	Code of containment practices [12]. Aquaculture Act (2005) [68]. NYTEK 23 regulation [69]. Action plan on containment: Vision No Escapees [70].	Environmental Impacts Assessment System (SEIA)[22]. General Law on Fisheries and Aquaculture[47].	Faroese Veterinarian Act on Aquaculture [71].	Best Management Practice guidelines [72]. A+ New Zealand Farmed Salmon Welfare Standards[73].	Environmental Code of Practice for Aquaculture Companies and Traders (ECOPACT)[74] Irish Salmon Growers' Associations (ISGA) code of practice [75].
Production requirement	Regulations address fish sourcing, prohibiting transgenic fish, employee training[55], and escape prevention plan [76].	Regulations cover equipment escape prevention [77], fish sourcing regulations, approved genetic marking, and mandatory CMS plan before fish stock [52].The code sets standards for equipment, procedures, site selection, fish transfers, predator control, and storm readiness [54].	Regulations cover: Installation design and maintenance, training, inspection, designing all equipment, materials, and structures to prevent escapes, inspection and record-keeping [77].	Regulations require inspections, maintenance, and adherence to ISO or certified engineering standards [56], including the use of triploid fish, escape-proof nets [78], and the implementation of escape management plans [55].	Regulations mandate comprehensive escape management plans [55]. Net maintenance is scheduled either at the start of a cycle or as needed [77].	Regulations require using Sapphire Ultracore net pen for escape prevention [55] implementing a mooring system [61], and scheduling net maintenance at the cycle's start or as required [77].	Regulations mandate preventive measures, including the use of all-female triploid fish by producers. [79]. Leases are required to strictly avoid intentional releases into state waters [63].	Regulations require license grantees to have a production plan [5], which must adhere to NYTEK 23: NS 9415 standards for escape prevention [64]. Measures include using sterile salmon, advanced surveillance, larger smolt, and increased digitization for efficiency [5].	Regulations mandate DNA-based identification for unreported escapees and the utilization of sterile fish [12]. Limit the risk of genetic introgression per the Scottish Planning Policy [5].	Regulations mandate green licenses/concessions[23,70], requiring compliance with the NYTEK 23: NS 9415 standard for escape prevention, mandatory tagging, and the use of sterile fish [70]. The national action program also requires a contingency plan [80].	Regulations focus on improving standards of the structures in farming [81].	Regulations require minimizing escapes following guidelines in the Containment of Farm Salmon [82]. Additionally, measures prevent population-level impacts on wild fish [83] and fish escapes from aquaculture units [84].	Regulations require adherence to a maintenance and net replacement plan [72]. NZ King Salmon deploys predator nets around the farms to prevent losses from seal and shark attacks. [77].	Regulations encompass improved operational procedures and the adoption of advanced fish farming technology [75,85]. The licensee must ensure cages don't block migratory fish and prevent salmon escape[86].
Reporting and recapture	Requirement to report 'significant' escapes (>3000; 1 kg or less; 1500 fish of 1 kg or more) [77]. Recapture plan requirement [87].	Requirement to report 25% or more of a cage population and/or more than 50 fish with an average weight of two (2) or more kilograms each (≥2 kg) [88]. Requirement to recapture escapes [55].	Report escape requirement [55]. Recapture requirement[77].	Report escape requirement [55]. Recapture efforts within 24 hours under the guidance of DFO but not all reported escape incidents require recapture efforts [56].	Report escape requirement [55]. Requirement to recapture escapes [55].	Reporting the escape of 50 or more finfish from a site shall be made in accordance with the Code of Containment for Finfish Aquaculture [60,61]. Recapture required, but not all escapes prompt action [61].	Report any escape of over 500 fish from a marine farm [89]. Recover of escaped fish required [63].	Report escape requirement [14]. Recapture requirement [14]. Contingency plan to recover fish required [64].	Report escape requirement [66]. Recapture requirement [90].	Requirement to report and recapture. Failure to report suspected escapes is a criminal offense [70]. A fund covers escaped fish removal costs [68,70].	Mandatory reporting of escape incidents[22]. Companies permitted to hire artisanal fishermen to contribute to the recapture efforts [81]. Recapture at least 10% of escaped fish required[91].	Report escape requirement [82]. Recapture requirement [83].	No requirement to report escapes [77].	Report escape requirement[86]. Guidelines for Anglers suspecting recaptured farmed salmon[92].
Monitoring	Monitoring of the net pen containment system but not facility audits [27]. Tracing back by otolith marking[27].	Monitoring and facility audit when a farmed fish is found in a river [27].	Monitoring but no facility audits [27]. Atlantic Salmon Monitoring: DFO's program in BC waters [69].	Monitoring but not facility audits [27].	Monitoring and facility audit if there is a breach in the containment system [27].	Monitoring but not facility audits [27].	No regulatory requirement to assess the environmental or biosecurity impact of escaped salmonids [35].	The Marine and Freshwater Research Institute monitors salmon rivers for farmed salmon escapes [53].	Regulations mandate 20m monitoring for escape detection using prescribed nets[40]. Monitoring for genetic introgression and sea lice [70].	Monitor the fish population outside the nets [43].	Farmers responsible for escaped fish must finance ocean monitoring for two years [56].	No monitoring for escaped farmed fish [58]. Marine pollutant monitoring covers both farmed and wild fish[71].	No monitoring requirements [50].	Enhanced regulatory monitoring [72]. Monitoring for environmental impacts, including sea lice. Monitoring upstream traps in rivers for escaped fish removal[73].
Sanction	No specific sanctions exist in the administrative code for escapes, but violations related to Inspection and Disease Control of Aquatic Farms are addressed[74]. Specific sanction by Clean Water Act[75].	No sanction	No sanction	Sanctions outlined in the NL Code of Containment, such as restrictions or revocation of an aquaculture license under the Aquaculture Act[28].	No sanction	No sanction	Escapes may be treated as an offence depending on circumstances[50].	Sanctions in cases of negative impact like sea lice[53]. stripping of a permanent fish farming licence due to the fish escape[76].	No sanction	Use of coercive fines, the withdrawal of licences, and the possibility of criminal prosecution leading to fines or imprisonment for up to two years[55].	Escape Sanctions: Consider escaped salmon count, recaptured fish, and past events[56].	No sanction	No sanction	No sanction

2.3 Results

We present the results of our detailed analysis of policies and frameworks in 14 production regions in table format (Table 2.1). A notable finding is that all 14 production regions have specific escape regulations that are either independent of, or embedded in, aquaculture legislation. The 4 regions that Naylor et al noted had no regulations for escapes (New Brunswick, Chile, Faroe Islands and Tasmania) have since establish frameworks and legislation. The three new salmon production regions since their 2005 study (Newfoundland and Labrador, Nova Scotia and New Zealand) have also implemented farmed escape frameworks (Table 2.1) [22]. This is an important finding as it points to the significance of this issue for regulators and for industry: there is no major farmed salmon producer globally that does not have specific regulations for escapes.

While all 14 production regions have policies for escapes, our results show a diversity of regulatory approaches.[3] Most of the regions have specific legislation (i.e. Acts) for aquaculture that includes measures to manage and regulate salmon escapes. At the same time, an important and notable development is the existence of 'codes of containment' which exist for a significant number of producing regions (Table 2.1). These are not laws but are rather regulations that govern the problem of escapes and aim for the effective containment of salmon within ocean net pens [25,26]. In this way, these codes sit alongside legislation as additional measures to regulate salmon escapes. The existence of both formal legislation and codes of containment points to how regulators are using diverse approaches and regulatory tools to manage and limit farmed salmon escapes.

[3] For a more detailed discussion of the different regulatory systems used to govern aquaculture, see Hishamunda, et al. [9].

The development and design of these codes, in several cases, is not through governments or regulators but instead was through the work of companies and/or the organizations that represent industry. In Nova Scotia [27] and New Brunswick [26,28], for example, the codes of containment were developed by their respective industry organizations. In New Zealand [29], similarly, the largest aquaculture companies are directly involved in developing best management practices for aquaculture production, including for escapes. The role of the private sector in developing regulatory codes for aquaculture production rather than government agencies obviously raises questions around the importance of arm's length regulatory systems. Having aquaculture companies themselves design regulatory frameworks may not be the most effective way of developing policy for escapes, and may lead to weak policy outcomes.

It is important to note that legislation and policy may affect aquaculture production even though it is not specifically designed to regulate this sector of the economy. A good illustration of this is the case of Washington State, which imposed sanctions on Cooke Aquaculture for a significant escape event in 2017 [30]. The company was charged under the US's Clean Water Act with the farmed salmon escapes considered a form of environmental pollution [31]. Washington State has since banned Atlantic salmon aquaculture in the state [32,33]. Our point is that while all 14 production regions have regulations specifically designed to manage the problem of escapes, it is possible that regulators invoke other environmental legislation that is not normally associated with aquaculture production.

As is well known, Norway has one of the most advanced regulatory systems for salmon aquaculture [34,35]. In addition to a code of containment and legislation they also developed an action plan on containment in the mid-2000s [36]. The plan was called 'Vision No Escapes' and had as its goal to have no harmful effects of salmon escapes on wild stocks by 2010 [37]. While regulators in Norway continued to focus on the problem of escapes, recent research suggests that this issue may have become less important as an indicator in assessing sustainability of the industry in the context of the significant sea lice problem affecting farmed salmon production [34].

In what follows, we provide a more detailed assessment of what these policies and frameworks do across the remaining themes we identified. We then compare and assess their effectiveness in reducing escapes and in mitigating their environmental impact.

2.4 Production requirements

The legislation, policies and codes across the 14 production regions all specify production requirements aimed at reducing escapes from happening. These include a wide range of provisions from nets to fish to maintenance and record keeping. For the nets that contain fish in ocean-based cages, several regions have specific requirements for net type and for maintenance and repair. In New Brunswick, for example, regulations mandate using a specific cage/net combination, which is designed to prevent escapes and provides fish with extra protection against predators such as seals and other fish [38]. In other places the guidelines are less specific but may include the need to install 'escape proof nets' (e.g. Newfoundland and Labrador) [39]. The need to maintain and replace nets on a regular basis is also a requirement in several production regions given that inadequate maintenance has been a contributing cause to several high profile and large scale escape events (e.g. Washington State) [30].

A notable provision in several production regions involves the types of fish farmed. The use of triploid fish – fish that have been sterilised – is a requirement in Iceland [40], Scotland [41], Ireland [42], Tasmania [43], Norway [44] and in parts of Newfoundland and Labrador [39]. These fish are not able to reproduce and so their ability to act as a source of genetic introgression into wild salmon populations has been all but eliminated [45]. The requirement to use triploid fish in Tasmania is notable given that there is no wild salmon population in that region and so their use is presumably to prevent a self-sustaining population of farmed salmon from establishing itself or to prevent disease transmission from farmed to other wild fish [43]. While triploid fish continue to be used in several production regions, Norway is in the process of moving away from triploid fish because of significant welfare concerns [46]. Another notable requirement associated with fish is the restriction on the use transgenic salmon. This is the case in Washington State, where the regulations specifically prohibit the use of transgenic fish [38]. To our knowledge there is only one commercially available transgenic salmon (AquaBounty), but its use is limited in the salmon aquaculture sector [47].

While the regulations in most production regions are very specific and may mirror the well-known and comprehensive Norwegian NYTEK 23: NS 9415 provisions [48], in other locations the provisions are more general. In Ireland, for example, producers are required to adopt 'improved operational procedures' and 'advanced fish farming technology', without specifying what these procedures are or what this technology might encompass [49–51].

2.5 Reporting and recapture

Reporting escapes and recapturing fish that have escaped are integrated into the policy frameworks we examined for the 14 production regions. Interestingly, in terms of reporting, what constitutes a 'reportable' escape varies across production regions. In Washington State an escape event is defined as one that involves more than 3,000 fish [52], while the equivalent number in Tasmania is 500 [53], in Maine [54] and New Brunswick 50 fish constitute an escape [28], while Newfoundland and Labrador recently changed a reportable event from 100 to a single fish [55,56]. In several other production regions there is no mention of a specific number for reporting an escape or the regulations do not include any stipulation on reporting escapes. In both Washington State and Maine in the United States, the regulations also change depending on the weight of the fish: more than 3,000 fish constitutes and escape, but if the fish weigh more than 1 kilogramme the reporting requirement changes to 1,500 fish escaping [52,54]. The variation in what constitutes a reportable event, even within production regions, combined with the problem of companies failing to report when escapes happen, raises several different issues [57,58]. For instance, it makes it difficult to accurately monitor escapes over time in a single production region and it makes it virtually impossible to assess the problem of escapes at a global scale. As a final point, reporting on its own does little to reduce the number of escapes unless it is combined with other measures including sanctions.

In practice, farmed salmon escapes are reported by anglers and other groups adjacent to salmon farms [59]. This form of reporting is obviously beyond regulatory measures and does not provide accurate numbers of escaped fish, but is nonetheless an important way in which escapes are reported to regulators or in the media. While this form of monitoring is not part of formal policy, in several production regions there are specific guidelines for anglers who suspect that they have caught a farmed salmon. In Ireland, for example, the guidelines include reporting it to Inland Fisheries Ireland, not returning the fish to the water, and freezing it for subsequent identification and reporting [60].

In terms of recapture requirements of fish that have escaped all production regions, apart from Ireland and New Zealand, require some form of recapture plan or action. At the same time, we found significant diversity across production regions in terms of the specific obligations on companies in terms of recapturing escaped fish. In some cases, the regulations emphasize having a recapture plan rather than stipulating that the company involved is required to recover escaped fish. In other cases, notably in New Brunswick [26] and Newfoundland and Labrador [25], an escape event that is reported may not require recapture efforts by companies. In Newfoundland and Labrador, and other Eastern Canadian provinces, the situation is complicated by the fact that when farmed fish escape they are, somewhat paradoxically, considered to be wild Atlantic salmon and thus fall under the provisions of the federal Fisheries Act. Under this Act, wild Atlantic salmon can only be caught by licenced anglers using specified fishing equipment [61]. For this reason, recapture efforts in Eastern Canada must happen under the guidance of the Federal Department of Fisheries and Oceans [62].

The framework for escaped salmon in Chile is somewhat unique across production regions in that regulations specify that a specific percentage of escaped fish must be captured to avoid a fine [63]. The regulations in Chile also allow for companies to hire artisanal fishers to help in the recapture efforts, although this is politically complicated because escaped fish remain the property of the aquaculture company even though they are in the wild [21]. This is not the only production region where salmon escapes are or have been highly politicised. In Washington State recapture efforts following an escape of over 250,000 fish from a salmon farm in 2017 led to significant tensions between Indigenous groups and the company, Cooke Aquaculture [33,64]. Indigenous fishers were mobilized to help in the recapture effort and were paid a set rate of $30 per fish recovered. Cooke offered the Indigenous groups a rate of $42 per fish if they agreed to suspend their protest action against net pen aquaculture in Washington State, an offer that the Indigenous groups rejected out of hand [65].

Recapturing escaped fish is potentially an important way of limiting the impact of escaped farmed species on ocean ecologies. However, and perhaps not surprisingly, studies indicate that efforts to recapture fish rarely recover anything more than a very small percentage of the fish that escape open net pens [66].

2.6 Monitoring

Monitoring fish escapes in the regulations we assessed involves two separate activities. The first involves regulations requiring companies to monitor net pens for escapes on an ongoing basis, which may also include a requirement for formal audits of fish production numbers relative to escapes [37]. A second aspect of monitoring, that is much less frequent in the regulations we examined, involves environmental monitoring in a post-escape event [67]. We consider each of these aspects of monitoring in turn.

In terms of monitoring escapes, all regions are required to monitor production facilities for fish escapes. Monitoring may trigger a formal audit of an aquaculture facility if a farmed fish is found in adjacent river but there has been no industry reports of an escape. This is the case in the US State of Maine and the Canadian Province of Nova Scotia [38]. Monitoring escapes when they happen is, of course, an important way of tracking escape numbers, but on its own monitoring the number of escapes – as is usually required in codes of containment – has no effect on reducing escapes particularly when monitoring is not complemented by other stronger measures including sanctions.

Monitoring the environmental effect of escapes on wild salmon populations and ocean ecologies adjacent to production regions may be undertaken by government regulators and by research scientists, but it usually happens sporadically rather than systematically in production zones. At the same time, scientists have been at the forefront of urging regulators to monitor the effects of escapes especially on wild fish species. In practice, government and research scientists often work together to assess the biosecurity and ecological risks associated with escapes. In Tasmania, for example, significant escape events in 2020 led to a collaboration between the government's Marine Farming Branch and research scientists based at the University of Tasmania's Institute for Marine and Antarctic Studies [68]. In Canada, research scientists from the Department of Fisheries and Oceans have been active in tracing the introgression of farmed salmon genes into wild populations especially in Newfoundland and Labrador [69]. While companies are largely not involved in these activities, the situation in Chile different. This country's most recent amendment to its escape regulations requires that companies finance ocean monitoring for two years following the escape event. The decision to make companies directly responsible for monitoring ocean ecologies following an escape is part of a broader and significant tightening of the regulations for salmon aquaculture in Chile [21].

2.7 Sanctions

Legislation or codes may allow for penalties and sanctions to be imposed on companies found liable for escape events. Most of the 14 production regions do not have formal sanctions for escape events. In the Naylor et al review of the mid-2000s, they also found that sanctions did not exist or were weak, noting that "the evidence indicates that where penalties for escapes exist, they generally provide an insufficient incentive to prevent escapes and are incommensurate with the ecological and socioeconomic risks" [22]. Our review of policies suggests, then, that not much has changed when it comes to sanctions for escape events.

For those regions that do have legislated sanctions, these tend to vary significantly in terms of their provisions. In Newfoundland and Labrador, for example, the sanction may involve a restriction or revocation of an aquaculture licence, although this has never happened in practice [25]. In Tasmania, the use of sanctions is contingent: "escapes may be treated as an offence depending on the circumstances" [52]. In other locations, the sanctions are much stricter. In Norway, for example, sanctions can include the permanent withdrawal of a fish farming licence, criminal prosecution, and imprisonment for up to two years [36]. Chile remains the production region with the strictest provisions and with a record of high profile fines on producers, although this was not always the case [70]. From the early 2010s, Chilean regulators began a concerted effort to strengthen sanctions. By 2020 the regulations provided regulators with the means to impose a fine of almost $USD7 million on MOWI following a large scale escape of 700,000 fish in 2018 [21,71]. In 2023, regulators in Chile continued to tighten provisions for escapes by linking the value of the fine to the value of the lost harvest and through a maximum potential license suspension of 4 years [70].

Sanctions, where they exist in production regions, typically involve the imposition of fines and the temporary withdrawal of licences. Of course, for Washington State, the escape of more than 250,000 salmon in 2017 following a net pen collapse opened the way for ultimate penalty: the decision to ban Atlantic salmon aquaculture in the state [32,33]. Overall, while sanctions across the 14 production regions are relatively weak or non-existent, escape events remain a high stakes challenge for industry with potential far reaching risks for production.

2.8 Assessing the strength and effectiveness of policies for a fish out of place

In their global review of salmon escape regulations, Naylor et al. highlighted the weaknesses of existing policies and frameworks and called for stronger measures given the environmental, social and economic risks associated with farmed salmon escapes [22]. Here we build on their work by assessing the strength and weaknesses of specific policy interventions through a qualitative assessment of the different mechanisms to address escapes along two axes (Figure 2.2). The first axis is for measures that reduce the likelihood of escapes from happening, and the second axis is for measures that attempt to limit the environmental impact of escapes. Plotting policy measures and technological innovations along these two axes allows us to assess the strength or weakness of policies in three-dimensional space.

Our analysis of the 14 production regions reveals a diverse array of strategies used to mitigate the environmental risks of salmon escapes. As we have discussed, these measures range from reporting and recapture, to monitoring to the use of technologies such as triploids and escape proof nets, and the use of sanctions imposed on companies. In this analysis, we also include measures such as offshore production [40], semi-closed containment systems [72], land-based production [73], and banning production altogether [32,33] as these also play a role in attempts to mitigate or eliminate the problem of salmon escapes. Our decision to plot these along two axes – one that reduces the likelihood of escapes and a second that reduces the environmental impact of escapes – is justified on the basis that the specific mechanisms that we identify attempt to address different aspects of the environmental problems associated with escapes. A good example is the use of triploid fish, which aim to address the problem of genetic introgression into wild salmon populations [74]. While this technology potentially reduces the environmental impact of escapes it does not necessarily, and on its own, reduce the likelihood of escapes from happening. Similarly, while monitoring, reporting and recapture policies may play some role in reducing the impact of escapes on ocean ecologies, they are not on their own always effective in reducing escapes from happening [66,67,75]. As a final example, banning salmon aquaculture or shifting production onto land will both reduce the likelihood of escapes and their environmental effect.

Plotting these policy instruments across the two axes of ‘reducing environmental impact’ and ‘reducing the likelihood of escapes’ provides a visual representation of our analysis of the wide range of mechanisms currently used to address escapes. While we acknowledge that policies and mechanisms may be used in concert – for example the use of triploid fish and ‘escape proof’ nets – the visual presentation is nonetheless useful to disaggregate the mechanisms across the two axes [76]. We identify 4 areas where policies are either strong or weak across the axes and we provide examples for each area. As we have already noted, banning production and shifting to land based systems represents a strong response across both axes: it reduces the likelihood escapes to virtually zero and therefore also reduces the environmental impact of salmon escapes. Reporting escapes, recapture efforts and monitoring and auditing escape numbers are weak on both axes: recording the number of escapes has little effect on reducing the number of escapes and recapture efforts in the open ocean are, not surprisingly, largely ineffective in recovering any more than a small percentage of the fish that escape. The use of triploid fish on its own represents a stronger response to the environmental problems as it prevents introgression, but the use of these fish clearly does nothing to limit escapes from happening. Finally, there are responses that are relatively stronger along both axes: these include escape proof nets, the use of semi-enclosed systems and farming offshore.

Disaggregating policies and mechanisms in terms of addressing the problem of escapes adds in important ways to the earlier analysis by Naylor et al. (2005) [22]. Through a careful analysis of the various policy mechanisms we were able to assess their purpose and compare their relative strengths and weaknesses. Of course, as we noted earlier, policy frameworks in practice often require several or more of these mechanisms to be used simultaneously. Nonetheless, by disaggregating the purpose of policy instruments we gain insights into the specific mechanisms and the role they aim to play in addressing the problem of escapes.

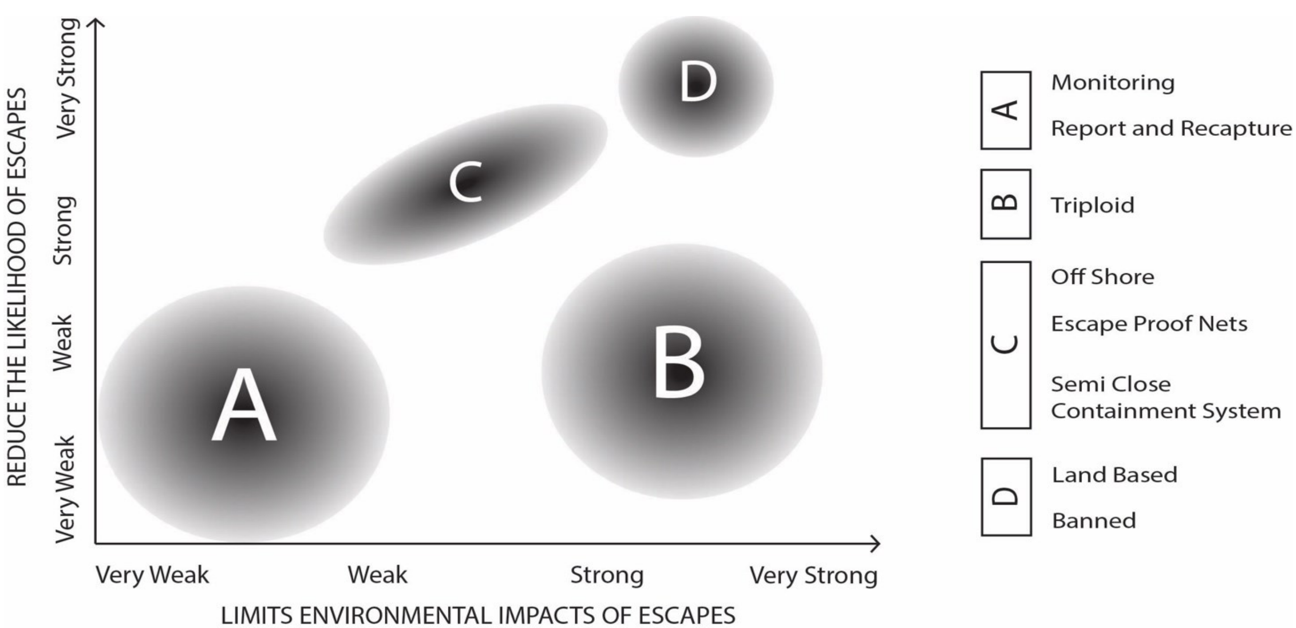

Figure 2.2: Effectiveness of approaches in reducing escapes and limiting environmental impacts.

There are several important caveats and limitations to our analysis of escape policies for salmon aquaculture, which may also provide opportunities for further research. Our work represents a snapshot in time, and we know from our analysis that policies and regulations are in flux and that new technologies may provide options for producers and regulators in attempting to manage the intractable problem of farmed salmon escapes. A second issue is that our analysis of policies and their strengths is qualitative; a quantitative scoring approach has the potential to additional insights to our analysis comparing regional frameworks and specific policies. In addition, we do not correlate the strength of policies against other variables including the volume of production or against the existence or otherwise of existing wild salmon populations. One would expect escape regulations might be stronger where salmon aquaculture production happens alongside threatened wild salmon populations, but even based on our qualitative analysis we think this might be difficult to sustain. Chile and Norway, for example, are two production regions with the strongest policies based on our analysis, but while Norway has wild Atlantic salmon, the same is not true for Chile. Overall, our assessment of policies and regulations for farmed salmon escapes and their strengths and weaknesses provides the foundation for further and more detailed analysis.

2.9 Discussion and Conclusion

Through a detailed analysis of farmed salmon escape policies, our paper aims to provide new insights into the role of aquaculture policy in addressing environmental concerns while realising the potential of this sector in the blue economy. A significant finding is that all 14 production regions have specific measures to address the problem of escapes. Even in a context where escape numbers are notoriously difficult to measure and monitor, addressing the problem of farmed salmon escapes remains a key concern for regulators and producers. Indeed, it seems untenable that any new production region for salmon aquaculture would not have policies to address the problem of salmon escapes.

Our visual representation of the specific mechanisms that aim to address the problem of escapes has allowed us to provide additional insights into the wide range of instruments that make up the regulatory systems in place. We were able to distinguish between mechanisms that are stronger and weaker in terms of their impact on reducing escapes and limiting their environmental effects.

All 14 production regions have policies and frameworks, but our conclusions are largely in line with Naylor's study of the mid-2000s [22]. Several production regions (notably Chile [21] and Norway [44]) have implemented very strict regulations, yet many other regions have policies that are unlikely to significantly reduce the number of escapes or their environmental impact. The main reasons include weak sanctions, an emphasis on monitoring and reporting, which do little to prevent escapes, and provisions that allow regulators to absolve companies from the responsibility of addressing escapes when they happen. It is also important to recognize, as Naylor et al. (2005) [22] did in their earlier work, that escapes from farmed salmon cages in the ocean will never be entirely eliminated [18,24]. Given the inevitability of escapes in open net aquaculture, the policies and frameworks aim to reduce escapes from happening rather than eliminating them entirely.

The policy adopted by Newfoundland and Labrador to require the reporting of even a single escaped salmon represents a stringent and precautionary regulatory measure. This low reporting threshold highlights the region's acknowledgment of the ecological risks associated with even small-scale escape events. Such a policy has the potential to improve accountability and transparency in the aquaculture industry. However, it also raises questions about feasibility, given the inherent challenges of monitoring and detecting "trickle escapes" or gradual leaks of fish from cages. While reporting single escapes is an ambitious step, its effectiveness ultimately depends on the capacity of regulators to enforce compliance and on the aquaculture industry's willingness to prioritize escape prevention.

If farmed salmon escapes are likely to persist into the future because of weak policies and because of the inevitability of escapes from ocean-based cages, what are the implications for escape policies and for the sustainability of salmon aquaculture production? We consider two interesting and notable responses. The first involves proposals to co-manage salmon that have escaped cages and the second is to acknowledge that wild populations have already been irrevocably changed by genetic introgression. As we noted in the paper, Chile is a country that has experienced significant escape events over the last several decades and has, in response, established a very strict regulatory system with substantial fines and obligations on companies [12,21,63]. At the same time, researchers have recently proposed the idea that escaped salmon should be co-managed in the future [77]. Co-management of escaped salmon would happen through the collaboration of key stakeholders including government, industry, small scale fishers, and recreational anglers [21]. For the authors proposing this idea, co-management has the potential to improve recapture rates and limit the environmental impact of escapes in Patagonian waters [77]. Establishing co-management arrangements for farmed salmon escapes may represent an important institutional innovation, but it may also be a consequence of coming to terms with the inevitability of farmed escapes from ocean based cages [22]. In other words, co-management may be one policy response to the realisation by regulators that containing salmon in cages is an impossible goal even with strict policies. This first response then points to new institutional arrangements that will improve the 'management' of farmed salmon that have become self-sustaining populations in the ocean.

A second and far more radical option involves coming to terms with the idea that we live in the Anthropocene and that ocean ecologies and species – including wild salmon – have been irrevocably changed through many decades of human activity in the ocean. This is an argument that is made in some industry circles when concerns are raised about the impact of escapes on wild salmon populations [78]. In Eastern North America, for example, when the issue of farmed escapes is raised as a problem, the aquaculture industry has pointed to the many decades of fish stocking that has happened in the region aimed at rebuilding native stocks of wild Atlantic salmon for recreational anglers. Wild salmon, according to this argument, are no longer wild because of decades of human intervention including through hatchery stocking [79]. This second response suggests that we should spend less time worrying about farmed salmon escapes because they are not substantially different than fish in the wild.

The argument that wild salmon are no longer wild because of human activity is not broadly supported by government regulators or within scientific circles [16,80]. Farmed salmon that escape continue to be seen as a 'fish out place' requiring regulation and response from aquaculture authorities and companies involved in farming salmon in the ocean. In addition, the problem of escapes is not only about genetic introgression; it is also about a much broader set of concerns around disease transmission and ecological change that comes about as farmed salmon find their way out of their cages and into the wild [17,81]. This broader set of concerns helps explain why frameworks and policies for this 'fish out of place' remain a key matter of concern for government regulators where salmon are farmed. At the same time, our research points to the need to significantly strengthen these measures especially in context where sanctions are weak or non-existent and where many specific policy instruments – including monitoring and reporting – do little to address the problem of farmed salmon escapes.

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https://www.cbc.ca/listen/live-radio/1-122-the-broadcast/clip/16053101-dfo-studies-effect-salmon-farm-escapes-seafood

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Supplementary Materials

Chapter Two

Appendix 1. Supporting information

We provide supplementary material including detailed data on the Government departments responsible for aquaculture and farmed fish escapes for our 14 production regions. We also include additional documents that were consulted that include information on the regulatory frameworks for the production regions. The aim here is to provide transparency and to allow for the reproducibility of our methods.

1- Washington State, United States

Departments responsible for aquaculture:

Washington State Department of Natural Resources

https://www.dnr.wa.gov/programs-and-services/aquatics

Washington State Department of Ecology

https://ecology.wa.gov/

Washington State Department of Fish & Wildlife (DFW)

https://wdfw.wa.gov

Other resources we consulted for this region:

Official website of the Washington State Legislature

https://leg.wa.gov

RCWs > Title 77 > Chapter 77.125 > Section 77.125.010

https://app.leg.wa.gov/rcw/default.aspx?cite=77.125.010

WACs > Title 220 > Chapter 220-370 > Section 220-370-110

https://app.leg.wa.gov/WAC/default.aspx?cite=220-370-110

WACs > Title 220 > Chapter 220-370 > Section 220-370-120

https://apps.leg.wa.gov/wac/default.aspx?cite=220-370-120

RCWs > Title 77 > Chapter 77.15 > Section 77.15.350

https://app.leg.wa.gov/rcw/default.aspx?cite=77.15.350

Official website of the United States Environmental Protection Agency (EPA)

https://www.epa.gov/newsreleases/epa-reestablishes-federal-water-pollution-standards-washington

Lee K, Windrope A, Murphy K. 2017 Cypress Island Atlantic Salmon Net Pen Failure: An Investigation and Review.2018 Jan. Available from: https://www.dnr.wa.gov/sites/default/files/publications/aqr_cypress_investigation_report.pdf?vdqi7rk#:~:text=Representatives%20of%20these%20three%20agencies,the%20nets%20containing%20the%20fish.&text=other%20marine%20organisms.&text=Breakdowns%20in%20net%20cleaning%20machines%20contributed%20to%20this%20condition.

article hosted by the DNR website.

https://www.dnr.wa.gov/news/commissioner-franz-ends-net-pen-aquaculture-washington’s-waters

article hosted by the DNR website.

https://www.dnr.wa.gov/programs-and-services/aquatics

2- State of Maine, United States

Departments responsible for aquaculture:

State of Maine Department of Environmental Protection

https://www.maine.gov/dep/

Maine Department of Marine Resources

https://www.maine.gov/dmr/home

Other resources we consulted for this region:

Maine Aquaculture Association

https://maineaqua.org

Maine Department of Environmental Protection. Net pen aquaculture general permit fact sheet, 2014.

https://www.maine.gov/dep/water/wd/net-pen-aquaculture/MEG130000-2014fact-sheet.pdf

Oceana

https://oceana.org/press-releases/us-state-of-maine-passes-law-to-set-limits-on-new-fish-farms/

3- British Columbia, Canada

Departments responsible for aquaculture:

Department of Fisheries and Oceans Canada (DFO)

https://www.dfo-mpo.gc.ca/index-eng.html

BC Government's aquaculture

https://www2.gov.bc.ca/gov/content/industry/agriculture-seafood/fisheries-and-aquaculture/aquaculture

Other resources we consulted for this region:

Government of Canada. Justice Laws Website. Pacific Aquaculture Regulations

https://laws-lois.justice.gc.ca/eng/regulations/SOR-2010-270/

Dow A. Norway vs. British Columbia: A Comparison of Aquaculture Regulatory Regimes. Environmental Law Centre Murray and Anne Fraser Building University of Victoria [Internet]. 2004; Available from:

http://www.elc.uvic.ca/wordpress/wp-content/uploads/2014/08/AquacultureReport.pdf

Aquaculture in British Columbia, DFO

https://www.pac.dfo-mpo.gc.ca/aquaculture/index-eng.html

Government of Canada, Escapes of cultured finfish from BC aquaculture sites

https://open.canada.ca/data/en/dataset/691dd994-4911-433d-b3b6-00349ba9f24e

4- Newfoundland and Labrador, Canada

Department responsible for aquaculture:

Department of Fisheries, Forestry and Agriculture

https://www.gov.nl.ca/ffa/

Department of Fisheries and Oceans Canada (DFO)

https://www.dfo-mpo.gc.ca/index-eng.html

Other resources we consulted for this region:

Government of Newfoundland and Labrador

https://www.gov.nl.ca

Government of Newfoundland and Labrador. Fisheries and Aquaculture

https://www.gov.nl.ca/ffa/programs-and-funding/fisheries-and-aquaculture/

Office of the Legislative Counsel, Newfoundland and Labrador, Aquaculture Act

https://www.assembly.nl.ca/legislation/sr/statutes/a13.htm

Newfoundland and Labrador Code of Containment

https://www.gov.nl.ca/ffa/files/DOC-2022-04405-Salmonid-Code-of-Containment-Updated-October-20222.pdf

Government of Newfoundland and Labrador Fisheries and Land Resources. Aquaculture Policy and Procedures Manual 2019 https://www.gov.nl.ca/ffa/files/licensing-pdf-aquaculture-policy-procedures-manual.pdf

Government of Canada. Proposed use of European-strain triploid Atlantic salmon in marine cage aquaculture in Placentia Bay, NL - Government of Canada Publications, Canada. Available from: https://publications.gc.ca/site/eng/9.820178/publication.html

Proposed use of European-strain triploid Atlantic salmon in marine cage aquaculture in Placentia bay, NL

https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/40621248.pdf

National Code on Introductions and Transfers of Aquatic Organisms (Code)

https://www.dfo-mpo.gc.ca/aquaculture/management-gestion/it-code-eng.htm

5- Nova Scotia, Canada

Department responsible for aquaculture:

Department of Fisheries and Aquaculture: https://novascotia.ca/fish/

Department of Fisheries and Aquaculture, Aquaculture Management page

https://novascotia.ca/fish/aquaculture/aquaculture-management/

Department of Fisheries and Oceans Canada (DFO)

https://www.dfo-mpo.gc.ca/index-eng.html

Aquaculture Association of Nova Scotia

https://seafarmers.ca

Other resources we consulted for this region:

Nova Scotia legislator- Fisheries and Coastal Resources Act

https://nslegislature.ca/sites/default/files/legc/statutes/fisheries%20and%20coastal%20resources.pdf

Doelle M, Lahey W. A New Regulatory Framework for Low-Impact/High-Value Aquaculture in Nova Scotia. SSRN Journal. 2014 ; Available from: https://novascotia.ca/fish/documents/Aquaculture_Regulatory_Framework_Final_04Dec14.pdf

Containment management for marine finfish in aquaculture sites, Nova Scotia

https://novascotia.ca/just/regulations/regs/fcraquamgmt.htm

6- New Brunswick, Canada

Department responsible for aquaculture:

New Brunswick Department of Agriculture, Aquaculture and Fisheries (DAAF)

https://www2.gnb.ca/content/gnb/en/departments/10/fisheries.html

Department of Fisheries and Oceans Canada (DFO)

https://www.dfo-mpo.gc.ca/index-eng.html

Other resources we consulted for this region:

Atlantic Canada Fish Farmers Association (ACFFA)

https://atlanticfishfarmers.com

General Regulation, NB Reg 91-158. NEW BRUNSWICK, REGULATION 91-158 under the, Aquaculture Act

https://www.canlii.org/en/nb/laws/regu/nb-reg-91-158/latest/nb-reg-91-158.html

Acts and Regulations, New Brunswick, 2022-30 - Aquaculture Products Health and Welfare

https://laws.gnb.ca/en/document/cr/2022-30

Code of Containment for Finfish Aquaculture

https://novascotia.ca/fish/documents/aquaculture-sites/jordanbay-stmarys/ACFFA_Code_of_Containment_of_Culture_of_Atlantic_Salmon_in_Marine_Net_Pens.pdf

7- Tasmania, Australia

Department responsible for aquaculture:

Department of Natural Resources and Environment Tasmania

https://nre.tas.gov.au

Tasmania Environment Protection Authority

https://epa.tas.gov.au

Other resources we consulted for this region:

Parliament of Australia-Overview of the fin-fish aquaculture industry in Tasmania

https://www.aph.gov.au/parliamentary_business/committees/senate/environment_and_communications/fin-fish/Report/c02

Department of Natural Resources and Environment Tasmania. Biosecurity Program: Tasmanian Salmonid Industry

https://nre.tas.gov.au/Documents/Biosecurity%20Program%20Tasmanian%20Salmonid%20Industry.pdf

This document provided by Department of Primary Industries, Parks, Water and Environment[4]

https://www.parliament.tas.gov.au/__data/assets/pdf_file/0029/56828/2021020920dpipwe20addendum.pdf

Marine Farming Planning Act 1995

https://nre.tas.gov.au/aquaculture/aquaculture-regulation-and-planning/marine-farming-development-plans/marine-farming-planning-review-panel

Institute for Marine and Antarctic Studies, University of Tasmania

https://www.imas.utas.edu.au/__data/assets/pdf_file/0010/1558567/Fishing-for-Atlantic-salmon-inferences-about-dispersal,-survival-and-ecological-impacts-following-to-large-scale-escape-events.pdf

8- Iceland

Department responsible for aquaculture:

Government of Iceland, Ministry of Food, Agriculture and Fisheries

https://www.government.is/ministries/ministry-of-food-agriculture-and-fisheries/

Iceland, Food and Veterinary Authority (MAST)

[4] The Department of Natural Resources and Environment Tasmania was previously known as the Department of Primary Industries, Parks, Water and Environment (DPIPWE) until December 2021.

https://www.mast.is/en

Institute of Marine and freshwater Research of Iceland

https://www.hafogvatn.is/is

Other resources we consulted for this region:

Icelandic Government, Ministry of Industry and Innovation,

https://www.reglugerd.is/reglugerdir/eftir-raduneytum/sjavaroglandbunadar/nr/19913

Risk of intrusion of farmed Atlantic salmon into Icelandic salmon rivers

https://www.hafogvatn.is/static/extras/images/5_risk_assesment_model_for_distribution_of_farmed_salmon_into_icelandic_rivers_corr_errata1431030.pdf

Björnsson B, Perez D, Martinsen S, Langhorn MP, Koralewicz A, Olsen G, et al. THE STATE AND FUTURE OF AQUACULTURE IN ICELAND [Internet]. Government of Iceland, Ministry of Food, Agriculture and Fisheries; 2023.

https://www.stjornarradid.is/library/02-Rit--skyrslur-og-skrar/The%20State%20and%20Future%20of%20Aquaculture%20in%20Iceland%20(1).pdf

9- Scotland

Department responsible for aquaculture:

Scottish Government, Scottish Fish Farm Production

http://www.gov.scot/publications/scottish-fish-farm-production-survey-2021/pages/8/

Fisheries Management Scotland

https://fms.scot

Scottish Environment Protection Agency (SEPA) https://www.sepa.org.uk

Other resources we consulted for this region:

Scottish Government's Marine Scotland Directorate, Aquaculture Code of Practice

https://www.gov.scot/publications/aquaculture-code-practice-containment-prevention-escape-fish-fish-farms-relation-marine-mammal-interactions/

Fisheries Management Scotland: Guidance on Capture of Escaped Farmed Fish

https://atlanticsalmontrust.org/wp-content/uploads/2020/11/Aqua-Guidance-on-escapees-FMS.pdf

The Aquatic Animal Health (Scotland) Regulations 2009

https://www.legislation.gov.uk/ssi/2009/85/contents

10- Norway

Department responsible for aquaculture:

Norwegian Ministry of Fisheries and Coastal Affairs.

https://www.regjeringen.no/globalassets/upload/kilde/fkd/reg/2005/0001/ddd/pdfv/255327-l-0525_akvakulturloveneng.pdf

Department for Aquaculture

https://www.regjeringen.no/en/dep/nfd/organisation/Departments/havbruksavdelingen/id2696730/

Norwegian Ministry of Trade, Industry and Fisheries

https://www.regjeringen.no/en/dep/nfd/id709/

The Norwegian Directorate of Fisheries

https://www.fiskeridir.no/English

Other resources we consulted for this region:

Technical requirements for fish farming installations, NYTEK23 and NS 9415:2021

https://www.regjeringen.no/globalassets/upload/kilde/fkd/bro/2005/0013/ddd/pdfv/255320-technical_requirements.pdf

The Aquaculture Act, Norwegian Ministry of Fisheries and Coastal Affairs

https://www.regjeringen.no/globalassets/upload/kilde/fkd/reg/2005/0001/ddd/pdfv/255327-l-0525_akvakulturloveneng.pdf

Nofima

https://nofima.com

11- Chile

Department responsible for aquaculture:

The National Fisheries and Aquaculture Service

https://www.sernapesca.cl/english/

The Undersecretariat for Fisheries and Aquaculture (SUBPESCA)

https://www.subpesca.cl/portal/616/w3-article-86158.html

Other resources we consulted for this region:

New General Law On Fisheries and Aquaculture N° 20.657

https://www.subpesca.cl/portal/617/articles-60001_recurso_1.pdf

Law 21,532 that prevents and penalizes the escape of salmon entered into force

https://seafood.media/fis/worldnews/search_brief.asp?l=e&id=121772&ndb=1

Chile's salmon industry new law on fish escapes

https://weareaquaculture.com/featured/chiles-salmon-industry-welcomes-new-law-on-fish-escapes/32296

Chilean salmon farmers face tough penalties if fish escape

https://www.fishfarmingexpert.com/chile-salmon/chilean-salmon-farmers-face-tough-penalties-if-fish-escape/1475798

12- Faroe Islands

Department responsible for aquaculture:

Ministry of Environment, Industry and Trade

https://www.government.fo/en/the-government/ministries/ministry-of-environment

Faroese Food and Veterinary Authority (Heilsufrøðiliga Starvsstovan)

https://www.hfs.fo/webcenter/portal/HFS

Other resources we consulted for this region:

Seafood Watch Consulting Researcher. Monterey Bay Aquarium's Seafood Watch program, Atlantic salmon Salmo salar, Faroe Islands Marine Net Pen.

https://www.seafoodwatch.org/globalassets/sfw-data-blocks/reports/s/seafood-watch-farmed-salmon-faroes-27921.pdf

Aquaculture - Legislation and Management

https://www.faroeseseafood.com/fishery-aquaculture/aquaculture-legislation-and-management

Executive order on the establishment of and disease-prevention in aquaculture facilities

https://www.hfs.fo/webcenter/ShowProperty?nodeId=%2Fhfs2-cs%2FHFS059686%2F%2FidcPrimaryFile&revision=latestreleased

13- New Zealand

Department responsible for aquaculture:

Department of Conservation

https://www.doc.govt.nz/nature/habitats/marine/new-zealands-marine-biodiversity/#:~:text=New%20Zealand%20is%20known%20for,kiwi%2C%20tuatara%2C%20and%20wētā

Ministry of Fisheries New Zealand

https://fs.fish.govt.nz/Page.aspx?pk=91

Ministry for the Environment for coastal marine aquaculture

https://environment.govt.nz

Ministry for Primary Industries

https://www.mpi.govt.nz

Environmental Protection Authority (EPA) NewZealand

https://www.epa.govt.nz/

Other resources we consulted for this region:

Fisheries New Zealand, Best management practice guidelines for salmon farms in the Marlborough Sounds

https://www.mpi.govt.nz/dmsdocument/53680-AEBR-294-Best-management-practice-guidelines-for-salmon-farms-in-the-Marlborough-Sounds

New Zealand Salmon Farmers Association Inc. Industry Standards

https://www.salmon.org.nz/industry-standards

The New Zealand King Salmon Co. Ltd.

https://www.kingsalmon.co.nz/wp-content/uploads/2019/03/2015-11-25-BMP-Guidelines-Operational-Final.pdf

14- Ireland

Department responsible for aquaculture:

Department of the Marine and Natural Resources

https://www.gov.ie/en/organisation/department-of-the-environment-climate-and-communications/

Department of Agriculture, Food and the Marine.

https://www.gov.ie/en/organisation/department-of-agriculture-food-and-the-marine/

The Irish Sea Fisheries Board (BIM)

https://bim.ie

Irish Marine Institute

https://www.marine.ie/site-area/areas-activity/aquaculture/aquaculture

Other resources we consulted for this region:

Environmental Code of Practice for Aquaculture Companies and Traders (ECOPACT) developed by The Irish Sea Fisheries Board (BIM)

https://bim.ie/wp-content/uploads/2021/02/BIM-Environmental-Sustainability-Atlas.pdf

McMahon, T. (2000). Regulation and monitoring of marine aquaculture in Ireland. Journal of Applied Ichthyology. https://doi.org/10.1046/j.1439-0426.2000.00263.x

North Atlantic Salmon Conservation Organization (NASCO). Ireland: national implementation plan meeting the objectives of NASCO resolutions and agreements

https://nasco.int/wp-content/uploads/2020/02/IP_Ireland.pdf

FAO, National Aquaculture Legislation Overview of Ireland

https://www.fao.org/fishery/en/legalframework/nalo_ireland

Additional resources covering more than one production region

North Atlantic Salmon Conservation Organization (NASCO):

https://nasco.int/conservation/aquaculture-and-related-activities/

Comparative Analysis of Aquaculture Regulatory Frameworks in Maine and Nova Scotia, Prepared by East Coast Environmental Law.

https://www.ecelaw.ca/resources-library/comparative-analysis-of-aquaculture-regulatory-frameworks-in-maine-and-nova-scotia?rq=Comparative%20Analysis%20of%20Aquaculture%20Regulatory%20Frameworks%20in%20Maine%20and%20Nova%20Scotia

An International Regulatory Review to Support Consistent and Improved Management of the Impacts of Sea Cage Salmon Aquaculture, 2016.

https://www.asf.ca/wp-content/uploads/2023/05/gardner-pinfold-value-wild-salmon.pdf

National Oceanic and Atmospheric Administration:

https://www.fisheries.noaa.gov/resource/document/regulatory-regimes-environmental-management-marine-net-pen-aquaculture-canada-and

Standing Senate Committee of Canada, Fisheries and Oceans

https://sencanada.ca/content/sen/committee/421/pofo/reports/2016-06-22_pofo_aquaculturevolume2_final_e.pdf

Atlantic Salmon Federation: https://www.asf.ca

A Joint-Report of DFO and NOAA. Regulatory Regimes for Environmental Management of Marine Net Pen Aquaculture in Canada and the United States. 2018 Apr; Available from: https://www.fisheries.noaa.gov/resource/document/regulatory-regimes-environmental-management-marine-net-pen-aquaculture-canada-and

Appropriate Assessment of the National Strategic Plan for Sustainable Aquaculture Development. Under Article 6 of the Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora; 1992.

Sim-Smith C, Forsythe A. Comparison of the international regulations and best management practices for marine finfish farming. Prepared for the Ministry for Primary Industries. 2013 Oct;(MPI Technical Paper No: 2013/47).

Dow A. Norway vs. British Columbia: A Comparison of Aquaculture Regulatory Regimes. Environmental Law Centre Murray and Anne Fraser Building University of Victoria [Internet]. 2004; Available from: http://www.elc.uvic.ca/wordpress/wp-content/uploads/2014/08/AquacultureReport.pdf

Chapter Three: Triploid Fish: A Dual-Edged Technology for Sustainability and Production

3.1 Introduction

Sustainable intensification has become an important policy goal aimed at increasing food production while minimizing environmental impacts [1]. This principle recognizes the environmental burden of food production but also the need to produce more food for a growing global population [2]. In aquaculture, sustainable intensification is especially important because the farming of fish is seen as a more sustainable method of food production and has significant potential for growth [1].

The Food and Agriculture Organisation has emphasized that sustainable aquaculture practices are crucial for ensuring food security and nutrition, supporting livelihoods, and promoting the responsible use of aquatic resources [3]. Industry claims of adopting sustainable practices are widespread, yet the implementation and outcomes of these practices can vary significantly [4]. This discrepancy is particularly evident in the discourse surrounding "sustainable intensification," a strategy purported to boost productivity while minimizing environmental impacts [5].

Technological innovation is often a key element of sustainable intensification. Improvements in breeding have been instrumental in advancing food-producing industries [6]. For example, the poultry industry has seen significant gains in growth rates over several decades, and dairy cattle have achieved substantial increases in milk yield per cow [7–9]. In aquaculture, breeding and other allied technologies play a crucial role in supporting the ongoing expansion and intensification of this form of protein production to meet the increasing demand for food [10]. Similar advancements have been achieved in the aquaculture sector, particularly with Atlantic salmon [11].

In aquaculture, selective breeding has long been an essential tool for enhancing future aquaculture production [11]. Research and development have focused on selecting traits such as body weight at slaughter, age of sexual maturation, disease resistance, flesh color, and fat content [12]. The development of breeding programs, spearheaded by pioneers like Prof. Harald Skjervold, transformed domestic animal production traits, including those of salmon. Early trials with various salmon strains in different Norwegian environments revealed that a single strain could thrive universally, streamlining the breeding process to focus on growth rate and delayed sexual maturation. This led to significant genetic improvements and a 30% increase in growth rate, reducing production costs and boosting industry efficiency [13]. However, the sector faced significant challenges, including devastating disease outbreaks that led to heavy antibiotic use. This prompted the development of vaccines for common diseases and a shift toward selecting for natural disease resistance, enhancing both fish health and industry sustainability [13].

While breeding aimed to improve production and efficiency, it failed to address the problem of salmon aquaculture's environmental impact [11–13]. This is particular the case with the escape of farmed fish into the wild and the wide range of environmental problems that have followed fish escapes [14]. While breeding success in salmon aquaculture has been highly successful, it has simultaneously generated significant environmental challenges [13,15].

Breeding has, however, also provided potential solutions to the aquaculture industry's efforts to balance production efficiency with environmental sustainability. This is particularly evident in the development of sterile fish, such as triploid salmon, which prevent the genetic impact of escaped farmed fish on wild populations while also enhancing production efficiency through selective breeding [13]. The use of triploid salmon represents a significant advancement in the industry's efforts to reconcile the conflicting priorities of production and environmental responsibility. By rendering fish sterile, aquaculture facilities can mitigate one of the primary environmental risks posed by salmon farming, which is the potential for escaped fish to breed with wild populations and alter their genetic makeup [15].

In this way, triploid salmon have the potential to address one of salmon aquaculture's most pressing environmental challenges, viz., the issue of introgression, where escaped farmed fish interbreed with wild salmon populations, threatening the genetic integrity of these wild stocks [16]. The use of sterile fish, such as triploid salmon, has emerged as a promising solution to address this problem [13,15]. This approach not only prevents the interbreeding of farmed and wild salmon but also aligns with ongoing efforts to enhance production efficiency through selective breeding [13,17]. The development of sterile fish represents a critical intersection between breeding innovations and environmental sustainability, offering a practical solution to protect wild populations while maintaining high standards of production [13].

The aquaculture industry's efforts to balance production efficiency with environmental sustainability are exemplified in the use of triploid salmon. Triploid (sterile) salmon have been introduced as a solution within this framework, addressing both production and environmental concerns [1,18]. Triploid salmon are genetically modified to be sterile, preventing early sexual maturation that can affect growth and quality. This also mitigates the genetic impact of escaped farmed salmon on wild populations, maintaining genetic diversity in natural populations [15].

In a recent article on sustainability in Norway's farmed salmon sector, Aarset et al. (2020) critically examine how the term "sustainability" is interpreted and implemented within the industry [19]. They argue that the concept of sustainability is often co-opted by industry players to align with their production goals. The study reveals that while the industry publicly promotes sustainability practices, these practices are frequently framed to support production efficiency and market demands [19]. In this chapter, I argue that while technological innovations like triploid salmon are often presented as environmental solutions, they also carry significant economic and production benefits. This underscores the challenge of separating environmental solutions from production priorities. At the same time, however, the development of triploid salmon show how production goals take precedence when the system faces challenges, reflecting a persistent tension within the industry in its goal of sustainable of intensification.

Consider Grieg Seafood as an example of how sustainability goals and production priorities are intertwined. Grieg is a multinational aquaculture company that has operations across the world. Founded in Norway, the company operates globally, including significant operations in Newfoundland and Labrador, Canada. In 2016, Grieg Seafood NL proposed using fertilized sterile triploid Atlantic salmon for its project in Placentia Bay from Stofnfiskur in Iceland in commercial production to prevent any negative effects on wild Atlantic salmon in the event of an escape [20].

Grieg Seafood NL states that "the use of normal sterile Atlantic salmon eggs from Stofnfiskur will ensure the Atlantic salmon produced at our hatchery will not mature, cannot reproduce, or mix with wild salmon. Stofnfiskur focuses on Atlantic salmon that grow fast, are disease-resistant with strong immune systems, and are accustomed to intensive culture, resulting in lower stress levels in these conditions [21]." This highlights that while triploid salmon are promoted for their environmental benefits (they cannot ‘mix with wild salmon’), production priorities are equally emphasized to support intensive farming (they ‘grow fast’ and are ‘accustomed to intensive culture’) [13]. In other words, while triploid salmon represent an environmentally sustainable option and a response to the problem salmon escapes, they are also fish that meet traditional production goals.

In this chapter, the aim is to understand the use of triploid fish as an environmental solution to the problem of escapes. In this way it complements chapter 2, which focuses on the policy responses to the environmental problems of salmon escapes, by assessing a technological response to the problem of salmon escapes. My analysis shows that triploid salmon may prevent introgression in wild populations, making it a good environmental model [22]. However, the analysis of three case studies—Newfoundland, Tasmania, and Norway—reveals that balancing environmental solutions and production priorities is often complex and varies by context. In Newfoundland, efforts to address early maturation in local strains of farmed Atlantic salmon led to ongoing requests by industry to use Norwegian strains of Atlantic salmon. These requests were denied until industry was able to import triploid Norwegian salmon, thus finding a solution to the long-term problem of early maturation while maintaining the benefits of higher production rates. In Tasmania, triploid salmon have been used not as a solution to the problem of escapes given that they do not have wild salmon stocks, but as a response to the warmer waters where salmon are farmed. Yet these triploid salmon, have become the source of controversy, as they may compromise fish welfare and they are the subject of environmental challenges, underscoring a different tension between maximizing production and ensuring sustainability. Norway, a leader in the Atlantic salmon aquaculture industry, has incorporated triploid salmon into its breeding programs to enhance productivity, often framing these efforts as sustainability measures. However, when farming with triploid salmon fails for production reasons, the use of these fish is discontinued in spite of their apparent environmental benefits in mitigating the impact of escapes.

By examining each case in detail, I will reveal the motivations behind the adoption of triploid salmon in aquaculture. This analysis will show how difficult it is to separate production from environmental concerns when it comes to triploid salmon, with the broader implications for the use of technology in sustainable intensification. I will also show that while environmental solutions and production priorities are intertwined, production efficiencies and growth will trump environmental concerns.

The cases analyzed will further reveal the complex relationship between production and environmental objectives in aquaculture. However, they will also highlight significant regional variations in the implementation and justification of triploid salmon, shaped by differences in regulatory frameworks, market demands, and ecological contexts. These variations emphasize the ongoing challenge of achieving truly sustainable aquaculture practices, where balancing production efficiency with environmental stewardship remains an elusive goal.

The geographical and regulatory environments also influence the use of triploids. For example, in Newfoundland, regulatory frameworks have allowed the import of sterile triploid salmon to mitigate ecological risks associated with introducing non-native species [20]. In Norway, strict regulations and "green licenses" govern the use of triploid salmon to balance production goals with environmental protection [19]. In Tasmania, the initial use of triploid salmon was primarily driven by production needs. However, this practice has since raised environmental concerns, highlighting the complex interplay between production efficiency and sustainability [23,24].

This chapter aims to critically examine the role of triploid salmon as both an environmental safeguard and a production tool. By exploring the three case studies, I will highlight how triploid salmon farming practices are influenced by both environmental and production priorities, with production often taking precedence, especially when challenges arise. The organization of this chapter is as follows. First, I will explain what triploid fish are and provide the historical background of triploid salmon applications in aquaculture. I will then explore my case studies in Newfoundland and Labrador, Tasmania and Norway. These case studies will provide insights into the development, challenges, and successes of triploid fish farming in these regions.

3.2 Methods

This section outlines the research approach used to explore the role of triploid fish as both a technology for sustainability and a means to enhance production efficiencies and growth in farmed fish production. The study employs a qualitative multiple case study design to investigate the application and impact of triploid salmon in Newfoundland, Tasmania, and Norway, with an emphasis on the interplay between environmental and production priorities in each context.

The selection of these three case studies was guided by their unique contexts and relevance to the use of triploid salmon in aquaculture. Newfoundland was chosen because its adoption of triploid salmon is a relatively new initiative, particularly involving the use of European strains, which raises specific regulatory and environmental considerations. Tasmania was selected as a case study because it lacks wild salmon populations, making the use of triploid salmon in this region a subject of debate regarding its necessity and purpose. Finally, Norway was included due to its pioneering role in the development of triploid salmon technology, as well as its long history and leadership in advancing this approach. These diverse contexts provide a comprehensive framework for evaluating the use and effectiveness of triploid salmon across different regulatory, environmental, and production settings.

Data were collected through a systematic literature review, involving the search and analysis of academic articles, government reports, industry documents, and regulatory frameworks relevant to triploid salmon. Sources were identified using databases such as Web of Science, Google Scholar, and Scopus, with search terms including "triploid salmon," "sterile fish aquaculture," "salmon farming," "genetic introgression," and "sustainable intensification in aquaculture."

For each case study, I focused on documents that provided historical context, technological developments, regulatory decisions, and industry practices. In Newfoundland, I reviewed government reports and industry publications from Fisheries and Oceans Canada, along with documents related to the regulatory approval of Norwegian-strain triploid salmon. In Tasmania, I primarily relied on the report by Jungalwalla (1991), titled "Production of non-maturing Atlantic salmon in Tasmania," which provided key insights into the historical context and technological developments in the region's salmon farming industry. Additionally, I analyzed reports from the Tasmanian Fisheries Development Authority, publications from Salmon Enterprises of Tasmania (SALTAS), and NGO reports such as those from the Tasmanian Alliance for Marine Protection (TAMP). For Norway, I examined policies related to "Green Licenses" and fish welfare regulatory guidelines from the Norwegian Food Safety Authority (NFSA), as well as scientific studies on the welfare impacts of triploid salmon.

The collected data were synthesized to draw insights into the environmental and production impacts of triploid salmon across the different regions. Key themes, such as the balance between production efficiency and environmental sustainability, were identified and compared across the case studies. This analysis highlights the challenges and trade-offs encountered in the implementation of triploid salmon, with a particular focus on how regional regulatory frameworks and market demands influence these dynamics.

3.3 Sterile Fish in Aquaculture

3.3.1 Early Maturity Challenges

In the quest to develop highly productive farmed salmon, researchers in Norway pioneered breeding programs aimed at producing fast-growing salmon that could thrive in cages and be fed industrial feed in ocean cages [25]. These efforts led to significant advancements in aquaculture practices, making large-scale production feasible [25]. However, a major challenge that emerged was early maturation. Early maturation in salmon has been a primary challenge since the early development of salmon aquaculture, significantly affecting the viability and productivity of large-scale commercial operations [15]. Early maturation is problematic because it can lead to several issues that affect the viability and productivity of aquaculture operations [23]. First, early maturing salmon tend to have reduced growth rates and smaller body sizes at harvest, which can significantly impact the economic returns from aquaculture. Smaller fish fetch lower market prices, reducing the profitability of the operation. Early maturing fish often divert more energy towards reproductive development rather than growth, further decreasing their overall size and meat quality [26]. Secondly, early maturing salmon are more prone to physiological stress and health problems, which can increase mortality rates and lead to higher management costs. This includes increased susceptibility to diseases and parasites, which can spread rapidly in aquaculture environments and require expensive treatments and interventions [27].

Thirdly, early maturation can lead to reduced genetic diversity in farmed populations, complicating selective breeding efforts [28]. When individuals mature earlier, they reproduce sooner, leading to a gene pool dominated by early-maturing alleles. This reduces genetic variability, making it challenging to enhance desirable traits such as growth, disease resistance, and quality through selective breeding. For instance, in Atlantic salmon, early maturation is linked to specific genetic markers, but this trait's selection can limit the genetic variation necessary for improving other traits like growth and resistance to diseases [29]. Furthermore, conservation of genetic resources becomes crucial as reduced diversity increases the risk of inbreeding, which can lead to the expression of deleterious recessive traits, making populations more vulnerable to environmental changes and diseases [30]. In response to these problems, the industry has developed sterilization techniques for farmed fish as a solution to early maturation [28].

3.3.2 Sterilization Techniques in Aquaculture

Sterile fish, which cannot reproduce, are often intentionally produced in aquaculture to prevent breeding and early maturity [31]. To produce sterile fish, different methods have been explored over time. These include:

Autoimmune Sterilization: Using the immune system to target and destroy reproductive cells.

Hormonal Sterilization: Administering hormones to disrupt reproductive processes.

Chemical Sterilization: Applying chemicals that interfere with reproductive cell development.

Irradiation Sterilization: Using radiation to damage reproductive tissues.

However, none of these methods have proven as effective or scalable as triploidy for commercial fish farming. While these techniques were considered, they were eventually rejected in favor of triploidy [31–33].

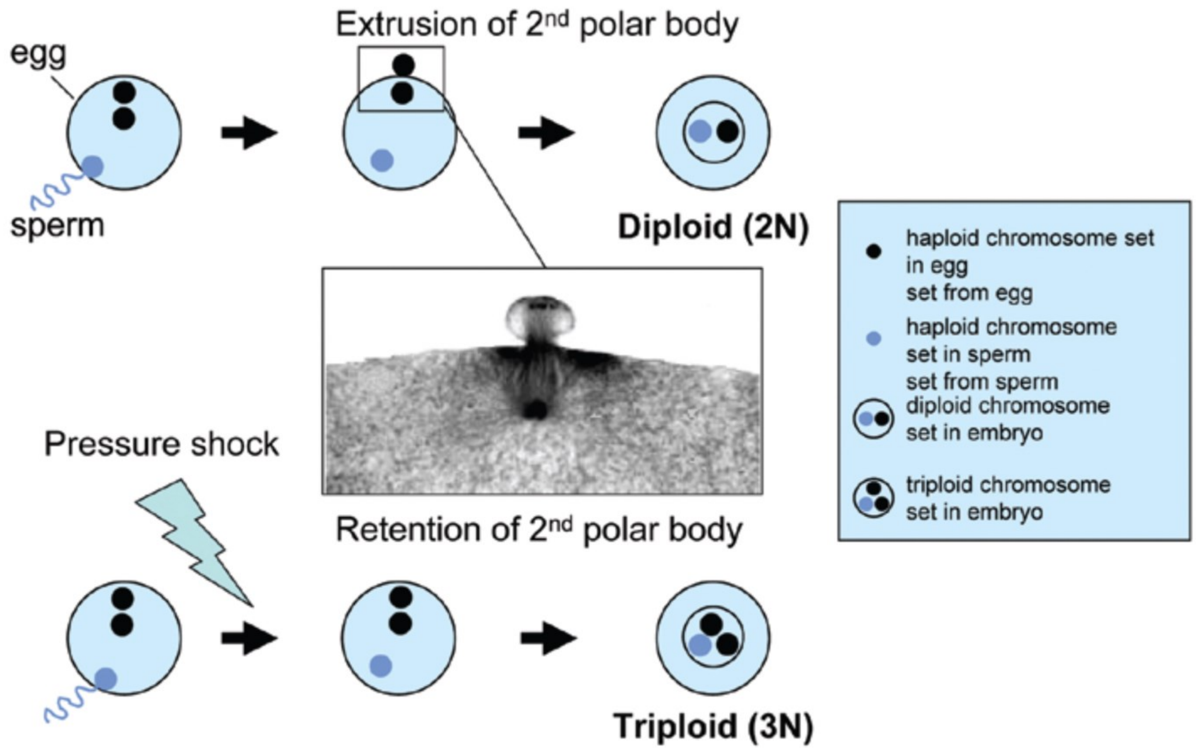

Figure 3.1: The process of triploidy induction in fish using high level pressure shocks[34].

3.3.3 Triploidy: The Preferred Method

Triploid fish, which have three sets of chromosomes, are artificially induced by subjecting newly fertilized eggs to temperature or pressure shocks [31]. These treatments disrupt the normal division of chromosomes during early egg development, resulting in an extra set of chromosomes [35] (Figure 3.1). Triploid salmon, while not transgenic, are considered genetically modified due to their significant biological and physiological differences from diploid counterparts [36]. In Norway, triploid fish, which are produced through genetic manipulation that results in individuals with more than two chromosome sets, do not fall under the regulations of the Gene Technology Act and thus are not classified as genetically modified organisms (GMOs) [37]. Significantly, if these fish escape from open net cages in the oceans, they cannot breed, thereby reducing the risk of genetic introgression into wild populations [38]. Triploid salmon then need to be seen as a biocontainment strategy that helps maintain the distinct genetic characteristics of wild populations [17]. At the same time, of course, suppressed sexual maturity in triploid fish allows for faster growth rates and improved feed conversion efficiency [25].

3.3.4 Challenges with Triploidy

While triploid fish have many benefits, there are also significant challenges associated with the use of triploid fish. The process of inducing triploidy can be technically demanding requiring precise control of temperature or pressure conditions, and may result in lower survival rates during early development stages [39,40]. Additionally, the long-term health and welfare of triploid fish need careful consideration to ensure ethical aquaculture practices [24]. Triploid fish are more vulnerable to temperature stress and deformities, which make them more susceptible to disease [41,42]. Moreover, triploids are not effective in preventing the spread of diseases or parasites, highlighting the need for comprehensive studies on their ecological impact before widespread adoption [43].

3.4 Triploid Salmon Applications in Aquaculture

The development of triploid fish involved both conventional techniques and later advancements that could be considered genetic modification, though not in the transgenic sense [15,33]. Initially, triploid fish were created using methods such as temperature and pressure shocks to prevent the extrusion of the second polar body during meiosis, resulting in sterile fish [17]. This method aimed to control early sexual maturation and prevent genetic interactions between farmed and wild fish populations [13]. Challenges in production and heightened sensitivity of triploid fish to stressors led to a shift away from this approach toward less effective alternatives, such as manipulating photoperiods[5] [24]. However, recent concerns regarding the sustainability of aquaculture and especially the problem of introgression, alongside enhanced insights into triploid physiology and optimal rearing conditions, have reignited interest in triploids as a strategy to mitigate the impact of fish escape on wild populations [24].

The idea of producing triploid Atlantic salmon dates back to the 1950s, with early successful trials involving hybrids with brown trout, though initially in small numbers [35]. In contrast to contemporary discussions around triploid fish, which focus mainly on the effectiveness of these fish in reducing the risks of introgression in wild salmon populations [38], the initial motivation for producing sterile was not related to environmental sustainability or introgression but to controlling sexual maturity [40]. It was well documented that there was a correlation between growth and maturation rates in fish [23]. Triploid salmon generally exhibited robust growth, sometimes surpassing their diploid counterparts, which was advantageous for production [24]. Therefore, using triploid salmon was an effective approach to support profitability; sterile fish do not expend metabolic energy on reproduction, which is instead redirected towards growth, allowing them to grow faster [9].

Despite the early realization of these benefits, widespread commercial interest in triploid salmon did not emerge until the mid-1970s [23]. Significant advancements in triploid salmon production, including pilot-scale tests in Scotland, Atlantic Canada, Tasmania, the USA, Ireland, and Norway, only materialized several decades later. However, triploid fish also suffered from higher mortality rates during critical development stages and the economically significant marine phase [41]. Due to

[5] Manipulating photoperiods refers to the practice of controlling the light and dark cycles that fish are exposed to in aquaculture environments. This technique is used to influence the biological rhythms and reproductive cycles of fish. By adjusting the length of day and night periods, fish farmers can control the timing of maturation, spawning, and other physiological processes in farmed fish.

these challenges, the adoption of triploid salmon farming remained limited. There was minimal interest from farmers in the UK, Norway, and Canada, and triploid salmon farming was largely confined to Tasmania, where it was used to address the issue of early sexual maturation in farmed fish [44]. Due to the warm sea temperatures in Tasmania, salmon farms typically employ all-female groups of either diploid or triploid fish. Females generally mature later than males, which is beneficial in warmer waters where early maturation is more prevalent [37]. As previously mentioned, there was less interest in using triploid salmon in countries other than Tasmania, but this did not deter efforts to optimize triploid production on a commercial scale. Consequently, the development of triploids in other countries continued as a long-term experimental endeavor. Ultimately, these efforts led to the adoption of triploids for large-scale commercial use, notably in Norway and subsequently in Canada [17,23,33,37].

The development and use of triploid salmon in aquaculture illustrate the complex interplay between production efficiency and environmental sustainability. While triploid fish offer significant advantages in terms of growth rates and genetic containment, they also present challenges, particularly related to health and welfare. To better understand the practical application and implications of triploid salmon, I will explore three detailed case studies. These case studies—Newfoundland, Tasmania, and Norway—highlight the diverse motivations, regulatory frameworks, and outcomes associated with the use of triploid salmon in different contexts.

3.5 Case Studies

3.5.1 Implementation of Triploid Salmon in Newfoundland

Establishing salmon aquaculture in Newfoundland was a complex and difficult process due to a multitude of factors that included environmental challenges, logistical hurdles, and financial constraints [45]. But a key problem was the early maturing of salmon [46], which results in lower yields at harvest and poorer meat quality of the farmed fish [47]. In Newfoundland, local salmon stocks were unsuitable due to their early sexual maturation [33]. Salmon farmers in the province sought to import late-maturing salmon stocks to produce 'domesticated' salmon, enhancing the economic viability of salmon farming in the region [33]. In 1988, the Department of Fisheries and Oceans (DFO) authorized the use of salmon stocks from rivers in neighboring provinces. This decision allowed aquaculture producers to use salmon from the St. John River in New Brunswick, with the rationale that, in case of escape, these ‘relatively local’ fish would have a smaller ecological impact compared to salmon imported from distant waters [33,46].

Yet, concerns about growth rates and early maturation persisted, even with these St John river fish. At the same time, research and development efforts in Norway made fish sourced from this country especially attractive given their rapid growth rates and their adaptability to commercial feed and ocean cage environments. [11,25]. Newfoundland salmon farmers were no exception, and around 2010, they sought to import Norwegian-strain fish to enhance the industry's production efficiency [48]. Specifically, aquaculture companies on the southern coast of Newfoundland showed interest in employing farmed European-origin Atlantic salmon in their facilities [49]. The main reason for this attraction was that these Norwegian-origin salmon had been included in various selective breeding programs, which allowed them to grow twice as fast as their wild counterparts and consume less feed [25]. However, the Department of Fisheries and Oceans Canada (DFO) did not grant permission for such importation [48]. DFO's decision to decline the importation of European strains was based on evidence of significant ecological risks. European salmon strains carry genes that could disrupt local wild salmon populations and lead to significant genetic consequences, including through disease transfer, predation, and competition [50]. Research shows that Norwegian farmed salmon have bred successfully outside their native range, raising concerns about interbreeding with wild salmon in Newfoundland's rivers [51]. European-origin salmon tend to outcompete wild salmon in both controlled environments and natural streams, posing a further threat to wild populations [52]. This interbreeding can alter gene expression related to metabolism, growth, and immune response, weakening the resilience of wild salmon [53]. These genetic risks, alongside the potential for escaped salmon to harm local stocks, contributed to the rejection of the proposal [48].

DFO's concern over importing European-origin salmon and its potential genetic and ecological impact was not unfounded. First, there was a concern over the illegal importation of European-origin salmon, which have subsequently bred with local wild populations. Historical interest in Norwegian-origin salmon for their fast growth and disease resistance has made them attractive for aquaculture, despite strict regulations prohibiting their use in Canada [25,54,55]. The discovery of European genetic material in wild and aquaculture populations suggests unauthorized or unreported importations. This poses serious ecological and genetic risks, as escaped salmon interbreed with local populations despite regulations against their use [20,54].

Second, evidence suggests that European-origin salmon have already escaped into Canadian waters. European salmon were introduced into Maine in the 1980s, and although a ban on European strains was imposed in 1993, their genetic material persists, partly due to shared aquaculture operations near the Maine-New Brunswick border. This proximity increases the risk of escaped farmed salmon with European ancestry interbreeding with wild populations, leading to significant ecological and genetic consequences [54,56,57]. European-origin salmon have been detected in aquaculture and wild stocks in this region, and the recent discovery of escapees with European ancestry at the Magaguadavic fishway emphasizes the ongoing issue [57].

Finally, the use of non-all-female triploid salmon has exacerbated existing concerns. While female triploid Atlantic salmon are typically sterile and fail to reach reproductive maturity, some studies show that male triploid salmon from farms can attract wild diploid females, potentially undermining the sterility goal of triploidy [58,59]. Additionally, concerns remain that not all triploid salmon used on the east coast of Canada are all-female, further complicating containment efforts [59].

Given the broader genetic and ecological concerns surrounding European strains of salmon, triploidy was considered a potential solution to regulatory bans. This approach was not new, as Newfoundland salmon farmers had previously experimented with triploid salmon as a strategy to address early maturation [33]. However, these early trials during the 1990s revealed significant challenges. The triploids often experienced bone deformities, ocular cataracts, and illnesses during the summer months, leading to reservations about further experimentation with this technology [24]. As a result, triploid salmon were not widely adopted at that time. Furthermore, the technology for producing non-maturing salmonids had not yet been proven effective under practical fish farm conditions, which was necessary for broader acceptance by salmonid farmers [46].

In March 2016, Grieg NL requested to import European-strain Atlantic salmon. This time, the request was approved because the application was for importing all-female triploid (sterile) salmon, which addressed previous environmental concerns around introgression [20]. Grieg NL's interest in importing European-strain Atlantic salmon, particularly the all-female triploid (sterile) variety, stems from a combination of regulatory and economic considerations. The use of sterile salmon, which has been a focus in both European and North American aquaculture practices, offered a potential solution to the significant environmental concerns associated with salmon farming, such as the risk of escaped farmed fish interbreeding with wild salmon populations [20]. The Norwegian salmon farming industry, in particular, has developed advanced techniques and technologies, including the production of triploid salmon, to address these concerns while maintaining high levels of production efficiency. Recognizing the success of these practices in Norway, Grieg NL sought to implement similar strategies in Newfoundland. This approach was aligned with Canada's broader regulatory framework, which endorses the use of sterile fish to minimize the ecological impacts of aquaculture under the North Atlantic Salmon Conservation Organization (NASCO) protocols [20]. The request submitted to the Canadian Food Inspection Agency (CFIA) and Fisheries and Oceans Canada (DFO) to import triploid Atlantic Salmon eggs from Iceland. The importation has been approved by the CFIA and an import permit was issued to the Grieg NL [20].

The Newfoundland and Labrador Introductions and Transfers Committee, which included representatives from the federal Department of Fisheries and Oceans (DFO) and the provincial Departments of Fisheries and Aquaculture (DFA) and Environment and Conservation, Department of Fisheries, Forestry and Agriculture (FFA), and the Canadian Food Inspection Agency (CFIA) was tasked with the risk assessment of the request [60,61]. This committee adheres to the principles of the National Code of Introductions and Transfers of Aquatic Organisms, which prescribes mitigation measures throughout various stages of the production cycle [62]. These measures can involve strategies at the organism, technological, and management levels. Specifically, at the organism level, they advise using all-female or reproductively non-viable strains (e.g., triploids, sterile) to minimize reproduction risks associated with potential escapes [60]. Therefore, all fish introductions and transfers must receive approval from the Newfoundland and Labrador Introductions and Transfers Committee before any movement occurs. Once approved, a licence is granted by the Department of Fisheries and Oceans (DFO) under Section 56 of the Fishery (General) Regulations, and a Permit to Transfer and Transport is issued by the Department of Fisheries and Aquaculture (DFA) [63].

In 2016, with approval from the Newfoundland and Labrador Introductions and Transfers Committee and a license issued by DFO, Grieg NL successfully imported Norwegian-strain triploid (sterile) Atlantic salmon from Iceland for marine cage aquaculture in Placentia Bay, Newfoundland [20] (Figure 3.2). The choice of triploid fish, which are sterile, is significant as it mitigates the genetic risks associated with introducing European-origin salmon [64]. Therefore, this measure allowed the industry to leverage the benefits of improved traits in European strains [57,64]. Through the approval of all-female triploid salmon in 2016, Newfoundland's aquaculture industry was able to incorporate productive European-origin salmon, benefiting from their faster growth rates and disease resistance—key components of intensification—while adhering to regulatory frameworks designed to protect local ecosystems.

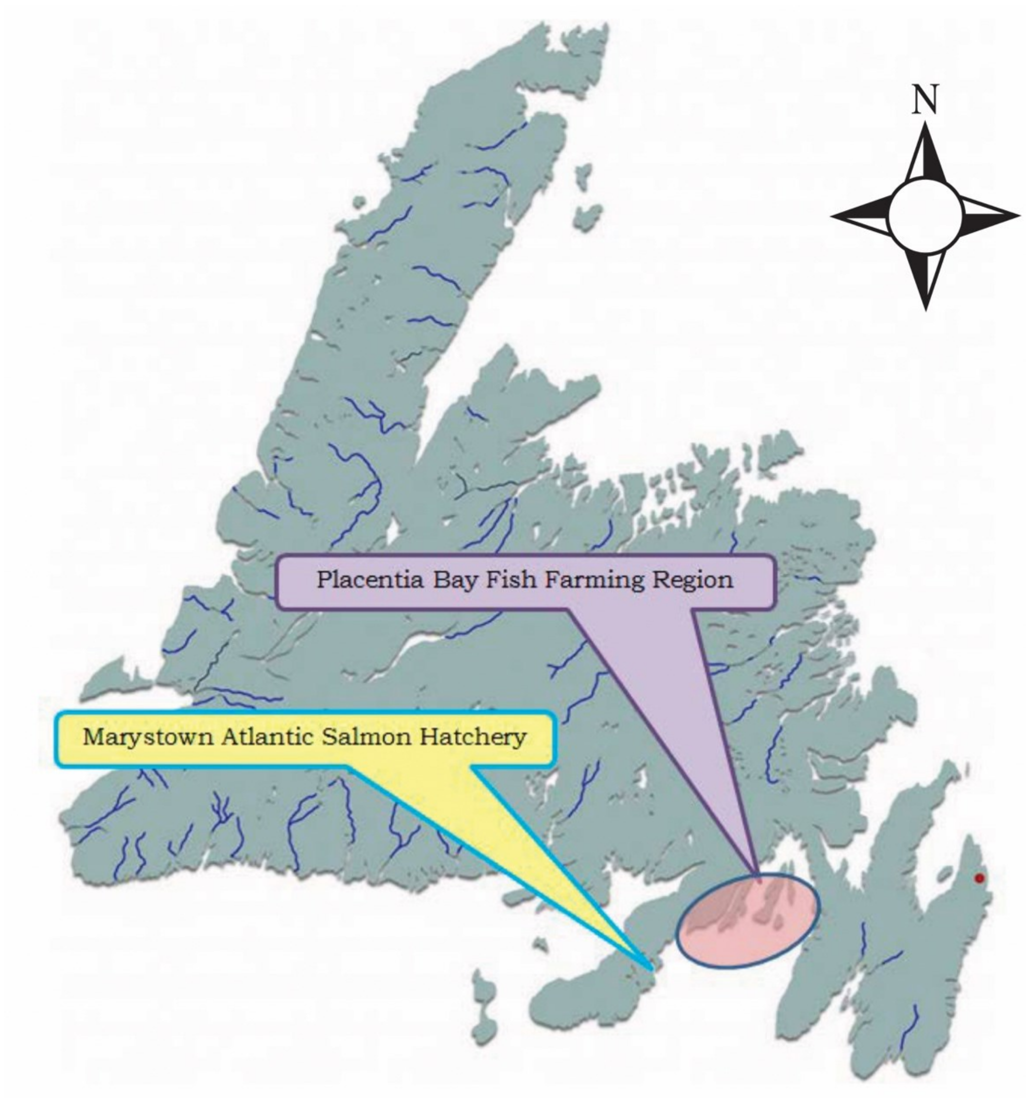

Figure 3.2: Location of proposed fish farms and salmon hatchery by Grieg NL[65].

Triploid salmon were introduced as a solution in Newfoundland and Labrador to address the twin problems of early maturation and the genetic introgression of farmed fish into wild populations. Their sterility prevents interbreeding with wild salmon, making them appear sustainable while supporting the industry's intensification goals by leveraging their fast growth and efficient feed conversion. This reliance on Norwegian strain salmon reflects a broader prioritization of production efficiency over the use of local strains, highlighting the tension between intensification and environmental sustainability. However, questions remain about the long-term ecological impacts and the actual sustainability of such practices, especially within Newfoundland's sensitive marine ecosystem [51].

The strategic implementation of all-female triploid salmon in 2016 illustrates the industry's response to both production and regulatory challenges. For companies like Grieg, triploids offered a way to meet regulatory requirements while benefiting from the faster growth and improved feed efficiency of Norwegian-origin strains. Although this strategy aimed to mitigate genetic risks and improve economic viability, the persistent presence of European genetic material in wild and farmed populations raises concerns about the effectiveness of these measures in preventing long-term environmental harm.

3.5.2 Implementation of Triploid Salmon in Norway

In Norway, the success of salmon aquaculture has been largely driven by pioneering selective breeding programs. The Norwegian Atlantic salmon breeding program started in the 1970s, concentrating on selective breeding to improve traits such as growth and disease resistance [66]. Significant strains, including Aqua Gen AS, Salmobreed AS, and Mowi, were created. The Mowi strain, initiated in the 1960s using wild salmon from Norwegian rivers, has gone through multiple generations of selection to boost production traits [67]. These initial steps were essential to the industry's advancement, revolutionizing salmon farming in Norway [25]. These programs operated on the understanding that the age at which fish first mature is influenced by their genes. Consequently, fish that matured later could be selectively bred to produce more offspring with the same late-maturing trait [12,25].

In 1993, Norway produced around 170,000 tons of salmon, resulting in large populations of farmed fish in aquaculture production areas. The problem of escapes from these farms was soon evident, which happened through storms and other challenges that compromised net integrity. Escape events revealed that up to 90% of salmon in some areas were from fish farms [13]. The large number of escaped fish especially relative to wild populations raised concerns about the impact on the genetic variation of wild strains. One solution to this problem was to farm sterile fish [13]. Since the mid-1990s, there has been a comprehensive evaluation of using sterile, triploid Atlantic salmon to minimize interactions between cultured and wild fish in Norway [37]. However, reports from the 1990s indicated that triploids experienced higher rates of bone deformities and ocular cataracts than diploids. Faced with industry competition and the need to sustain commercial fish farming in Norway, further research was essential to explore the viability of triploid salmon production [37]. By 2010, it was recommended that triploids be fed specialized diets to mitigate bone deformities and cataracts, enabling their use for commercial-scale production [13].

At the same time, the Norwegian government had proposed a comprehensive regulatory system in a White Paper presented to the Parliament in March 2015. This system emphasized environmental sustainability and predictable growth in the salmon farming industry. The regulations focus on minimizing the environmental impact, particularly concerning genetic interactions with wild fish, disease transmission, and aquaculture's ecological footprint [68].

Norwegian regulations have been focused on ensuring that aquaculture production is conducted in a way that ensures animal health, welfare, and environmental protection [69]. The governance of welfare concerns in Norwegian aquaculture, particularly in relation to salmon farming, has become increasingly critical [70]. The Norwegian government has implemented a complex regulatory framework designed to ensure that fish welfare is maintained alongside environmental and economic goals. This framework is governed by multiple agencies, with the Norwegian Food Safety Authority (NFSA) playing a central role in overseeing fish health and welfare [71,72]. A key component of this governance structure is the management of specific welfare challenges, such as those posed by salmon lice and pancreas disease (PD) [70]. The regulations are stringent, particularly in their effort to balance the needs of the industry with the welfare of the fish. For example, the salmon lice regulations include specific limits and mandatory delousing operations, which have been criticized for sometimes compromising fish welfare. Similarly, the management of PD through zoning and eradication efforts highlights the tension between maintaining fish health and ensuring the industry's economic viability [70,73,74].

The use of triploid salmon was part of this new regulatory regime and was governed under "green licenses," which mandated strict conditions to prevent negative impacts on fish welfare and the environment [75]. These licenses, introduced in 2013, were part of a broader strategy to stimulate the development of new technologies and production methods that reduce environmental impacts, such as sea lice levels and fish escapes [75]. In the same year, five aquaculture research and development (R&D) licenses were authorized for triploid salmon production, followed by eleven "green aquaculture licenses" in 2014, specifically for producing sterile salmon [69]. These licenses allowed trials within commercial settings in Norway [69]. Despite being welcomed as a positive regulatory tool by both aquaculture companies and environmentalists, there were debates about the design and effectiveness of these licenses. Critics, however, acknowledged that these licenses were the only viable option to permit growth at that time [76].

Since 2013, the Norwegian Food Safety Authority (NFSA) has conducted trials on 35 million sterile triploid salmon to assess their effectiveness for commercial aquaculture [77,78]. By 2019, these trials achieved a success rate of 100% in all but one batch [37]. However, the production of triploid salmon in ocean cages encountered severe challenges, particularly due to widespread viral and bacterial diseases, including an increased susceptibility to infectious salmon anemia (ISA) [79]. These health concerns have led to reassessments of the use of triploid salmon under current farming conditions [78].

In response to these problems in the use of triploid salmon, Norway Royal Salmon (NRS), a company committed to sustainable practices through green licenses, announced it would gradually reduce triploid salmon production and transition to diploid salmon by the end of 2023, while maintaining other conditions for their green licenses unchanged [80]. This decision reflects a shift prompted by welfare considerations and regulatory developments, with the NFSA recommending a thorough review of triploid salmon production [80]. Additionally, a study across four Norwegian aquaculture companies found that triploid Atlantic salmon had lower survival rates, higher occurrences of emaciation, and received lower quality ratings during processing compared to diploid salmon [81]. Reports from the NFSA and the Institute of Marine Research (IMR) have highlighted the health issues associated with triploid salmon, such as skeletal deformities, heart problems, and increased disease susceptibility [69]. They suggested that triploid salmon may not be suitable for commercial farming in Norway without significant adjustments to farming practices, such as changes in diet and environmental conditions. The ongoing evaluation by the NFSA is expected to determine whether triploid salmon can be sustainably integrated into Norway's aquaculture industry

[69]. Currently, the industry is awaiting the outcome of a review on triploid welfare conducted by the Norwegian Food Safety Authority, expected in 2024 [37] (Figure 3.3).

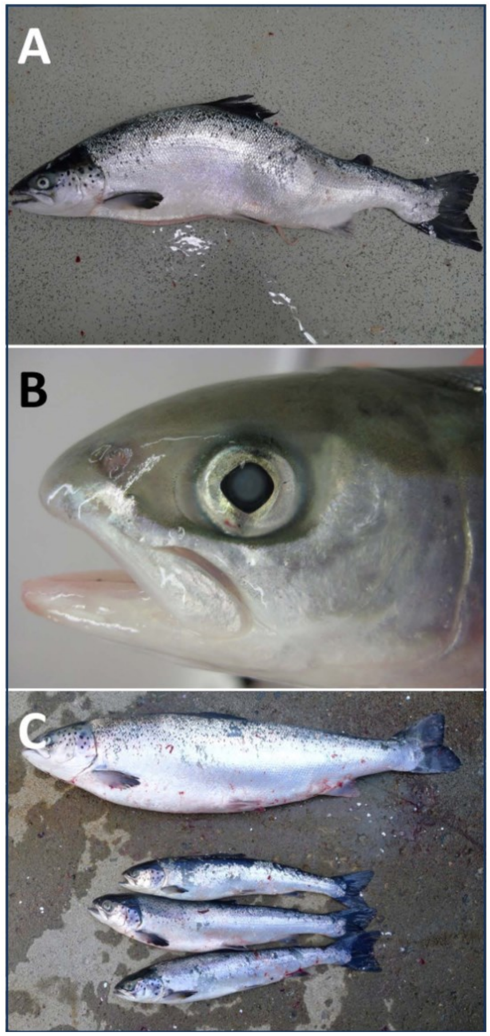

Figure 3.3: Welfare issues in triploid salmon. (A) Vertebral deformities are more frequently found in triploids at harvest. (B) Ocular cataract (cloudy eye) in a smolt. (C) "Loser" fish more frequently found in triploids at harvesting. The fish at the top is not a loser and is the same age and from the same sea-cage[37].

Despite the environmental benefits of triploid salmon, including reduced risk of genetic contamination of wild populations, the welfare problems associated with triploid fish have become a major concern [82]. Triploid salmon are often harvested earlier and at a smaller size due to welfare concerns, with more classified as lower quality, and they require specialized feed, increasing production costs [83]. The significant welfare problems associated with triploid fish, such as higher susceptibility to diseases, lower survival rates, and deformities, have become a major concern [27,42,81]. These welfare and economic challenges prompted the Norwegian Food Safety Authority to block new projects for testing triploid salmon. Consequently, NRS decided to revert to diploid salmon, which are generally healthier and more robust [80].

Norway's approach to salmon aquaculture, particularly with the implementation of triploid salmon, exemplifies the complexities of sustainable intensification in aquaculture industry. The industry's goal of intensifying production—using fast-growing, selectively bred salmon strains—was seen as compatible with environmental sustainability by employing triploid, sterile fish to prevent genetic introgression with wild populations. However, the use of triploid salmon was primarily motivated by economic reasons. As Reinertsen and Haaland (1995) pointed out in *Sustainable Fish Farming*, "…. One way to avoid this, is to make sterile fish for farming. This work has been encouraged by other reasons, and usually more powerful ones, the economy…." [13]. This highlights how economic pressures influenced the adoption of triploids, even as they aimed to address environmental concerns.

While triploid salmon addressed a key environmental concern of genetic introgression from wild to farmed fish, the persistent welfare problems associated with their production—such as increased disease susceptibility—reveal the limits of this approach. The governance system of managing fish welfare faces challenges. While there is consensus on the importance of welfare, the implementation of these regulations can be difficult due to conflicting interests and the complexities of the aquaculture environment [70]. The green licenses that were intended to balance growth with environmental sustainability became entangled in welfare debates, as the health of triploid salmon deteriorated under commercial farming conditions. This reflects a broader challenge in aquaculture: the pursuit of sustainable intensification often results in a focus on production efficiency, potentially sidelining other critical aspects like animal welfare. As evidenced by NRS's decision to revert to diploid salmon, the economic and welfare compromises associated with triploids ultimately undermined their long-term viability in Norway's aquaculture industry.

3.5.3 Implementation of Triploid Salmon in Tasmania

The history of Atlantic salmon in Tasmania dates back to 1865, when the first release of Atlantic salmon fry was attempted into the Plenty River [84]. Despite repeated introductions that failed to establish a breeding population, these efforts eventually laid the groundwork for the successful introduction of commercial salmon farming in the region [85]. The Tasmanian Fisheries Development Authority (TFDA) started exploring aquaculture in 1981, leading to the establishment of production in 1983 with government and local industry support [23]. Salmon Enterprises of Tasmania (SALTAS) was founded in 1985 under specific legislation, holding an exclusive license for Atlantic salmon hatchery operations for ten years [23]. SALTAS was founded through a collaboration between the Tasmanian government and the Norwegian company Noraqua, with the aim of supplying Atlantic salmon smolts for Tasmania's developing salmon farming industry. In addition to producing smolts, SALTAS made contributions to research and development. About 25% of the revenue generated from smolt sales was allocated to research projects aimed at improving smolt availability, boosting farm survival rates, and refining feeding practices [86].

In Tasmania, production priorities have historically been at the forefront of aquaculture development. The rapid growth of Atlantic salmon, reaching harvest size in just 15 months due to favorable water temperatures, has always made the suppression of maturation a key goal [23]. Techniques such as sex-reversal and triploidization have been used to produce all-female triploid stocks, which have resulted in improved performance compared to diploid stocks despite some physiological issues in post-smolts [15,37]. Moreover, since female salmonids reach maturity later than males, creating stocks that mature later by enhancing female traits was a favoured option. For industry, all-female stocks were expected to provide significant advantages in salmon farming [15]. Thus, Tasmania's latitude and water temperatures, combined with the specific salmon strain used by the industry, cause the fish to mature rapidly, naturally constraining production. Consequently, the Tasmanian industry was distinctive from other salmon production sites in its early development of all-female and triploid fish production [23,37]. Triploid technologies have been utilized primarily to control fish maturation, aligning with industry production priorities. Unlike regions where the risk of introgression with wild salmon populations is a pressing concern, Tasmania's lack of wild salmon means this issue is not relevant. However, escaped salmonids may still pose ecological challenges, particularly if they survive and feed on native fauna[87].

However, the intensive focus on production has come at a cost. While triploid salmon provided industry with a solution to higher water temperatures and rapid maturation, the technology has introduced health challenges for the fish that have been experienced by producers including in Tasmania. As I noted earlier in the case of Norway, studies have documented health issues associated with triploid salmon, including deformities in skeletal structure [88], heart problems [89], abnormalities in the lower jaw [90], highlighting the complex implication of triploid salmon production in Tasmania. These health and welfare problems of triploid salmon have allowed anti-aquaculture groups to make the case for the unsustainability of the industry and have raised broader questions about the ethical implications of using triploid fish in Tasmania.

The salmon farming industry in Tasmania is currently facing significant scrutiny, particularly concerning the farming of triploid fish. Numerous campaigns are being developed to address the issue, with the Tasmanian Alliance for Marine Protection (TAMP) leading the charge. TAMP has dubbed the practice of triploid salmon production as "Genetic Torture of Farmed Salmon, The Misery of Mutants," highlighting the severe health concerns associated with genetically manipulated salmon. They argue that the industry misleads consumers by claiming that these fish are not genetically modified organisms (GMOs) [36].

Figure 3.4: Triploid salmon with jaw deformities, grown on Tasmania's West Coast. Image sourced from Environment Tasmania's Facebook page [78].

Aquaculture companies have attempted to contest the concerns of environmental groups. Huon Aquaculture, for instance, has argued that triploid fish, along with other triploid species, are not genetically modified but rather are 'hybrid' fish. While it is true that these fish do not fall under the Tasmanian Gene Technology Act regulations, triploidy is indeed a form of genetic manipulation and should not be confused with hybridization [91,92]. Hybrid fish result from breeding two different species to combine desirable traits, a process distinct from creating triploid fish. The term "hybrid" is more palatable to consumers, as it implies natural breeding rather than genetic manipulation [93].

This deliberate obfuscation highlights the industry's prioritization of economic interests over ethical transparency and consumer awareness. By blurring the lines between hybridization and genetic manipulation, companies not only mislead the public but also undermine trust in the aquaculture industry's commitment to responsible and sustainable practices.

While Tasmania might initially appear to be a simple case of prioritizing production, the involvement of environmental NGOs highlights how environmental concerns are also integral to the narrative. In Tasmania, although production decisions are prominent, the environmental issues raised by NGOs reflect the intertwined nature of production and environmental sustainability. This practice has raised substantial concerns about the ongoing health issues faced by triploid salmon, which the industry appears to largely disregard in favor of protecting its interests [36] (Figure 3.4). The welfare of these genetically manipulated fish continues to be a contentious issue, drawing criticism from environmental and consumer advocacy groups [36]. The continuous growth and uniform size of triploid salmon ensure a steady supply of marketable fish throughout the year, supporting economic stability and efficiency in salmon farming operations [88].

The health challenges associated with triploid salmon in Tasmania, which are framed as welfare issues, are being highlighted as environmental concerns by environmental groups. These health issues are not just about the welfare of the fish but are being used by NGO groups to argue against the broader environmental sustainability of salmon farming. The controversy over whether triploid salmon should be considered "genetic manipulation" versus "hybrids" further complicates the environmental narrative. Although Tasmania's salmon farming industry has always prioritized production, the environmental concerns raised by NGOs demonstrate that sustainability cannot be easily disentangled from these production goals. The health and welfare issues associated with triploid salmon have become a focal point in the broader debate over the environmental impact of intensive aquaculture in Tasmania. This case highlights the inherent tension between intensifying production and maintaining environmental and ethical standards—a key theme in the ongoing global conversation about sustainable aquaculture practices.

3.6 Discussion and Conclusion

International concern about the impact of aquaculture on wild stocks has prompted efforts around the world to monitor farmed fish escapes and their impacts on wild populations [33]. This focus intensified in the early 1990s, following significant regulatory changes and international discussions, such as the 1990 Norwegian meeting on the influence of aquaculture on wild stocks, which underscored the potential risks to local wild salmon populations [33]. To balance the evaluation of farming potential with the need to protect wild populations, foreign salmon imports were carefully limited. Yet imports were allowed as long as later maturing salmon were sterilised through triploidy, which provided a biocontainment solution to genetic introgression in the event of an escape [17]. In this way, triploid salmon addressed a key environmental concern with salmon aquaculture: they reduced the risk of genetic changes in wild populations due to interbreeding with escaped farmed salmon [15].

While triploid salmon are presented as a biocontainment solution to escapes, in this chapter I focus on its dual role in promoting sustainability and enhancing production efficiency. The study examines the application and impact of triploid salmon across three case studies: Newfoundland and Labrador, Norway, and Tasmania. The analysis explores why the Norwegian strain of triploid salmon was introduced in Newfoundland, where native Atlantic salmon exist, and why Tasmania, lacking native salmon, uses triploids without facing genetic introgression concerns. In the case of Norway, I examined how triploidy was incorporated within the broader framework of aquaculture innovation, driven by the need to balance production efficiency with environmental stewardship. The case of Norway illustrates the complexities and limitations of triploid technology, particularly in addressing welfare issues and navigating regulatory challenges. These factors significantly influenced the adoption and implementation of triploid fish technology in the Norwegian aquaculture industry.

The case studies reveal the difficulty of separating production efficiency from environmental protection. This intertwining is evident across different case studies, each demonstrating this complexity in different ways. In Norway, triploid salmon initially appeared to be a promising solution for sustainable intensification, but their implementation revealed a persistent tension between sustainability goals and production pressures. Although sustainability and production efficiency are often presented as complementary, in practice, efficiency takes precedence. The welfare problems associated with triploid fish, such as deformities and increased disease susceptibility, have become significant issues for policymakers, though they are frequently overshadowed by the industry's focus on maintaining production efficiency. The shift away from triploids in Norway underscores the difficulty of separating environmental protection, animal welfare, and industry growth, suggesting that sustainable intensification, as currently practiced, still prioritizes production over genuinely sustainable outcomes.

In Tasmania, although production decisions were paramount in the choice to use triploids, the environmental issues raised by NGOs reflect the intertwined nature of production and environmental sustainability. Despite the focus on production triploid salmon face significant health challenges, including deformities and other physiological issues. Environmental NGOs have criticized the industry for prioritizing economic gains over fish welfare and for misleading consumers about the genetic manipulation involved. This case highlights the complex balance between production efficiency and ethical considerations, illustrating how sustainability and production are closely interconnected.

The Newfoundland case further complicates the narrative. Initially, local fish were deemed unsuitable due to early maturation, leading to the importation of salmon stocks from neighboring provinces. Norwegian-origin fish were, in contrast, favored by fish farmers for their high production rates and delayed maturation. Yet due to environmental concerns and regulatory challenges, local producers were for many years not allowed to use Norwegian origin fish for fears that these fish would genetically contaminate local stocks. This regulatory issue was overcome when industry requested the importation and use of Norwegian triploid fish. These fish provided a solution to production efficiencies while addressing the regulatory obstacles related to environmental issues. The long-term presence of prohibited European salmon in Canadian waters raises significant questions about regulatory effectiveness and industry motivations, especially concerning genetic and ecological risks. Here, triploids represent a solution to regulatory hurdles for an industry that had long wanted Norwegian bred fish. While efforts towards sustainable intensification aim to balance these goals, production goals were always the primary reason why producers were interested in farming Norwegian salmon strains. In other words, the primary focus was on enhancing production, while triploids provided a solution to regulatory obstacles.

The implementation of triploid salmon technology in aquaculture reflects a fundamental tension between production goals and environmental sustainability. The industry's persistent focus on production efficiency often comes at the expense of fish welfare and ecological balance. This tension is evident in the case of Norway, where NRS's shift from triploid to diploid salmon underscores the reality that while sustainability remains a key narrative, production efficiency ultimately dominates decision-making in the industry. This raises critical questions about the true motivations behind the adoption of such technologies and whether the proclaimed benefits genuinely align with sustainable practices or are merely a facade for underlying economic priorities.

The inherent challenges and failures of triploid technology in aquaculture underscore the complexities and contradictions within the industry, leaving us to question whether the pursuit of a perfect solution is inherently flawed in a system fraught with deeper, systemic issues. As we examine the interplay between production efficiency and environmental sustainability, we are left to contemplate: is true sustainability achievable within the current frameworks of aquaculture, or does the relentless drive for production inevitably compromise the broader ecological and ethical considerations that are equally critical? This reflection forces us to reconsider the very foundations of what we deem as sustainable intensification in the industry.

3.7 References

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Chapter Four: Conclusion

4.1 Discussion and Conclusion

The salmon aquaculture industry has emerged as an important player in aquaculture food production, driven by the rising demand for protein-rich food [1]. While enormously successful from a production and profit point of view, this industry has also been the focus of significant environmental concerns, particularly regarding the escape of farmed salmon and its implications for wild salmon populations and marine ecosystems [2,3]. In this thesis I critically examined the environmental impacts of salmon aquaculture, particularly focusing on the pervasive problem of farmed salmon escapes from marine open cages and I evaluated the responses by regulators and industry through policy and technological solutions. The findings indicate that, while current policies and technological advancements, such as the use of triploid fish, offer some hope for mitigation, they fall short of addressing the fundamental issue: the inevitability of farmed salmon escapes in salmon aquaculture [4].

In Chapter 2, I explored the critical challenge of balancing the sustainability and food production potential of aquaculture with its environmental impacts, particularly through the lens of policy development. I focused on the issue of farmed salmon escapes from open net pens, a recurring problem that poses significant risks to wild salmon populations and ocean ecosystems. Drawing on the foundational work of Naylor et al. [4], I examined how policy frameworks have evolved over the past two decades, particularly in regions where escape policies were previously weak or non-existent.

I analyzed escape policies across 14 global salmon production regions, organizing them into five key themes: regulatory frameworks, production requirements, reporting and recapture regulations, monitoring requirements, and sanctions. This thematic approach allowed for a detailed comparison of the strengths and weaknesses of these policies. I found that while all regions have established escape regulations, the diversity in regulatory approaches, including the development of codes of containment by industry organizations, highlights both the progress and the ongoing challenges in effectively managing escapes. My analysis revealed that although monitoring and reporting are integral components of these frameworks, they often fall short in preventing escapes or mitigating their environmental impact. Additionally, the use of triploid fish and escape-proof nets, while innovative, are not uniformly effective across all regions.

This chapter concluded by arguing that despite advances in policy, the inevitability of escapes in open net pen aquaculture highlights the weakness of current policies and frameworks, which aim to reduce escapes rather than eliminate them entirely. In response to these challenges, there are two notable approaches being considered. One approach involves co-managing escaped salmon through collaboration between government, industry, and local stakeholders. This co-management could potentially improve recapture rates and limit the environmental impacts, acknowledging that complete containment of salmon is nearly impossible. Another, more radical view argues that wild salmon populations have already been irrevocably altered by human activity. According to this perspective, concerns over farmed salmon escapes are less relevant since wild salmon are no longer truly wild due to decades of human intervention. However, the broader consensus maintains that escapes remain problematic not only because of genetic concerns but also due to issues like disease transmission and ecological disruption. This ongoing debate highlights the complexities and unresolved challenges that continue to shape the future of salmon aquaculture.

In Chapter 3, I investigated the implementation of triploid fish technology as a potential solution to the problem of farmed salmon escapes. This chapter begins by situating triploid salmon within the broader discourse of sustainable intensification, a policy goal aimed at increasing food production while minimizing environmental impacts. I explored how technological innovations, particularly genetic modifications like triploidy, have become integral to aquaculture's expansion and intensification.

Triploid salmon, which are genetically modified to be sterile, are often touted as an environmentally sustainable solution to the problem of escaped farmed fish interbreeding with wild populations. However, this chapter critically examines the complexity of triploid salmon's role, revealing that while they are framed as an environmental safeguard, they are equally, if not more, significant for their production benefits. I illustrated this duality through a detailed analysis of three case studies: Newfoundland, Tasmania, and Norway. Each case study highlights the intricate interplay between environmental objectives and production goals, showing that when challenges arise, production priorities frequently dominate.

The introduction of triploid salmon in Newfoundland was initially driven by the challenge of early maturation in local salmon stocks, which threatened both the economic viability of the industry and its environmental sustainability. Efforts to introduce Norwegian-origin salmon, known for their advanced traits, faced significant regulatory challenges due to concerns about their potential environmental impact. These challenges reflected broader regulatory hurdles in balancing industry needs with environmental protection. This impasse was eventually overcome in 2016 with the approval of all-female triploid salmon, which regulators permitted as a compromise to address production goals while attempting to mitigate environmental risks. The Newfoundland case highlights the ongoing tension between sustainability and production in the aquaculture industry, with triploid salmon exemplifying the complex interplay between technological solutions and regulatory frameworks.

Tasmania presents a case where triploid salmon were initially introduced to control fish maturation in an environment with no native wild salmon populations. While this practice was aligned with production goals, it also raised significant environmental and ethical concerns, particularly around the health and welfare of the triploid fish. Environmental NGOs have criticized the industry for prioritizing economic gains over fish welfare, highlighting the ethical dilemmas inherent in using triploid salmon as a production tool.

In Norway, the chapter examined how the use of triploid salmon was initially embraced as part of a broader strategy to balance environmental sustainability with production efficiency. However, despite the environmental benefits of triploid salmon, including reduced risk of genetic contamination of wild populations, the significant welfare and production efficiency challenges associated with triploid fish has led to their gradual phasing out. Norway's experience underscores the difficulty of reconciling production efficiency with environmental sustainability, as the production issues ultimately outweighed the perceived environmental benefits.

This chapter reveals the inherent tensions and trade-offs involved in the use of triploid salmon in aquaculture. While triploid fish are often promoted as a sustainable solution to mitigate the genetic impacts of farmed salmon escapes, their adoption is frequently driven by production imperatives, especially in response to ongoing challenges. By examining the intertwined nature of environmental and production priorities across different contexts, this chapter contributes to a deeper understanding of the complexities involved in achieving truly sustainable aquaculture practices. It also raises critical questions about the true motivations behind the adoption of triploid salmon, suggesting that production goals often overshadow environmental stewardship within the aquaculture industry.

The broader implications of these findings extend beyond the specifics of salmon aquaculture. They reflect a deeper tension between environmental sustainability and the demands of food production. This tension is increasingly shaped by the pervasive reliance on technological solutions, a discourse that positions innovation as the primary pathway to sustainability while often sidelining more systemic or community-oriented approaches. This 'techno-logic of solutionism,' evident in salmon aquaculture, risks eroding welfare (of fish, humans, and ecosystems) and reinforces the prioritization of efficiency over resilience in the economies of provisioning. The sustainability of salmon aquaculture, often promoted as a solution for global food security, demands rigorous scrutiny[5]. Despite claims of "sustainable intensification" [6,7] and innovative eco-intensification strategies [8] , the persistent issue of farmed fish escapes and their profound environmental consequences casts doubt on the industry's true commitment to environmental stewardship. While salmon farming's contribution to global food production may seem substantial within industry circles [9], its actual impact is marginal when viewed in the broader context of global food systems [10]. Yet, the significance lies not in its share of the market but in its potential to exert a disproportionate impact on marine ecosystems, raising concerns about environmental damage. This challenges the prevailing narrative that promotes marine aquaculture, particularly offshore finfish farming, as a panacea for global food security and environmental sustainability [11].

This thesis reveals that the industry’s focus on increasing production efficiency and meeting regulatory demands often overshadows the critical need to address the root causes of environmental degradation. The industry's narrative, which equates technological advancements and regulatory compliance with sustainability, needs to be critically assessed [5]. The persistent escapes of farmed salmon and the resultant genetic changes of wild populations underscore the limitations of relying on current practices. The continued expansion of this industry, under the guise of sustainability, reflects a broader tension between the economic imperatives of food production and the ethical obligations to preserve our natural environment.

In this context, the concept of "sustainable blue food production" within salmon aquaculture appears increasingly untenable [12]. The industry's reliance on political and technological fixes, rather than confronting the inherent environmental challenges, raises fundamental questions about its viability as a sustainable food source. As we face the growing pressures of global food demands, it becomes imperative to critically reassess whether the current trajectory of salmon aquaculture aligns with the principles of true sustainability or if it merely perpetuates environmental degradation under the banner of production efficiency [5]. The industry's failure to address these challenges suggests that a paradigm shift is necessary—one that prioritizes ecological integrity over the relentless pursuit of growth and market dominance.

In this thesis, my intention has been to illustrate, through various examples, that the current model of fish farming cannot be relied upon as a sustainable source of food. My research demonstrates that, despite technological advancements and policy efforts, the inherent challenges of open-net aquaculture—such as farmed salmon escapes and environmental degradation—persist. These challenges highlight the limitations of this approach in achieving true sustainability in food production. Given these realities, can we truly expect aquaculture, in its current form, to provide a sustainable solution for global food demands? Is the current trajectory of the salmon aquaculture industry, with its emphasis on production efficiency, sufficient to meet the challenges of sustainable food production in a world where marine ecosystems are increasingly under stress?

My emphasis on the inherent challenges and environmental dilemmas associated with marine fish farming serves as a clarion call for a paradigm shift. If the recurrent issue of fish escapes and its consequential environmental devastation persist unabated, prudence dictates a reassessment of the viability of maintaining fish farming in the marine environment. As we navigate the delicate balance between meeting global food demands and preserving our ecosystems, are evaluation of priorities becomes imperative. While ending the industry may mitigate future harm, the specter of irreparable harm to wild salmon populations looms large, the irreversible damage inflicted upon wild salmon genetics serves as a poignant reminder of the lasting consequences of our past actions.

Moving forward, future research should explore the systemic reliance on technological solutions as a pathway to sustainability, critically examining whether such approaches adequately address the root causes of environmental degradation. Questions remain about the long-term viability of solutions such as triploid salmon, closed containment systems, and semi-closed containment systems, particularly in light of their limited capacity to fully eliminate escape risks and their broader impacts on fish welfare and ecosystems.

Furthermore, there is an urgent need to investigate alternative governance models that prioritize ecological resilience over production efficiency. Research could also focus on how to balance production goals with the preservation of marine ecosystems in a way that transcends techno-centric solutionism. For instance, understanding the socio-political and economic barriers to adopting more precautionary, ecosystem-based management strategies could provide a new avenue for improving regulatory frameworks.

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