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A Review of Loss in Norwegian Salmon Aquaculture Production: Mechanisms and Measurements

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Abstract

To maintain economic, environmental, and ethically sustainable production in the food industry, minimizing losses is a key objective. This thesis investigates the mechanisms driving losses and how losses are quantified and measured in the Norwegian Atlantic salmon aquaculture industry. The objective is to provide an increased understanding of losses and measurements to aid towards the reduction of food loss (FL). Based on a review of available literature and statistics, it is found that losses in the industry are driven by a complex set of mechanisms. The majority of losses occur due to mortality during production at sea. Salmon delousing treatments are a key contributor to losses and can lead to episodes of high mortality when performed in conjunction with underlying health impairments. The most frequently performed delousing regimens, thermal- and mechanical treatments, are associated with the highest mortality increases.

Norwegian salmon is at risk of contracting to a series of diseases and infections, where the most detrimental are complex gill disease, cardiomyopathy syndrome, and winter ulcers. It is found that each year approximately 16 % of all salmon end up as a loss. On the national level, losses exhibit a decreasing trend. However, the average weight of harvested salmon is decreasing, likely caused in part by high pressure on farmers to keep lice levels low. Losses and mortalities vary significantly depending on year and location, and no county produces a consistent number of harvests per lost individual. Several challenges exist relating to quantity control and loss measurement during production, and current measurement technology is imprecise and can cause negative health effects in fish. Monthly reports of biomass and loss numbers are associated with significant uncertainties. The industry would benefit of precise equipment for stock measurements during production at sea, and increased data generation is necessary to improve the current understanding of factors driving losses and mortalities.

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This master's thesis marks the conclusion of a 5-year engineering study for us at the University of Stavanger, and we would like to use this opportunity to express our appreciation to family and friends for their continuous support and encouragement throughout these years.

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1. Introduction

Food loss, food waste, and food security are problems yet to be resolved. Frequently cited studies estimate that globally, a third of all food produced is being lost or wasted (FAO, 2011; HLPE, 2014; Hoehn et al., 2023). Food loss and waste (FLW) can occur along all levels of the supply chain. Its implications are depletion of the environment, generation of avoidable greenhouse gas emissions, and increased strain being put on land and water resources, all contributing to negative societal impacts (Europe, 2023). Challenges exist in quantifying the FLW problem, where differences in definitions and methodological approaches lead to complications in data gathering and comparison (Hoehn et al., 2023). By building an understanding of food loss (FL) at the primary production stage, the EU-wide research project FOLOU aims to implement a comprehensive approach involving monitoring, measurement, and knowledge transfer in the industry. An action plan will be developed for producers, policymakers, and other participants in the food supply chain, enabling the reduction of FL through implementing recommended proposals (Europe, 2023). This thesis is intended as a contribution to the FOLOU project by investigating FL in Norwegian Atlantic salmon (Salmo Salar) aquaculture production.

Norway has achieved great success in its aquaculture ventures, and farmed salmon has become the country's most important export industry after oil and gas. In 2022, production reached 1.55 million tons, and Norway remains responsible for around half of worldwide production (Hersoug, 2021).

Traditional salmon farming is performed in open cages in the sea, making stocks subject to environmental factors like salinity, temperature, oxygen, currents, wind, and light conditions in addition to diseases and parasites. Sea lice are parasites that can inflict wounds and related health issues for farmed salmon. Moreover, salmon farms contribute to spreading these parasites to wild salmon stocks. Regulations require producers to manage the sea lice numbers through frequent treatments and handling of the stock. Sea lice mitigating measures can by themselves cause negative health impacts including increased mortality (Sommerset et al., 2023). Losses occur for several reasons, including death due to disease and infections, treatment-related mortality, escapes, and, for various reasons, discarding during processing (Carvajal et al., 2021; Sommerset et al., 2023). These losses are reported monthly to the Directorate of Fisheries (Directorate of Fisheries, 2022). Loss of growth potential due to intentional starvation or decreased appetite in fish related to handling and environment also occur (Bang Jensen et al., 2020; Walde et al., 2023).

1.1 Scope and Objective

This thesis will explore FL in the Norwegian salmon farming industry. Specifically, it will focus on identifying factors contributing to losses, assess how these losses are quantified and challenges related to the measurement of losses, and analyze available loss statistics. Potential areas for improving loss measurements are investigated. By addressing these issues, this thesis aims to contribute to a better understanding of FL in the Norwegian salmon aquaculture industry.

1.2 Organization of the Thesis

Chapter 1 introduces the thesis by defining research objectives and the applied methodology. Chapter 2 introduces the challenges related to FLW and measurements, and why these issues are necessary to investigate. The role of salmon as a source of livestock and Norway as an important producing country in a food-security setting is presented. Terminologies pertaining to FLW are discussed to ensure clarity is maintained throughout the thesis. Chapter 3 provides a comprehensive overview of the Norwegian salmon aquaculture industry. The regulatory framework is first defined to explain how the industry is structured. The different stages of the production process are explained to provide an understanding of when and where losses originate. Procedures on how quantity control and loss management is performed throughout production are explained, as well as challenges related to this. Chapter 4 presents and analyses available statistics to provide an understanding of the scope and historical development of losses in the industry. Chapter 5 summarizes causes and contributing factors to losses and measurements, based on related studies and relevant literature. Chapter 6 discusses findings based on the literature presented in this thesis. Chapter 7 provides a concluding summary. Recommendations for the industry and future research are made.

1.3 Methodology

This section describes the methodology used for investigating losses in Norwegian salmon aquaculture. In order to achieve a comprehensive understanding of FL in the industry, various methods were applied, including literature reviews, analysis of available statistical data, and interviews with representatives from one of the governing bodies in the Norwegian aquaculture industry, the Directorate of Fisheries.

1.3.1 Desk Review

A literature review was conducted of relevant articles and industry reports relating to losses in the industry. Articles on production processes, delousing treatments and ramifications, mortalities and causes, and health conditions and impacts were analyzed. Legal- and regulatory frameworks pertaining to the industry were studied. Technologies and industry trends were examined to investigate how these can affect losses and stock measurements, as well as current ways of managing and measuring losses in the industry.

Because the industry is subject to mandatory and frequent reporting of much of its production data, large amounts of historical and recent statistics is available. Data on losses, stockings, and harvests, as well as delousing treatments and welfare incidents was examined to obtain an understanding of the scope and possible factors contributing to losses in the industry.

1.3.2 Interview

A qualitative approach was made by interviewing two representatives from the Norwegian Directorate of Fisheries. This method aimed to uncover limitations and gaps in existing loss management and measurement methods, such as the reliance on self-reporting, insufficient measurement technology, common errors, and contributing factors.

2. Food Loss and Food Security

FLW is defined as the decrease in quality or quantity of edible food intended for human consumption (Hoehn et al., 2023; Rezaei & Liu, 2017). A differentiation is made between the terms “food loss” and “food waste”. This differentiation is typically characterized by the point in the supply chain where food finishes all manufacturing stages, meaning food loss occurs during production, processing and packaging, and food waste occurs during distribution and consumption.

Quantifying FLW is a challenging task, and no consensus exists on the total amount of FLW generated each year. Estimates range between 10-40 %, some up to 50 % (Hoehn et al., 2023). A report published by FAO in 2011 (FAO, 2011) estimated FLW at approximately one third of all food produced worldwide, and is frequently cited in academic literature. The definitions and findings presented in this report have been debated since (Hoehn et al., 2023). Complex flows and manufacturing processes result in various products of economic and nutritional value being taken out of the food supply chain (FSC) at different stages, and differences in methodological approaches therefore result in different quantifications (HLPE, 2014; Hoehn et al., 2023). FLW examples that common quantification approaches are unclear on include food that is removed to maintain market prices, losses due to excessively strict sanitary requirements, agriculture crops being lost due to diseases and pests, food products discarded due to not meeting standardized size or required visual appearance, etc. (Hoehn et al., 2023). The full extent of the FLW problem therefore remains inconclusive.

FLW in a world where people suffer from hunger is a testament to a suboptimal global food system. The reasons for food-insecurity are however complex and cannot be attributed solely to FLW. A reduction in FLW in food-secure countries will not necessarily result in increased supply in countries troubled by food-insecurity. Nevertheless, the implications of FLW on food security are several: FLW reduces global and local availability of food. Reduced availability will for consumers lead to decreased access through rising prices. Subsequently, producers can incur economic losses through decreased sales, or by having to decrease profit margins. In the long term, unsustainable use and depletion of natural resources will affect future production, contributing to future food-insecurity (HLPE, 2014).

The social impact of increased prices due to FLW will vary depending on the portion of household budgets dedicated to food. In developing countries, food costs typically represent a significantly larger portion of household budgets compared to developed countries. It follows that FLW can affect developing countries disproportionately (HLPE, 2014).

2.1. FOLOU Project

FOLOU is an EU Horizon research project part of the Farm-2-Fork strategy initiated in 2023. The project name is an abbreviation of the title *"Bringing Knowledge and Consensus to Prevent and Reduce FOod LOss at the Primary Production Stage. Understanding, Measuring, Training, and Adopting".* As the title suggests, the project aims to challenge obstacles in the reduction of FL by bringing knowledge and recommendations to the industry. FOLOU recognizes the key challenges to reducing FL as:

Regulatory:

- Technical (lack of measurement technology and methodology).
- Scientific (lack of understanding drivers of FL).
- Social (lack of skills in stakeholders).

The main objective is defined as setting up necessary mechanisms to:

- Measure and estimate, through harmonized methodology.
- Monitor and report, through national and EU FL registers.
- Assess the magnitude and impact of FL.

Project outcomes are intended to be transferred to stakeholders in primary production chains, including primary producers, retailers, consumers, policy makers, and researchers (Europe, 2023).

2.2. Norwegian Atlantic Salmon in a Food Security Perspective

The global demand for animal products is rising, and increased pressure is put on limited natural resources through population growth (Cassidy et al., 2013; Fry et al., 2018). It is estimated that globally, approximately 36 % of crop-based calories are used for livestock feed. Because perfect feed conversion is impossible in any animal, only 12 % of calories administered to livestock enter the human diet through animal products (Cassidy et al., 2013). Aquaculture is viewed as having an important role in improving future global food security due to its production efficiency. Animal production efficiency is commonly measured by feed conversion ratio (FCR), pertaining to the relationship between the weight of feed administered and weight gained in the animal. A lower FCR indicate more efficient conversion; the animal gains more weight using less feed (Fry et al., 2018). Typical FCRs for animals produced using commercial feeds include (Fry et al., 2018):

- Cattle: 6.0 - 10.0
- Pigs: 2.7 - 5.0
- Chicken: 1.7 - 2.0
- Farmed fish and shrimp: 1.0 - 2.4

Part of the reason for more efficient FCRs in aquatic animals can be attributed to its characteristics. Due to buoyancy, they expend less energy by moving and staying upright than terrestrial animals. Most are also ectothermic, thus using less energy to regulate body temperature (Fry et al., 2018).

A few limitations are associated with using FCR for efficiency measurement, as it only accounts for the weight of feed input and animal. For proper efficiency assessment, nutritional content of feed, edible portion and nutritional quality of the produced animal should be considered. Fry et al. (2018) found that Atlantic salmon had the highest retention rates among nine major aquaculture species, at 25 % of calories and 28 % of protein in feed being converted to edible product. In comparison, the weighted average for aquaculture species in the study, based on global production numbers, was 10 % for calories and 19 % for protein (Fry et al., 2018). By these measures, Atlantic salmon is only second to chicken, at 27 % of calories and 37 % of protein being retained. The efficient nutrient retention in Atlantic salmon can be attributed to a low FCR (1.2-1.5) and high edible portion (0.58-0.88). Calorie and protein retention rates are illustrated in Figure 1.

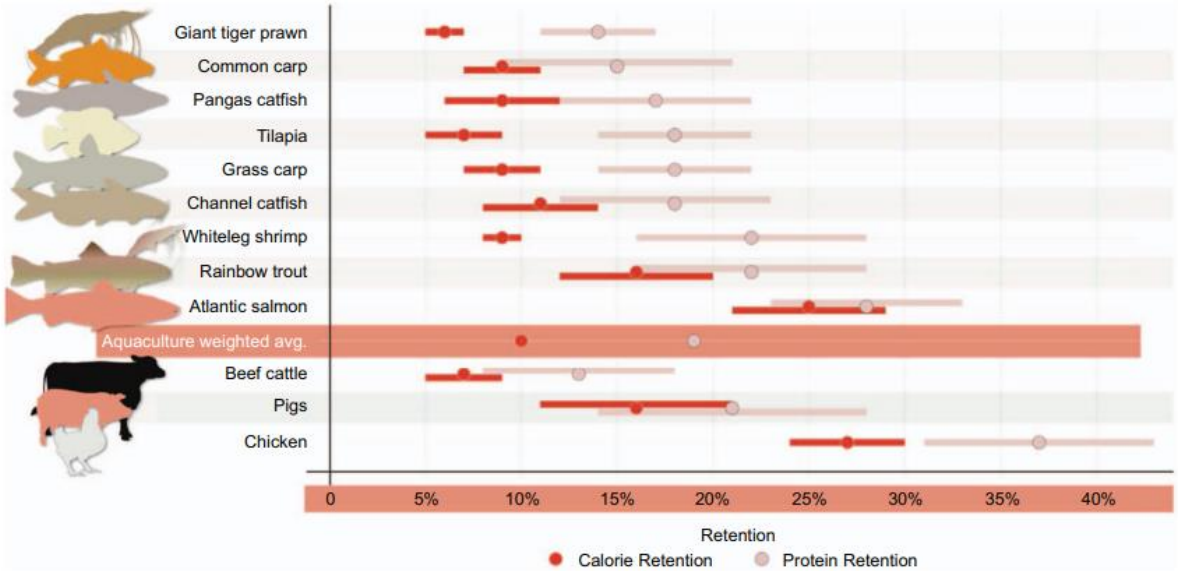

Figure 1: Calorie and protein retention of selected species. Dots represent sample means; bars represent standard deviation. Adapted from (Fry et al., 2018).

Globally, salmon is the second largest aquaculture species by value, next to shrimp, and Norway is the leading producer at approximately 50 % of worldwide supply (Afewerki et al., 2022; Hersoug, 2021). In agriculture, it is argued that innovations commonly take place in select countries, and global adoption occurs from here. This makes Norway a potential hub for important innovations, both in salmon aquaculture and in aquaculture in general as processes and technology is adapted to other species (Afewerki et al., 2022).

In conclusion, Atlantic salmon is highly efficient in terms of nutrient conversion and retention compared to other species. Norway is a key producer in the aquaculture industry, with potential to develop innovations in the aquaculture industry at large. This makes the Norwegian salmon aquaculture industry an important candidate for research in a FLW and food-security perspective.

2.3. FLW Definitions and Terminology in Norwegian Aquaculture

The definition set by the Industry Agreement (Norwegian title: Bransjeavtalen) is commonly used in Norwegian literature when discussing food waste:

"Food waste includes all usable parts of food produced for humans that is discarded or removed from the food chain for purposes other than human consumption, from the time animals and plants are slaughtered or harvested" (authors translation) (Agriculture, n.d.).

Carvajal et al. (2021) specifies that to be considered food waste in Norway, parts and products must be considered food in Norway, despite the same parts and products being considered food in other markets. When discussing food waste in Norwegian aquaculture production, this applies especially to heads, backs, and swim bladders. These are not considered food in Norway and therefore not considered food waste, but side products. Side products are generally utilized or processed in the Norwegian seafood industry, and therefore often categorized as "usable" by the industry (Carvajal et al., 2021; Norwegian Food Safety Authority, 2014). In the context of the above definition, the word "usable" refers to parts and products usable for, and considered as, food in Norway.

When translated to English, the definition becomes somewhat ambiguous when applied to discussions of fish production. In the English language, both the terms "slaughter" and "harvest" are natural to use when describing the final stages of salmon aquaculture production, and the terms carry different connotations. The Norwegian translation of the term "harvest" (Norwegian: "høste") is more commonly used regarding crops in agriculture production and would not normally be used in the context of fish production. It follows that when applied to aquaculture production, the definition puts emphasis on the term "slaughtered". Norwegian regulations define the term "slaughter" as stunning, bleeding and killing when used in the context of fish (Norwegian Food Safety Authority, 2021b). Gutting and any further handling and preparation is defined as "processing" (Norwegian Food Safety Authority, 2021b). Accordingly, it can be derived that food waste in Norwegian salmon production occurs from the point at which death is intentionally inflicted upon fish for the purpose of food production.

Norwegian literature is less clear on the definition of food loss, but it is natural to deduce from the definitions discussed above that in terms of fish production, food loss refers to the reduction of quantity or quality of fish up until the point at which death is intentionally inflicted for the purpose of food production. In the context of discussing salmon aquaculture production, the following definitions are presented and used throughout the thesis:

- Food loss: Any reduction in quality or quantity of fish occurring during production, up until the point at which death is intentionally inflicted for the purpose of food production.
- Food waste: All parts of fish considered edible on the Norwegian market discarded or removed from the production chain after the point at which death is intentionally inflicted for the purpose of food production.

This thesis uses both the terms “slaughter” and “harvest” in discussing salmon aquaculture production. The terms are used according to their recognized definitions and common usage in the English language, with their different connotations. Although used interchangeably in much of literature, this thesis does not, to limit the risk of ambiguity. Where possible, the term “harvest” has been used due to its suggestion of a controlled approach to utilize fish for food production. For clarification, the following definitions are presented, and used throughout the thesis:

- Slaughter: To intentionally kill fish, for any reason.
- Harvest: To catch or gather fish with subsequent utilization in food production, or intent to utilize in food production.

3. Norwegian Salmon Aquaculture

The production of farmed Atlantic salmon in Norway has undergone immense growth since its humble beginnings around 1970. Over the last decades, salmon aquaculture has grown to become the country's second largest industry. In 2022, production reached 1.55 million tons at a value just over 100 billion NOK (Norwegian Food Safety Authority, 2021a). This is equivalent to a threefold increase in volume over the last twenty years. Globally, Norway is the largest producer of farmed salmon and responsible for around half of world production (Afewerki et al., 2022).

3.1. Industry Organization and Regulations

Despite its success, the industry is faced with its share of challenges. Emissions of feed waste and feces from production sites can impact local, surrounding ecosystems (Grefsrud et al., 2022). Salmon lice transferring from farms pose a threat to wild salmon stock. Through breeding, farmed salmon escapees can incur genetic effects on wild salmon (Grefsrud et al., 2022). Concerns are also raised regarding the use of chemicals for cleaning aquaculture cages and medicinal feed for treatments, and potential consequences emissions from these processes can have on marine species (Grefsrud et al., 2022; Sommerset et al., 2023). Producers must also ensure the welfare and ethical treatment of farmed salmon itself (Sommerset et al., 2023).

To maintain environmental sustainability, the industry is regulated by various management schemes (Hersoug, 2021). Total production is limited by Maximum Allowable Biomass (MAB) in combination with a limited number of salmon production licenses. MAB pertains to the amount of living fish measured by weight allowed at any given time for individual licenses in operation. MAB applies both at the farm- and locality level, meaning that a farmer is limited by their production license (or licenses), and new licenses can only be issued if allowed by the limit set for the location (Directorate of Fisheries, n.d.).

Norway has been divided into 13 geographical production zones. MAB is initially the same for all salmon production licenses but can be adjusted according to the environmental situation in each zone (Directorate of Fisheries, n.d.). The environmental situation is assessed by a committee based on lice numbers and lice occurrence in wild salmon (Hersoug, 2021). A traffic light system is used for classifying environmental risk, where low, medium, and high-risk zones are classified as green, yellow, and red, respectively (Produksjonsområdeforskriften, 2017).

Farms in green zones are permitted an increase in production of 6 % above the zone MAB limit. Farms in yellow zones must maintain levels within zone MAB limits. Farms in red zones must decrease production to levels 6 % below the zone MAB limit. Regardless of the risk class set by the traffic light system, special permits for limit increases can be given to individual farmers if certain criteria are met. As of 2023, these criteria are a maximum of 0.1 adult female lice per fish in a cage in given weeks for 2021 and 2022, and a maximum of one medicinal treatment per cage or cohort over a production cycle (Produksjonsområdeforskriften, 2017). The system is structured such that farmers in a zone are collectively responsible for the zone environmental situation and can expect changes to MAB based on this situation (Hersoug, 2021).

Exceeding MAB limits can be met with legal reactions and/or fines (Forskrift om håndheving av akvakulturloven, 2013). In addition to limits set by MAB, number of fish in a production unit cannot exceed 200,000 as per Akvakulturdriftsforskriften (2008) §47a. The number of female adult lice in a production unit cannot exceed 0.5 per fish on average, and a farmer is required to harvest or slaughter if these levels cannot be maintained (Norwegian Food Safety Authority, 2016). Other requirements include periodic reporting of stocking numbers, biomass levels, and losses to the Directorate of Fisheries. All escapes must also be reported (Thorvaldsen et al., 2015). According to Norwegian Food Safety Authority (2016) §10, lice numbers are reported each week to the Norwegian Food Safety Authority. These reports enable regulatory bodies to monitor the current production and environmental situation (Forskrift om håndheving av akvakulturloven, 2013; Hersoug, 2021; Norwegian Food Safety Authority, 2016; Sommerset et al., 2023).

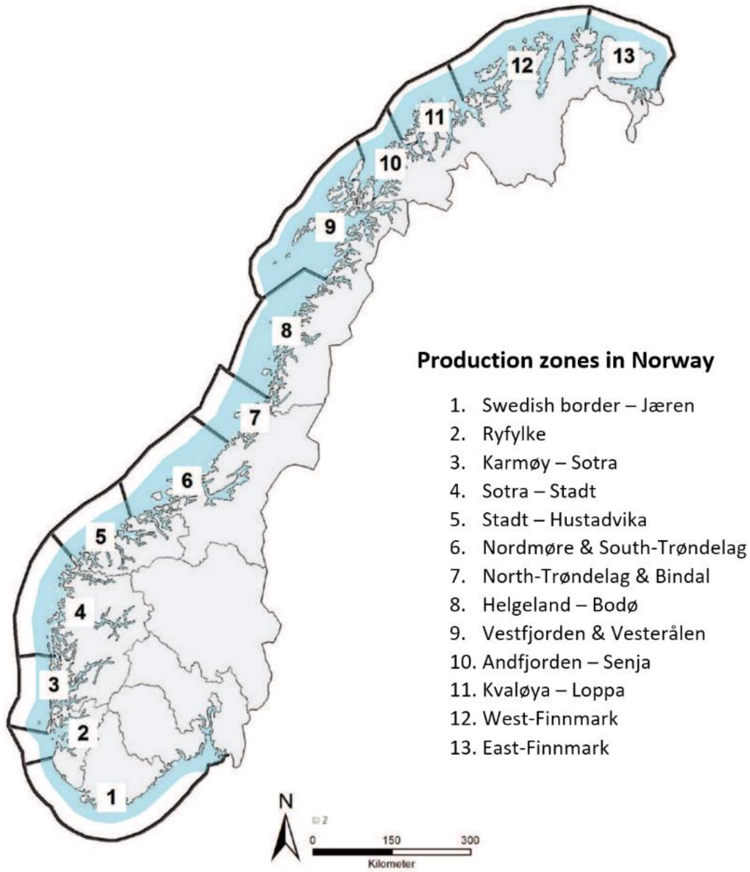

Figure 2: Production zones. Adapted from (Sommerset et al., 2023.)

3.2. Production Process

In order to explain the challenges related to biomass- and quantity control in Norwegian salmon farming, a thorough understanding of the farming process is necessary. The process consists of several stages. A variety of different operations can be performed depending on the individual producers' routines and strategies. This chapter presents a general overview of the production process and the different operations it can include. Common causes of loss and routines and operations related to counting and quantity measurements are outlined to describe when and why biomass- and quantity control challenges occur.

3.2.1. Hatchery Production

Broodstock is carefully selected based on its genetics and reproductive potential. The selected salmon is then placed in spawn tanks, where they are stimulated to spawn by manipulating environmental factors such as lighting conditions and water temperature. Eggs and sperm are collected and mixed in order to promote fertilization (Bjelland et al., 2012; Mylonas et al., 2010). Sorting of eggs is conducted by machines, which provides relatively accurate counts (Bjelland et al., 2012). The fertilized eggs are hatched in incubation tanks and become fry, before being placed in tanks with conditions for optimal growth. Eggs and fry stock can be split or merged, in which case quantities are measured based on volume (Bjelland et al., 2012).

The growing period from fry to smolt is conducted in fresh water and takes 10-16 months. Towards the end of the process, the salmon undergoes a process called smoltification, which is a series of biological changes which prepares it for a life in the sea. At this stage, a smolt typically weighs 60-100 grams. The period in which salmon is biologically prepared to transition from fresh- to saltwater is referred to as the smolt-window (Bjelland et al., 2012; Iversen et al., 2015). Smolt quantities are measured using pipe counters, volume measurements and/or by feed consumption (Bjelland et al., 2012).

Sorting, splitting, and merging populations can be done to achieve homogenous distributions in fish groups. Some producers report that this can contribute to a more efficient production, while others avoid it entirely as the mechanical sorting process can cause stress and injury to the fish. Depending on the availability of tanks and limited production areas at a facility, some producers might need to perform sorting and splitting operations. These operations can serve as opportunities for performing quantity measurements, but they can also degrade the quality of previous, more precise, quantity measurements, such as the vaccination quantity (discussed in chapter 3.2.2.). No standard practice exists regarding these operations, and routines will vary among producers (Bjelland et al., 2012).

Because hatchery fish are kept in closed tanks, producers can effectively monitor and manage deaths. Dead fish are manually removed from tanks and losses are registered. In cases of high mortality, quantities are estimated based on volume (Bjelland et al., 2012).

3.2.2. Vaccination

During smolt production, typically at a weight of 30-50g, the fish undergo vaccination (Bjelland et al., 2012). The vaccination stage is the only time during the production process, next to harvesting, where fish are handled individually. The quantity control provided by the vaccination process is highly precise with low or insignificant error margins and critical for providing quantities used throughout the rest of the production process (Bjelland et al., 2012); Personal communication with representant at Directorate of Fisheries, April 2023).

Deformed or damaged fish are removed and discarded before the vaccination to not affect the count. Depending on which service providers and equipment are chosen for the vaccination, a counting device is fitted directly to the syringe, or a photocell is fitted in the tubing where fish are transferred after injection. In cases of counting devices fitted in syringes, errors can occur if the operator does not subtract any potential vaccine doses not set in fish. Counting by photocell provides a more precise number of fish that have been vaccinated and returned to the production facility (Bjelland et al., 2012).

In 2012, it was common for most vaccine equipment that a count must be manually transferred to the production management system. Errors or loss of data can here occur due to human error. Counting devices are typically connected to the power grid or powered by batteries, making power outages a potential risk for data loss from an ongoing operation. Other less common sources of errors include pipes being misconnected, causing fish to end up in the wrong tanks, and fish being left in pipes after the operation (Bjelland et al., 2012).

In cases of high mortality between vaccination and transfer to sea, maintaining precise control over the surviving quantity can be difficult. Hatcheries rarely have equipment for counting large amounts of dead fish. In such cases, quantities will be estimated based on volume, leading to uncertain quantity control. However, high mortality episodes are reported to be rare at this stage (Bjelland et al., 2012).

3.2.3. Stocking

After hatchery fish have completed the smoltification process and reached the desired weight, they are transferred to sea cages at production sites using wellboats (vessels for carrying live fish stock).

Wellboats are equipped with pipe counters, but these are less accurate than the counters used at the vaccination stage. Fish quantities can be measured during loading and unloading operations. In general, it is desirable to perform these operations at high speeds to limit labor hours and reduce the duration of time fish are subjected to stress. This can entail transferring fish at or above the recommended rate for the pipe counter, leading to inaccurate quantity measurements (Bjelland et al., 2012).

Hatchery fish are often sold to farms in entire tanks. Quantity data can then be carried over by the farm, maintaining accurate quantity control for the initial stocking of fish. Splitting of tanks can occur in cases where wellboats load only part of a tank, or a tank is split and stocked in multiple cages. In these cases, farmers need to rely on measurement data provided by pipe counters on the wellboat. A trade-off between counting accuracy and time fish spends under stress will then be imperative. It is reported that quantities measured on the wellboat during unloading tend to be more precise than during loading, due to unloading operations providing improved control over how fish is fed into tubing and machinery. Both loading and unloading operations provide opportunities for comparing wellboat and hatchery (vaccination) measurements. Typically, these are reported to exhibit discrepancies (Bjelland et al., 2012).

3.2.4. Sea Cage Production

Quantity data supplied by hatcheries and wellboats lay the foundation for quantity control in the sea phase. A sea cage can contain up to 200,000 fish, and the size of the stock is registered in production management software specific to each cage (Akvakulturdriftsforskriften, 2008). The software is used to track quantity and standing biomass throughout the production process (Bjelland et al., 2012). Norwegian law requires farmers to manage and remove dead fish from cages on a daily basis, except for when conditions like weather make this process unfeasible (Akvakulturdriftsforskriften, 2008). In periods of increased mortality, it can become necessary to remove losses several times per day (Norwegian Food Safety Authority, 2021a). Losses are counted manually when occurring in manageable amounts and estimated based on volume in episodes of high mortality. Stock records in the production management software are updated based on the daily loss management, and each month losses are reported to The Directorate of Fisheries (Akvakulturdriftsforskriften, 2008; Bjelland et al., 2012).

Dead fish are collected in sea cages using either net collectors or pump systems, both of which are fitted to the center of the conical cage bottom. Net collectors transport losses to the surface by being winched up inside the cage, allowing live fish to swim away. The net collector is typically connected to the cage in such a way that when it is lifted, it raises the bottom of the cage to allow potential dead fish stuck in the netting towards the cage bottom to be released. Several passes are typically done with the net collector to ensure all dead fish are removed.

Pump systems transfer losses to the surface by pumping pressure when activated by an operator. A challenge related to using pump systems is that the bottom of the cage remains fixed, potentially allowing dead fish to get stuck in the net and gather in pockets before reaching the pump area. If left over time, these fish can disintegrate and/or be eaten by predators from outside the net before being accounted for, impacting quantity control and loss records. Regardless of the type of collection system used, it is critical for accurate recordkeeping that dead fish quickly reach the cage bottom and are collected (Bjelland et al., 2012). This area of the cage is often monitored by cameras to ensure that loss collection occurs as intended (Bjelland et al., 2012; Sommerset et al., 2023).

In the period shortly after hatchery fish have been transferred to sea cages, increased mortality is a common occurrence (Bang Jensen et al., 2020; Bjelland et al., 2012). Losses at this stage can be challenging to manage as the fish are small and can easily get stuck in the net on the way down to the collection system, subsequently disintegrating or being eaten by fish from outside the cage (Aunsmo et al., 2013). Another possibility is that losses reach a state of decomposition before entering the collection system that makes accurate loss measurements difficult to achieve (Aunsmo et al., 2013; Bjelland et al., 2012).

As production in the sea cage progresses, biomass is managed by the production management software, utilizing empirical models for fish growth (Aunsmo et al., 2013; Bjelland et al., 2012). Feed rations are determined based on the stock size and its estimated biomass, water temperature and predicted growth (Bjordal et al., 2020). Fed amount is recorded in the software on a daily basis, and biomass development is modeled based on feed quantities and subsequent conversion into biomass using an expected feed conversion ratio (FCR). Mean weight for the stock is derived from total biomass divided by stock size (Aunsmo et al., 2013).

Feed intake and utilization will vary depending on the environment and can decrease because of disease outbreaks, operations, and other factors (Bjelland et al., 2012; Hevrøy, 2021). These variations in appetite can impact the precision of modeled biomass, and samples from the cage are frequently weighed in order to adjust FCR and mean weight estimations (Aunsmo et al., 2013). Similarly, deviances from the expected growth rate can over time give an indication of imprecision in the registered stock size. Monitoring systems like biomass estimator frames; measuring fish as it swims through it, are often installed in cages to provide automatic and continuous biomass measurements from samples in the cage (Bjelland et al., 2012).

Over the course of the sea cage production phase, quantity control is managed by the production management system based on numbers from the initial stocking and daily recordings of losses (Bjelland et al., 2012). In addition to mortality, losses can occur due to escapes and predation by birds or other animals (Directorate of Fisheries, 2023c), where precise loss recording will be difficult to achieve. It follows that, as production progresses, quantities present in cages become increasingly uncertain due to the lack of precise measurements.

3.2.5. Sorting, Splitting, and Counting Operations

During the sea phase of production, different operations involving wellboats can be performed, providing opportunities for supplemental quantity measurements. Similar to practices in hatcheries, the use of sorting and splitting operations varies among different farmers (Aunsmo et al., 2013). Frequent sorting and splitting of stock can enable the farmer to better utilize their capacity set by MAB, but these operations can also cause stress and increased risk of disease in the fish. Pipe counters on wellboats can provide updated quantity measurements following these operations, but measurements recorded here are associated with uncertainties and will have to be weighed against data from the production management system. Bjelland et al. (2012) reports that adjustments to the recorded quantity distributions between cages based on feed usage can occur following these operations.

The different geographical location of individual production sites implies differences in weather and environmental conditions, and this can entail limitations in time frames allowing operations to be performed. For production sites more exposed to the elements, it follows that certain operations are forced to be performed at rates or speeds closer to the limits set by the counting equipment. This can lead to measurements being less precise than if performed at slower paces (Bjelland et al., 2012).

Regarding the precision of counting equipment on wellboats, Vikingstad (2022) describes an event from the industry involving a 3 m tear in the net of a sea cage. In conjunction with a subsequent delousing operation, the stock has been counted while loading onto a wellboat. The measurement indicates an absence of 4,800 fish. This difference equals 2.4 % of the stock, which is within the margins of the counting equipment on the wellboat. The farmer expresses doubt regarding the escape of any fish (Vikingstad, 2022).

Another event is described involving a 1 m tear in the net of a sea cage. The farmer performs a counting operation and the measurement indicates the absence of 10,000 fish. Wishing to confirm this, a second counting operation is performed, and the subsequent measurement indicates an excess of 1,500 fish (Vikingstad, 2022).

The examples above describe two events from the Norwegian salmon farming industry and were presented by the Directorate of Fisheries during a conference (September 8th, 2022) regarding the research project “PRESAL – Precision in Counting of Salmon” (FHF, 2022; Vikingstad, 2022).

3.2.7 Harvesting

Salmon is typically harvested after 14-20 months in sea cages, ideally at a weight of >5 kg (Bang Jensen et al., 2020; Barrett et al., 2022). Long grow-out periods are often pursued by farmers, as fish in higher weight-classes fetch a higher price per kg (Bang Jensen et al., 2020; SjømatNorge, 2023). However, more time spent at sea implies longer exposure to risks of disease and infections, injuries from additional delousing treatments, etc. A farmer will therefore consider risks and rewards in selecting a harvesting date, based on the overall health and condition of the stock (Bang Jensen et al., 2020). Some farmers perform partial harvestings to better utilize capacity set by MAB limitations, by sorting out the biggest fish and leaving the remaining for an extended grow-out period (Bjelland et al., 2012).

At some point in the days leading up to the harvest, a harvesting report is submitted to the processing facility by the farmer. This report contains data on quantity, mean weight, and size distribution of the harvest, and is used for logistics planning at the processing and sales stages

(Aunsmo et al., 2013; Bjelland et al., 2012). Generally, the report relies on data from the production management system, adjusted based on potential recent measurements and the farmers impressions of the stock (Aunsmo et al., 2013; Bjelland et al., 2012). Some farmers utilize the measurements provided as the harvest-sized stock is loaded onto wellboats for transportation, but this data is typically obtained too late to be used for planning of later stages (Bjelland et al., 2012).

Prior to harvesting, the fish are starved for a period of several days. Starvation is performed to reduce oxygen requirement and improve stress tolerance in the fish, as well as empty its digestive system to improve hygiene during processing. Starvation times are determined based on fish size and water temperature. Generally, larger fish require a longer period of starvation. Starvation times vary depending on producers, and periods of up to 30 days are reported (Kristiansen & Samuelsen, n.d.). At harvesting weight, salmon is typically resilient to extended periods of starvation without exhibiting behavioral or health-related problems (Kristiansen & Samuelsen, n.d.). However, starvation entails a loss of growth potential (Liu & Bjelland, 2014; Walde et al., 2023). In cases where partial harvestings are performed, the remaining stock will undergo an increased number of total starvation time (Bjelland et al., 2012), implying a loss of potential growth.

3.2.8. Processing

Traditionally, the stock is transferred to wellboats before being transported live to the processing facility. Holding pens can here be used for temporary storage to allow for flexibility in timing between harvesting and processing, as well as providing processers with continuously available supply (Bjelland et al., 2012; Kristiansen & Samuelsen, n.d.). In recent years, however, an increasing trend has been observed in the use of stun-boats (harvesting vessels equipped with stunning, bleeding, and chilling equipment (Barrett et al., 2022), also referred to in literature as stun-and-bleed vessels (SBVs) (Ringvall, 2020)) for partial processing at the cage site (Barrett et al., 2022; Sommerset et al., 2023). By abandoning the use of holding pens and stunning the fish directly out of the cage, the risk of injury or death by transportation and extra handling will be limited (Barrett et al., 2022). The degree of processing performed at the cage site will vary depending on the vessel (Ringvall, 2020), but commonly include stunning, bleeding and chilling (Barrett et al., 2022). As the fish are fed into stunning machines, quantities can be measured by counting equipment in tubing or in the stunning machine itself. The quantity registered here is relatively precise, but only intended for planning of later stages down the processing line (Bjelland et al., 2012). Further processing includes bleeding out, chilling, gutting, and cleaning by use of various machinery (Bjelland et al., 2012; Carvajal et al., 2021). Counting and weighing at these stages vary depending on equipment and machines. This data is used primarily for management at the different processing stages, such as assigning fish to suitable gutting machines based on weight (Bjelland et al., 2012).

Conclusive data on weight and quantity produced are obtained by individual weight measurement of gutted and cleaned fish while sorting in weight classes. This data is used by the farmer for sales and future production management (Bjelland et al., 2012), and is reported to the Directorate of Fisheries as required by law (Akvakulturdriftsforskriften, 2008). Precision regarding the total number of fish produced obtained at this stage is considered to be 100 %, unless technical errors have occurred (Bjelland et al., 2012).

Losses at the processing stage consist of fish that are unsuitable for human consumption, which are removed and discarded (Directorate of Fisheries, 2023c). These include fish of other species (commonly juvenile coalfish), fish that is dead prior to stunning, sexually mature fish, runt fish (fish that for various reasons are poor-growers and have underdeveloped muscle mass (Georgiadisa et al., 2000)), and fish with significant damage or deformity (Bjelland et al., 2012; Directorate of Fisheries, 2023c). Fish that end up on the floor during processing are also discarded. In some processing facilities, discards are handled manually and counted individually. Others collect and weigh discards in bulk, and estimate quantities based on the average weight of the harvested stock (Bjelland et al., 2012). The discarded quantity is reported to The Directorate of Fisheries, as required by law (Akvakulturdriftsforskriften, 2008).

Food waste at the processing stage occurs mainly due to fish ending up on the floor (Carvajal et al., 2021). In addition, food loss occurs as fish of degraded quality due to injuries, wounds, pigment spots, and incorrect cutting is removed from the process (Carvajal et al., 2021). The filet is defined as the edible part in salmon, but trimmings, bits, and pieces of otherwise edible fish meat are also produced during processing. Some producers utilize this for food, but others use this for animal feed where it subsequently becomes food loss. For the Norwegian seafood industry in general, the main causes of food loss emerge from the category of management and design. Fish falling to the floor, training and experience in personnel, planning and time constraints are pointed to as the most important contributing factors (Carvajal et al., 2021).

3.2.9. Stock Measurement Precision

Aunsmo et al. (2013) investigated the accuracy and precision of quantity, mean weight, and biomass estimation for sea cages in advance of harvesting. 240 sea cages belonging to three major Norwegian salmon producers, which were harvested over a one-year period from 2009 to 2010 were analyzed. Farmers' best estimates based on records in production management systems, any additional measurements and experience were compared to true values obtained through harvesting and processing of the cages. Differences between estimates and post-processing, true values for corresponding cages were examined.

It was found that precision at the cage level was low, with approximately 50 % of estimates having errors exceeding 3 % compared to true values. Approximately 10 % of estimates had errors exceeding 10 % compared to true values. Mean absolute error of biomass estimation at the cage level was found to be 5.1 %. Collectively, accuracy was high with errors being symmetrically distributed around zero. Mean estimation error at cage level was 0.33 % for quantity, -0.38 % for mean weight, and -0.17 % for total biomass. When aggregated to site- and company level, errors were reduced due to errors in opposite directions cancelling each other.

The symmetric distributions around zero indicates that the poor precision is a result of random errors. Standard deviation was reduced from cage- to site level, indicating that errors occurred within production sites, as opposed to between production sites. For quantity estimates, it can suggest that farmers are aware of quantity present at the site, but not in individual cages. A possible explanation for this can be sorting and splitting operations performed using imprecise counting equipment, resulting in the farmer not knowing exact proportions between split stock.

By analyzing factors with suspected influence on estimation accuracy, it was found that mortality rates above median were associated with underestimating fish quantities in a cage. This indicates imprecise loss recording, and that farmers tend to overestimate losses in cases of increased mortality. An inverse relationship was found between errors in quantity estimation and mean weight estimation. No effect was found for cage size, number of fish in a cage, or company, suggesting that errors are of general character and that different producers are faced with similar challenges. Notably, no positive effect was found for counting during sorting and splitting operations. This suggests that these measurements were of little use to the farmers by lacking precision, or not used by the farmers due to low confidence in their precision (Aunsmo et al., 2013).

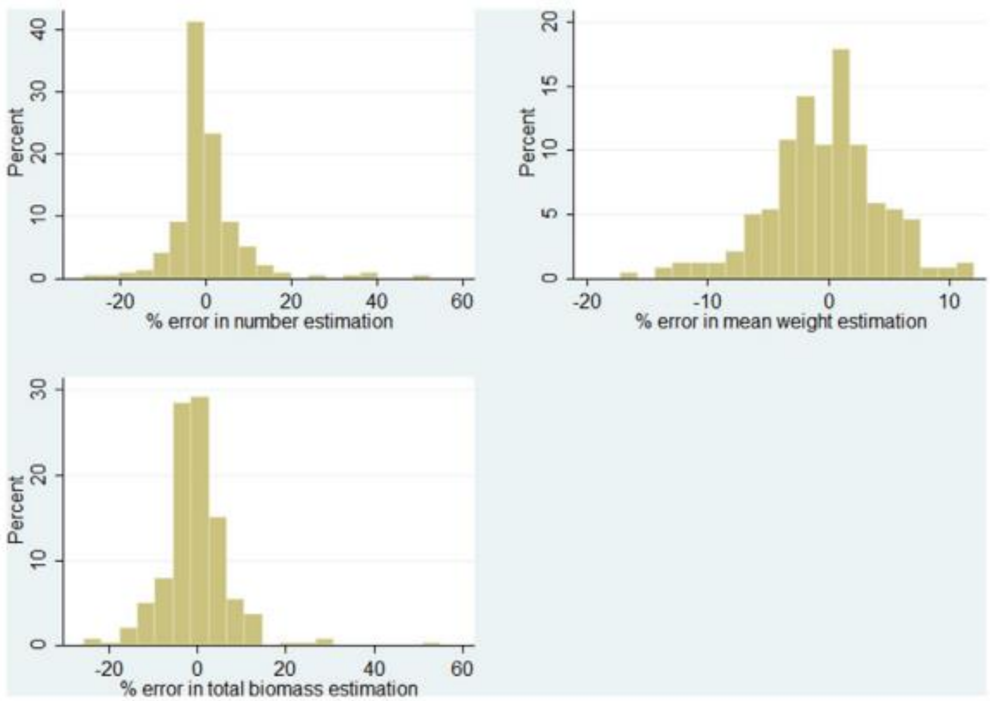

Figure 3: Percentage errors in numbers, mean weight, and total biomass (Aunsmo et al., 2013).

4. Statistics

As mentioned in Chapter 3.1, Norwegian aquaculture farmers have an obligation to report production data to the Directorate of Fisheries. This data includes species, numbers for stockings, present biomass, harvests, and losses. For biomass and harvests, both quantity and weight are reported. For stockings and losses, only quantity is reported. Weights are presented as “round weight”, referring to the weight of stunned and bled fish. Round weight is based on gutted weight obtained during processing, converted using standard conversion factors (Bjelland et al., 2012; Directorate of Fisheries, 2023b, 2023c). Reporting is done on a monthly basis for each locality and active production unit (cage). The reporting system was initiated in 2006 (Directorate of Fisheries, 2023b), and a large set of historical data is available for the industry. This data is public, however presented on the level of counties and production zones to maintain confidentiality for individual farmers. This chapter will present and analyze historical data relevant for losses and measurement in the industry.

As we have discussed in Chapter 3.2, several challenges exist relating to precise quantity and biomass measurements during production. It follows that data reported prior to harvesting is associated with uncertainties. The Directorate of Fisheries publishes data in two categories: Biomass statistics and Aquaculture statistics. Biomass statistics are published monthly on the level of production zones, according to reports from farmers (Directorate of Fisheries, 2023b). Aquaculture statistics are published yearly on the level of counties, based on quality assured biomass statistics. Quality assurance is performed by the Directorate of Fisheries, using the following equation:

$$\textit{Stock January 1st} + \textit{Stocked quantity} - \textit{Harvests} - \textit{Losses} = \textit{Stock December 31st}$$

(Directorate of Fisheries, 2022)

Since precise quantities in a cage are revealed post harvesting, loss quantities are corrected based on harvest numbers. The category «Other» in losses can be used to correct for counting errors (Directorate of Fisheries, 2022). Because of the uncertainties associated with published biomass statistics, aquaculture statistics have been used in this chapter where available.

4.1 Harvest Number and Size

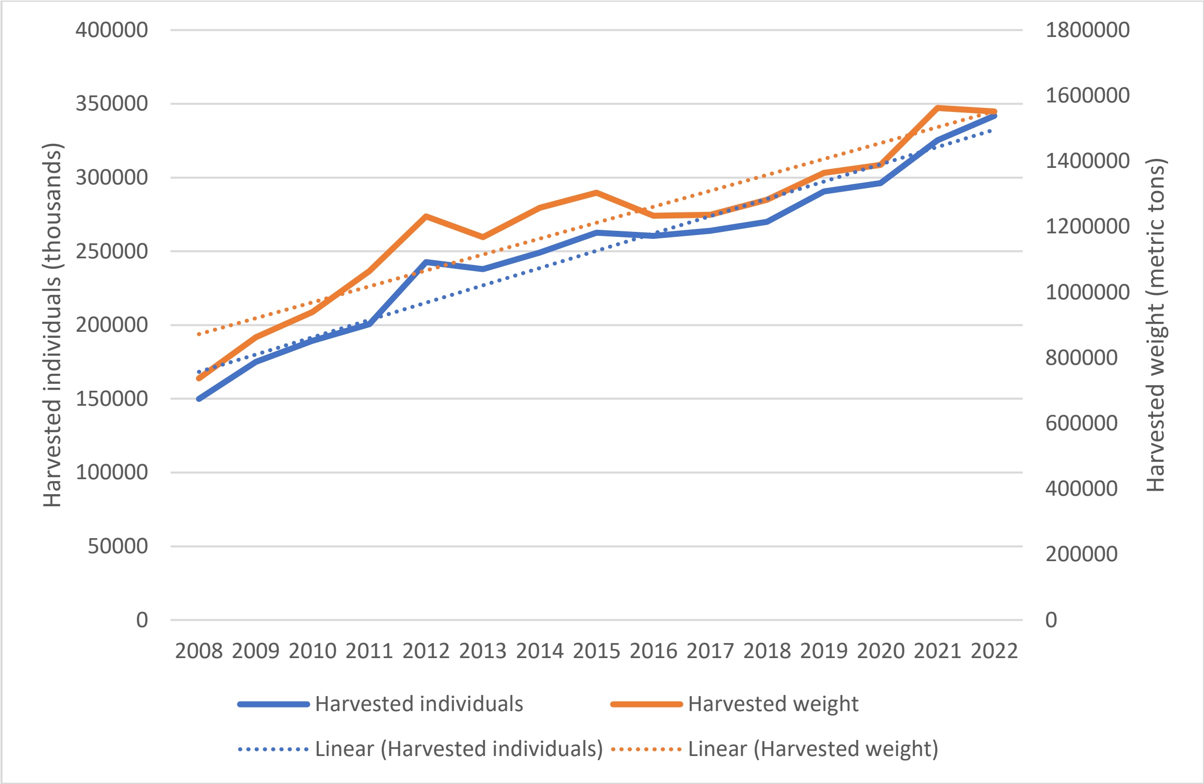

Figure 4: Harvested individuals and weight, based on aquaculture statistics. Individuals are presented in thousands. Weights are presented in metric tons round weight.

Since 2008, both harvested individuals and harvested weight have more than doubled, at increases of 128% and 110% respectively. Harvested individuals and weights follow similar patterns over the last years, illustrating that when more fish are harvested, more weight is also harvested, which is logical. It is observed that harvested individuals have increased more than harvested weight, which indicates that the average weight of harvested fish is declining.

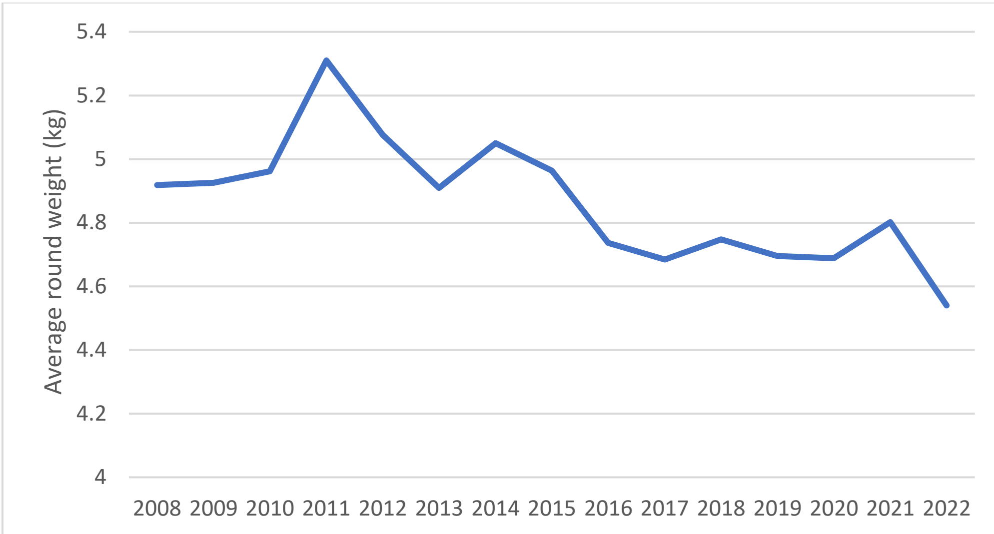

Figure 5: Average weight of harvested salmon, based on aquaculture statistics. Weights are presented in kilograms round weight.

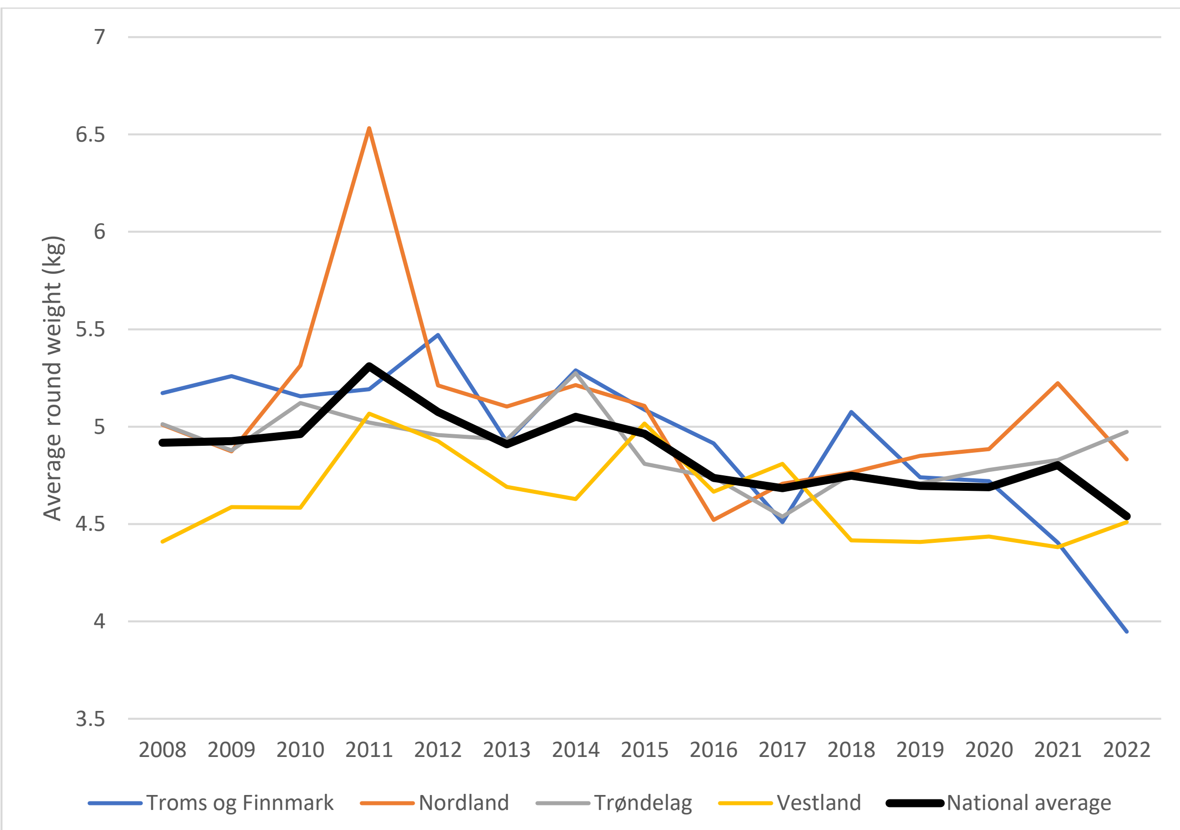

Figure 6: Average weight of harvested salmon, based on aquaculture statistics. Averages for the 4 largest counties by total harvest weight are shown together with the national average. Weights are presented in kilograms round weight.

Average weight of harvested salmon varies between years. In Figure 6, a declining trend can be seen over the 15-year period, with the lowest average weight being in 2022 at 4.54 kg. In Figure 7, the national average is shown together with the four largest counties by weight. In the period 2008 to 2022, these counties make up between 78 % and 88 % of national harvested weight each year, where each county contributes between 15 % and 25 % of the national total harvested weight each year. The remaining three counties have been omitted to improve readability.

The average weight varies within and between counties. The high national average weight in 2011 is to a large degree caused by a spike in average weight in Nordland. A high average weight is also observed in Vestland this year, but not in Trøndelag, which is located between them. The low national average weight in 2022 is to a large degree caused by a low average weight in Troms og Finnmark. Both northernmost counties, Troms og Finnmark and Nordland, exhibit decreasing averages from 2021 to 2022, but develop in opposite directions in other years. Vestland exhibits an average weight lower than the national average most years. This is also the county with the highest number of active production sites in all years. Most importantly, county averages appear to follow similar patterns of variation and general trend, with few exceptions. This suggests that the declining trend in the national average weight is caused by factors affecting the entire industry, and that no single county or counties are responsible for the decline.

4.2 Loss Numbers

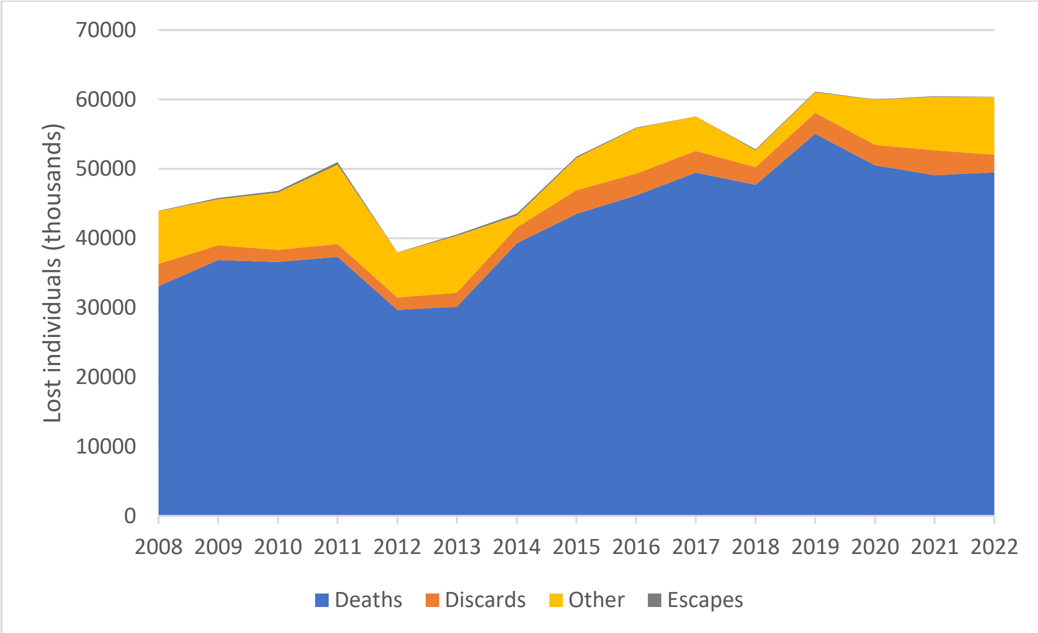

Figure 7: Losses by category. Based on aquaculture statistics.

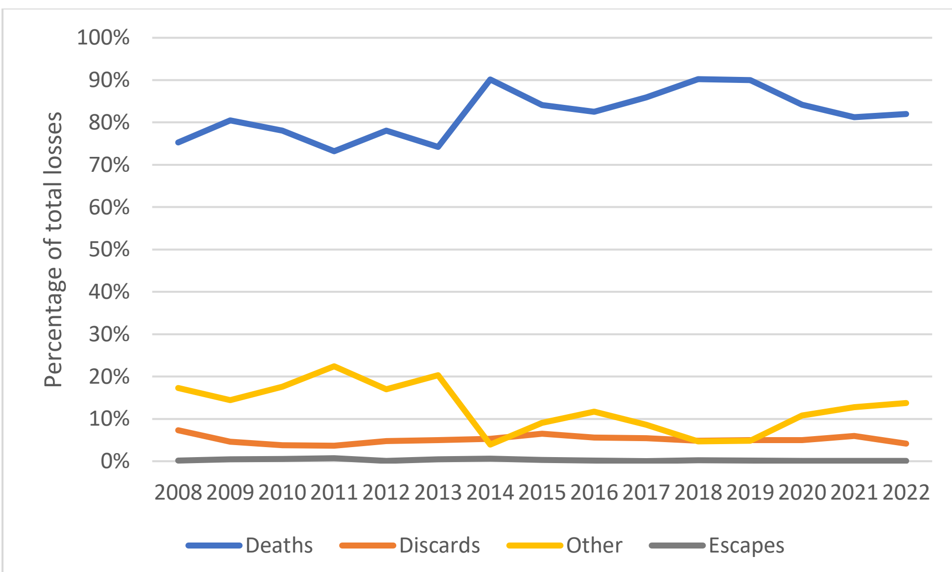

Figure 8: Loss category dominance. 100 % represents total losses in a year. Based on aquaculture statistics.

Death is the dominating loss category in all years, followed by "other" in most years. Although escapes are a significant environmental threat, it is a marginal contributor to loss numbers. Discards and escapes remain relatively constant in all years. A shift in the category dominance happens around 2013, where deaths make up a larger part, and "other" a smaller part of total losses in subsequent years. Deaths and "other" seemingly exhibit an inverse relationship, suggesting that many of the fish in the category "other" are actually deaths. It is possible that in years of underreported deaths, these losses become evident during processing, and are subsequently reported as counting errors in the category "other".

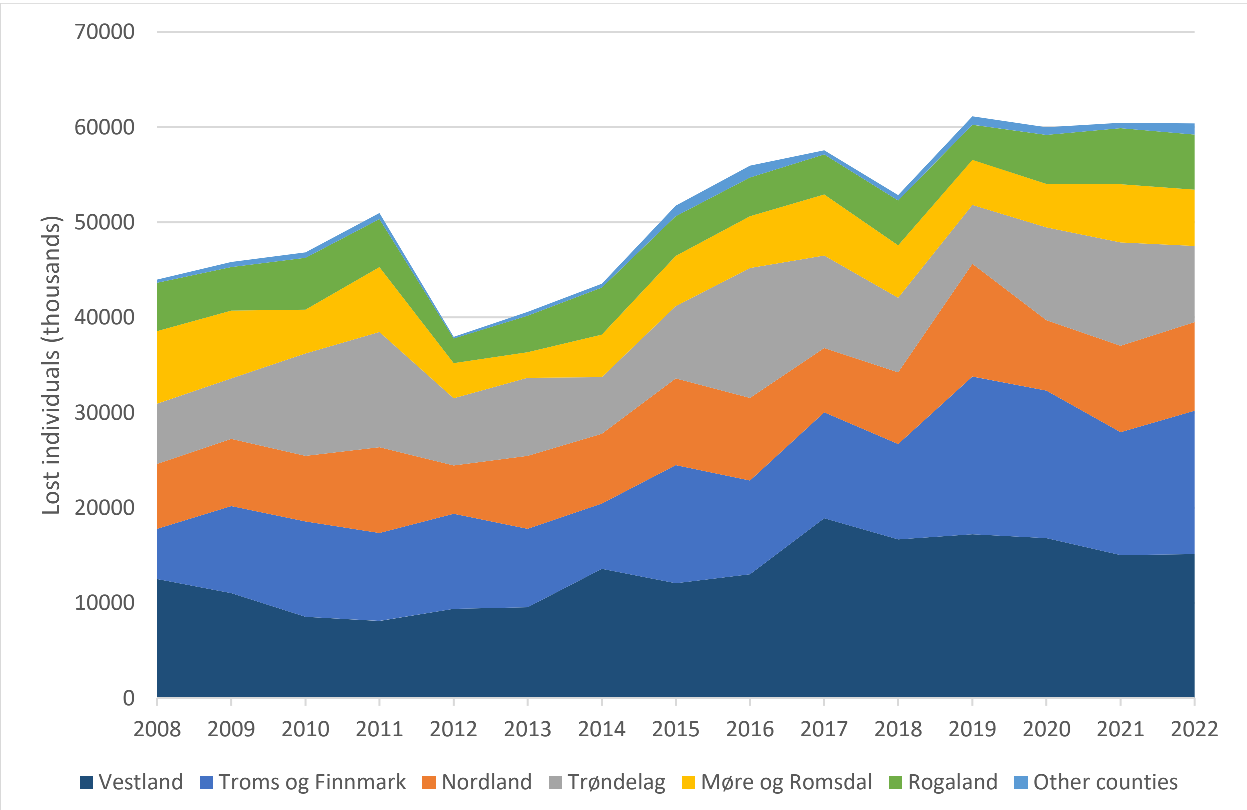

Figure 9: Losses by county. Based on aquaculture statistics.

At the county level, the four largest counties by production volume contribute to most of the losses, which is expected. However, the contribution to total losses is not equivalent to the contribution to total production. Table 1 and Table 2 illustrate these differences. Vestland has a higher ratio of losses to production output than other counties in most years, signifying high mortality rates. Nordland has a higher ratio of production output to losses in all years, contributing to a large portion of total production, but a low portion of total losses. No county contributes consistently equal to harvests and losses, indicating variations in loss rates each year.

Table 1

Ratio of harvested individuals to lost individuals, by year and county. Midpoint (neutral color) has been defined as the median value (Directorate of Fisheries, 2023a).

Harvests per loss	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Troms og Finnmark	5.5	6.7	4.0	5.4	5.6	5.9	3.8	4.1	6.4	6.0
Nordland	6.0	6.1	5.6	6.4	8.1	7.0	5.3	8.2	7.6	8.1
Trøndelag	5.6	9.9	6.9	4.0	4.3	8.6	6.9	6.9	4.8	7.8
Møre og Romsdal	9.4	5.3	6.9	3.4	5.1	2.9	8.4	3.8	6.2	3.4
Vestland	5.9	4.3	4.4	4.6	2.8	3.4	3.4	3.8	4.1	4.4
Rogaland	4.2	2.6	3.9	3.8	3.9	3.0	5.2	3.8	3.2	3.9
Other counties	7.8	11.8	3.0	2.7	7.9	4.9	4.6	2.9	7.5	3.2

Table 2

Difference in percentagewise contribution to national harvest- and loss numbers, by year and county. Zero indicates equal contribution to total harvest- and loss numbers in a year. Negative values indicate a higher percentagewise contribution to losses than harvests in a year, positive values indicate a higher percentagewise contribution to harvests than losses in a year. The table minimizes the effect of low production numbers, which is present in Table 1. Midpoint (neutral color) has been defined as zero. Based on aquaculture statistics (Directorate of Fisheries, 2023a).

Contribution diff.	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Troms og Finnmark	-1.2%	2.8%	-4.9%	2.8%	4.4%	3.1%	-5.5%	-4.3%	3.9%	1.4%
Nordland	0.4%	1.1%	1.9%	5.7%	8.9%	5.3%	2.3%	8.2%	6.1%	6.7%
Trøndelag	-0.9%	9.9%	5.2%	-3.2%	-1.2%	10.1%	4.6%	6.6%	-1.9%	5.1%
Møre og Romsdal	4.0%	-0.8%	3.7%	-2.7%	1.4%	-4.5%	5.9%	-1.7%	1.6%	-3.9%
Vestland	0.0%	-7.8%	-3.2%	-0.3%	-12.8%	-10.3%	-7.9%	-6.3%	-6.0%	-5.4%
Rogaland	-2.7%	-6.3%	-1.8%	-1.4%	-1.1%	-3.6%	0.6%	-2.0%	-4.0%	-3.0%
Other counties	0.3%	1.0%	-0.8%	-0.9%	0.5%	0.0%	0.0%	-0.5%	0.4%	-0.9%

4.3 Loss Ratios

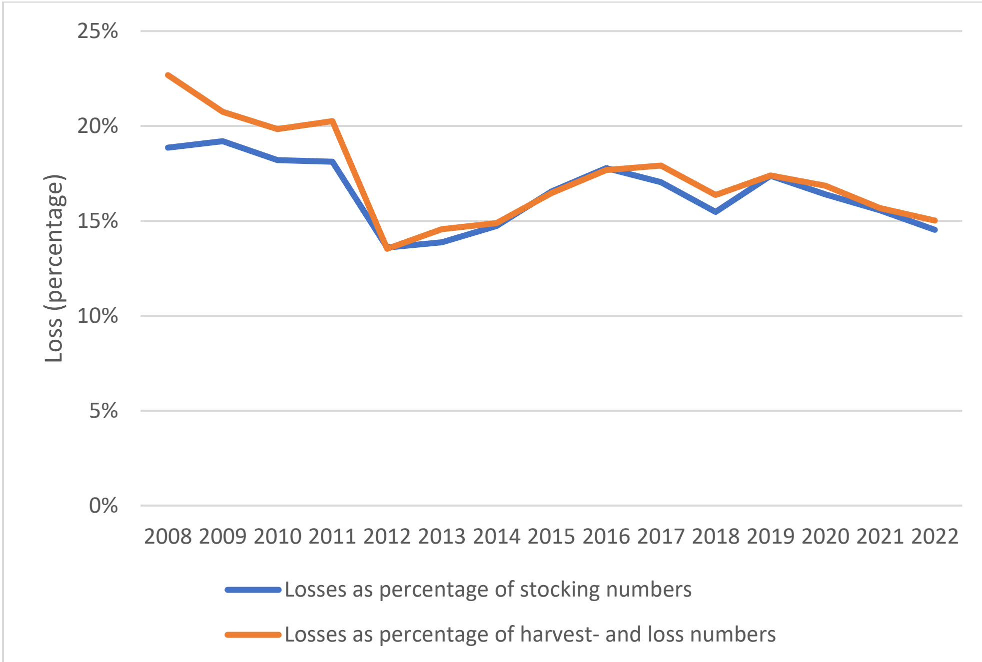

Figure 10: Losses as percentage of total stocked and total harvest- and loss numbers, based on aquaculture statistics.

After being stocked in a cage, fish exit the cage either for harvesting purposes or through becoming a loss. Losses as a percentage of the total number of fish exiting the cage in a year is presented in Figure 11. It was chosen to present losses in this manner rather than as a percentage of just harvests, as these numbers will affect each other. Harvested numbers will be lower in years of high losses, and vice versa. When presented as a percentage of stockings or harvests and losses, a declining trend in loss numbers is seen, suggesting that nationally, an increasingly larger part of the stock is harvested rather than lost.

The relationship between stocked individuals and lost individuals are also shown. The two graphs vary due to stocking numbers varying between years. If stocked individuals were increased each year, loss percentages could be misrepresented. Each graph has some limitations. It is not necessarily the case that a fish lost in one year should have been harvested the same year, or that fish stocked in one year is lost the same year. Both graphs have been included to show different perspectives of the loss quantification problem.

A third approach for loss estimation is used in the Norwegian Fish Health Report (Sommerset et al., 2023). Here, mortality rates are calculated based on reported deaths divided by the average stock present in a cage in a month, for all active production sites and all months. Average monthly mortality rates are then calculated for production zones, counties, and nationally (Norwegian Veterinary Institute, 2022). These estimations are based on cage-specific data which are not publicly available, and monthly reports of stock numbers and losses. As we have discussed earlier, these reports are associated with uncertainties and undergo quality assurance based on data obtained through individual handling during processing.

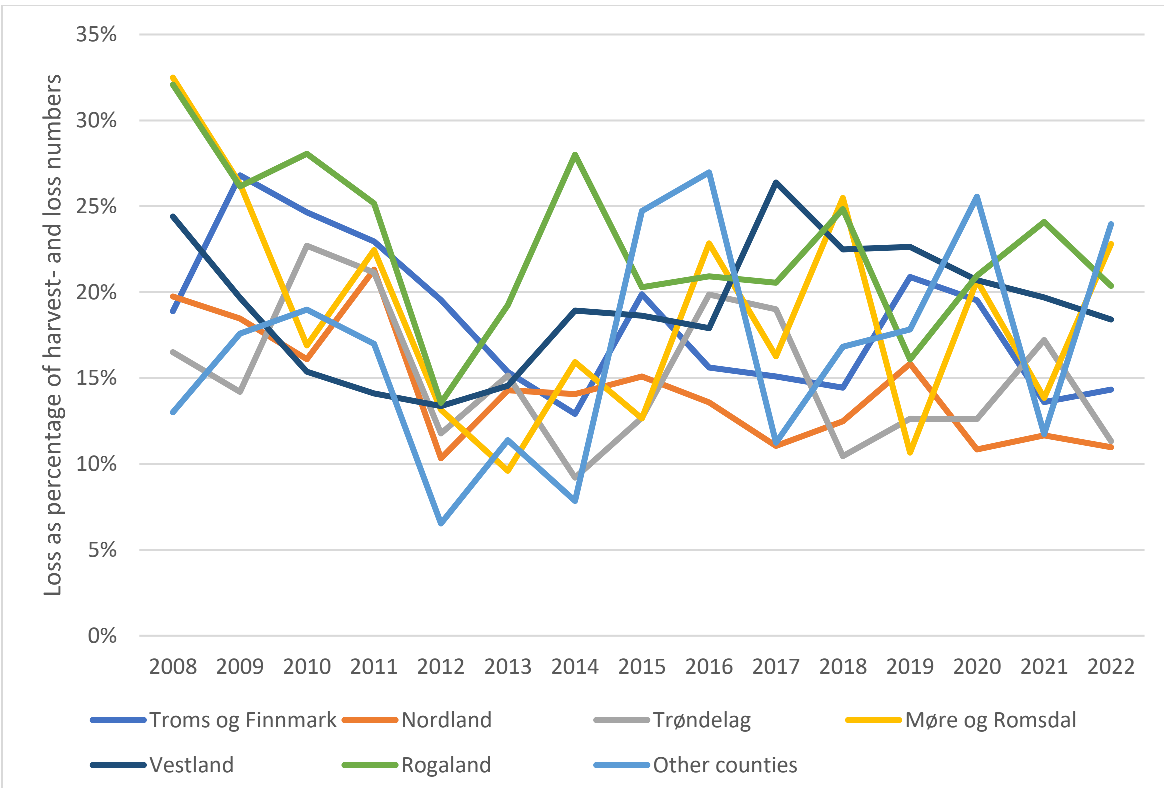

Figure 11: County level losses as percentage of total county harvest- and loss numbers. Based on aquaculture statistics.

When presented at the county level, losses as percentage of total number of fish exiting production in a year behave similarly in each county. These similarities include large variations between years, and loss percentages that commonly fall between 10 % and 25 %. “Other counties” has the largest variation, taking the lowest or highest national values in many years. This county is however responsible for 1-2 % of national production by weight each year, and a larger variation is expected in a smaller sample size. Nordland appears to be the best county in terms of loss percentage. This county has a high number of production licenses, but also large amounts of coastal space. It is located north in Norway, but south of Troms og Finnmark, where weather and temperature conditions are expected to be harsher.

Table 3 compares losses as percentage of total numbers of fish exiting production each year to production volumes and active production sites. Loss percentages are highest in the southern counties, and that production volume seemingly has no effect on loss percentage. Vestland has a high production volume and the highest number of active production sites, and a higher loss percentage than other counties with high production volume. It is possible that a high density of production sites affects losses.

Table 3

5-year loss ratios, production numbers and active production sites, by county.

County	Loss ratio 5-year avg.	Loss ratio 5-year max	Production volume (MT), 5-year avg.	Production volume (MT), 5-year max	Production sites, 5-year avg.	Production sites, 5-year max
Troms og Finnmark	16.6%	20.9%	323,691	361,624	183.6	196
Nordland	12.4%	15.8%	315,829	365,713	207.0	219
Trøndelag	12.8%	17.2%	281,479	322,784	165.6	178
Møre og Romsdal	18.7%	25.5%	131,154	205,998	89.8	120
Vestland	20.8%	22.6%	273,846	302,313	270.8	281
Rogaland	21.3%	24.8%	86,141	100,852	63.4	72
Other counties	19.2%	25.6%	17,633	24,221	9.0	10
National	16.2%	17.4%	1,429,773	1,562,415	989.2	1,015

Loss ratio at the national level is found to be 17.0% for the past 15 years and 16.2% for the past 5 years. In all counties, the majority of recorded losses comprise of mortalities. Table 4 Shows the percentage of total losses consisting of mortalities, and percentage of total fish exiting production consisting of mortalities.

Table 4

Mortalities as a percentage of losses and exits.

County	Mortalities as % of loss 5-year avg.	Mortalities as % of exits 5-year avg.	Mortalities as % of loss 2022	Mortalities as % of exits 2022
Troms og Finnmark	80.2%	13.1%	73.6%	10.6%
Nordland*	86.7%	10.7%	80.3%	8.8%
Trøndelag	90.2%	11.5%	96.2%	10.9%
Møre og Romsdal	87.1%	14.8%	81.1%	18.5%
Vestland	86.6%	18.0%	84.4%	15.5%
Rogaland	83.0%	17.5%	82.7%	16.9%
Other counties*	85.4%	17.2%	76.1%	18.2%
National	85.4	13.8%	82.0%	12.3%

* Nordland and “Other counties” have negative values for losses in the category “Other” in some years.

4.4 Errors in Reports

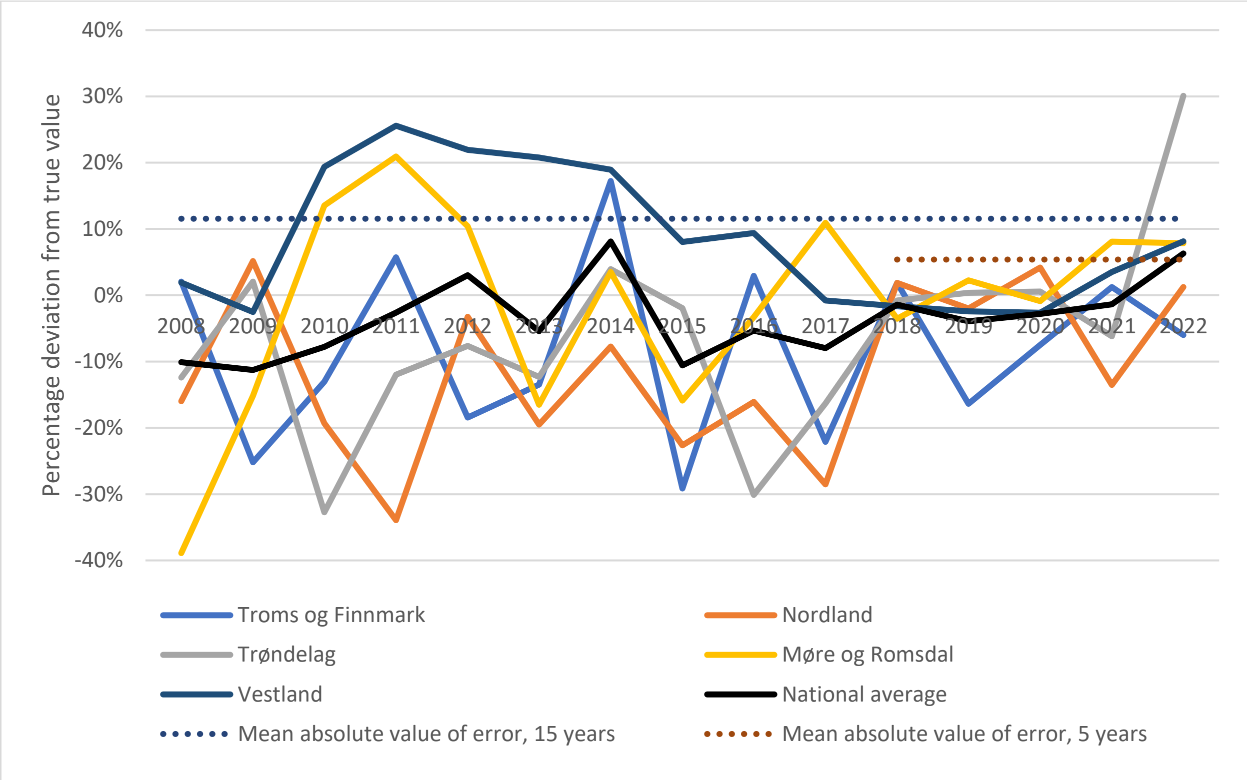

Figure 12: Errors in loss reports. Differences, measured as percentage, in biomass statistics compared to aquaculture statistics. Based on reported losses from biomass statistics and aquaculture statistics. Rogaland and "Other counties" have been omitted due to not being comparable between the two statistics.

Figure 13 illustrates the magnitude of error in reported losses. As discussed in previous chapters, reports are made according to farmers' best estimates, but exact quantity and biomass data are obtained only after harvesting. Reported values from biomass statistics deviate significantly from "true" values in aquaculture statistics in most years. On average, farmers underestimate losses most years. Mean absolute value of error percentages is found to be 5.4 % for the last 5 years, and 11.5 % for the last 15 years. Estimations have seemingly improved after 2017. The recent improvement can be explained by improvements in technology, farmers developing better routines, etc. However, the lack of precision in loss estimation and reporting is still evident. Statistics at the production zone level are only available through biomass statistics. Because losses in biomass statistics deviate significantly from what is considered to be true values, it was decided to not analyze losses at this level.

4.5 Welfare Incidents

Parties involved in Norwegian aquaculture production have a duty to report incidents that involve death, injury, or other significant negative health impacts to fish (Norwegian Food Safety Authority, 2021a). This duty exists to ensure decent treatment, while also serving as a tool for regulatory bodies to spot potential emerging diseases.

The increasing trend in welfare incidents portrayed in Figure 14 can indicate an increase in occurrence, but can also be attributed to producers becoming better at reporting. Incidents related to non-medicinal delousing with fish handling is for all years 2018 to 2022 the largest category. Although relatively stable, a peak is seen in 2019 and reports in this category have decreased since. This can suggest that farmers are improving routines for these treatments through experience, as non-medicinal delousing treatments were adapted at large by the industry in 2016-2017 (Sommerset et al., 2023).

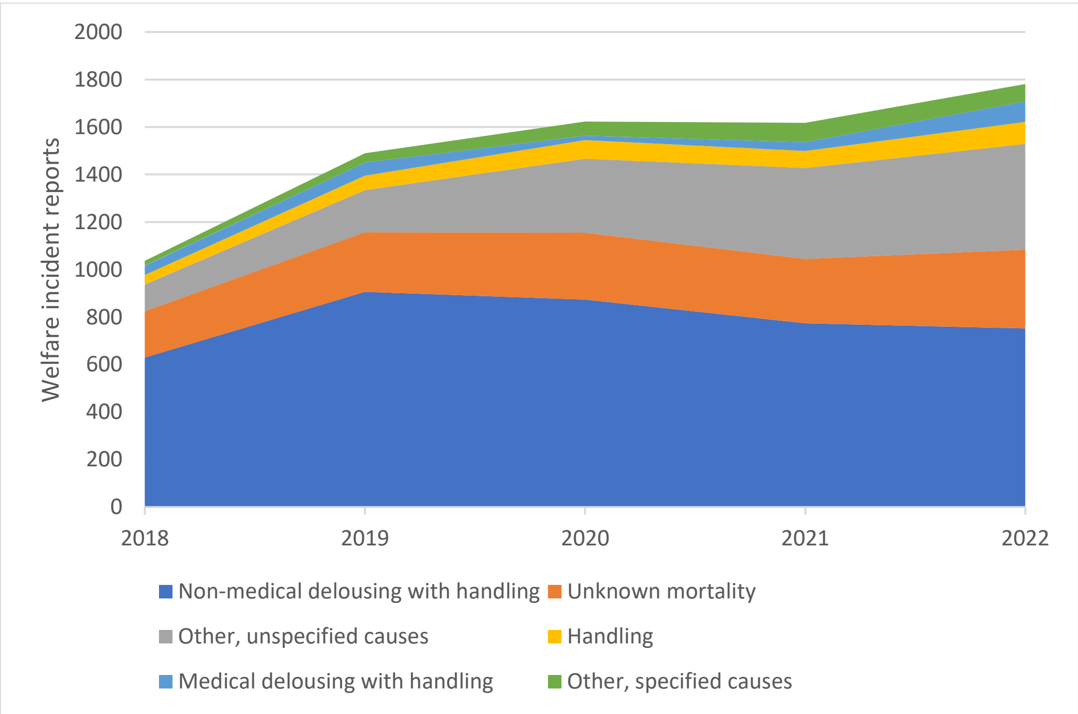

Figure 13: Number of reported welfare incidents for fish in the sea phase, 2018-2022 (Sommerset et al., 2023). "Other, unspecified causes" have been reported as such. "Other, specified causes" include incidents reported in less common categories, and have in this chart been combined to improve readability.

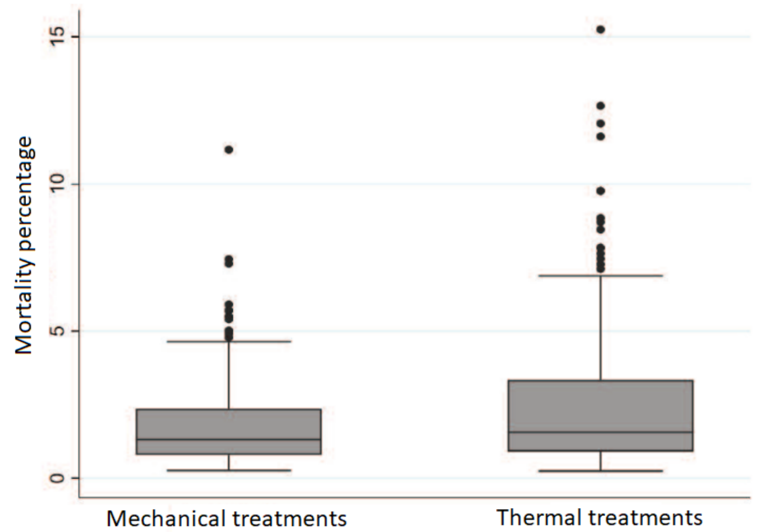

Figure 14: Reported mortality following delousing related welfare incidents (Sommerset et al., 2023). Based on reports in the category “non-medicinal delousing with handling” where treatment type was specified (n = 312 for mechanic, n = 244 for thermal).

5. Causes of Loss

In the following, the most important causes of loss in the Norwegian salmon farming industry are discussed. While statistical data allow decomposition of losses in a few major categories, it is more difficult to decompose number of deaths by cause. Deaths is the major source of FL and therefore insights into the causes of death are important. The discussion will identify major causes of death some insights into their occurrences. Moreover, production practices associated with higher mortality rates in salmon farming are discussed. Understanding these causes is important for promoting FL mitigating strategies.

5.1. Delousing Treatments

Common non-medicinal delousing treatments include thermal baths and mechanical removal by brushing lice off the fish (Sommerset et al., 2023; Walde et al., 2023). These treatments require substantial handling of the fish and carry a risk of causing negative health effects and increased mortality (Sommerset et al., 2023). In 2022, 42 % of 1781 reported welfare incidents in aquaculture production were related to non-medicinal delousing treatments (Sommerset et al., 2023). In a survey of 63 fish-health personnel for Norwegian Fish Health Report 2022 (Sommerset et al., 2023), mechanical injuries related to delousing (Norwegian: "mekaniske skader relatert til avlusing") were rated among the top causes of both mortality and reduced welfare in sea cage production of salmon.

Walde et al. (2021) investigated cage-level mortality distributions following different delousing treatments. 295 of the 717 total farms actively producing salmon in Norway during 2014-2019 supplied data for the study. In total, 4,644 delousing operations in 1,837 cohorts were analyzed. Changes to mortality rates were examined by comparing baseline mortality 7 days prior to treatments to post-treatment mortalities.

It was found that increased mortality was expected for all treatment regimens examined in the study; thermal, mechanical, hydrogen peroxide, medicinal bath, freshwater bath, and combination treatments. Thermal and mechanical treatments caused the highest increases in mortality rates, and mortalities remained higher than baselines two weeks after the treatments. High variability within, and variation between, changes to mortality rates was observed for the different treatment methods.

This can be explained by variations in the treatment method itself, health conditions of the fish prior to treatment, environmental, or managerial factors. When comparing fish of similar year- and weight classes, a decreasing trend in mortality changes was observed for thermal treatments after its introduction as a delousing method in 2015. This suggests that mortalities can decrease as farmers adapt and become familiar with new treatments (Walde et al., 2021).

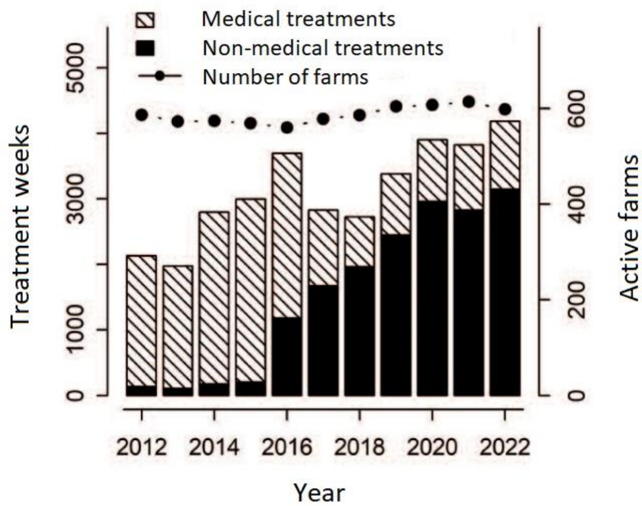

Figure 15: Lice treatment incidence duration. Adapted from (Sommerset et al., 2023). Farmers report number of weeks involving delousing treatments at locations. Exact statistics on the yearly number of delousing operations are not available.

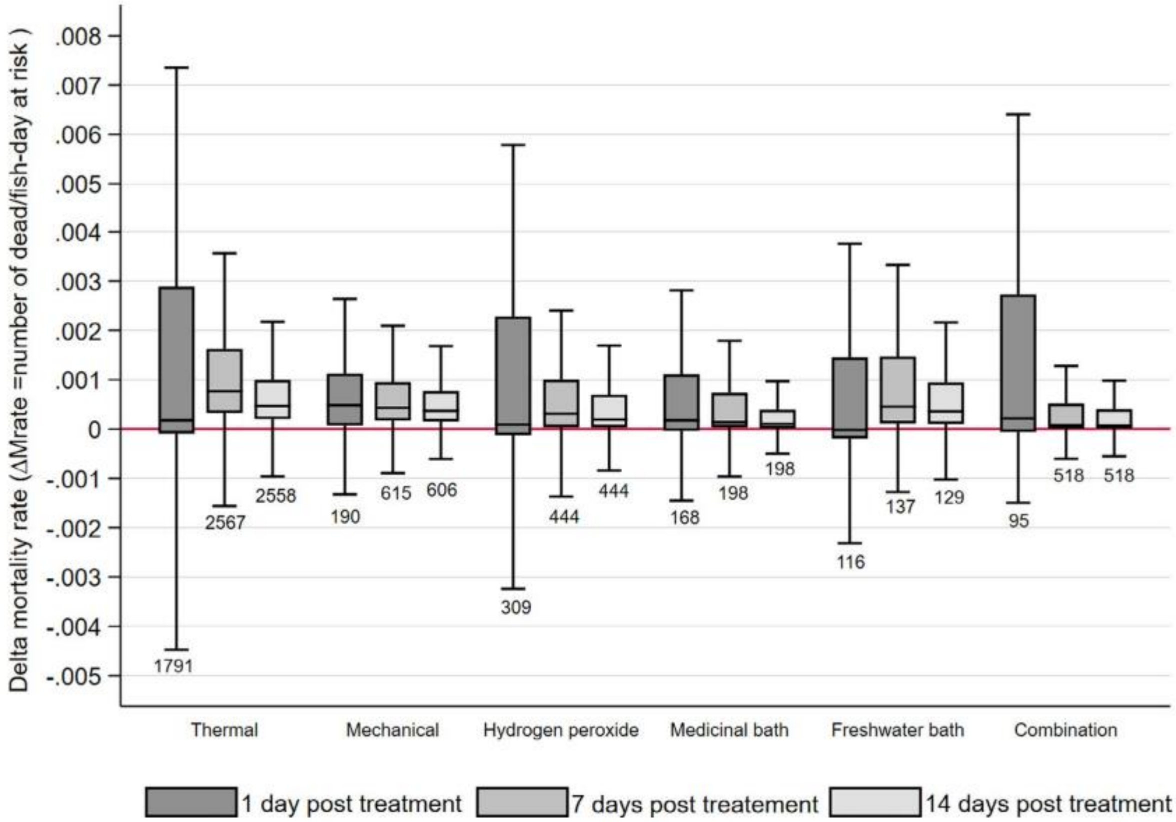

Figure 16: Boxplots of changes in mortality rates (Walde et al., 2021).

5.2. Diseases and Infections

Salmon are at risk of contracting a series of diseases and infections during production. Some of these are required to be reported to the Norwegian Veterinary Institute. Currently, there is no widely adopted system for reporting causes of loss and deaths in the industry. Health conditions are generally well documented based on disease reports and surveys, but in the absence of mortality cause reporting, diseases and infections cannot be reliably linked to mortality numbers (Sommerset et al., 2023). This chapter briefly presents some of the most important health conditions in Norwegian salmon.

Pancreas disease (PD), heart and skeletal muscle infection (HSMI), and cardiomyopathy syndrome (CMS) have been the most frequently reported health impairments in later years. In 2022, PD was detected at 98 locations, HSMI at 147 locations, and CMS at 131 locations (Grefsrud et al., 2022; Sommerset et al., 2023). For reference, 989 production locations were active at the end of 2022 (Directorate of Fisheries, 2023a). These conditions result in varying mortality rates, but stress caused during handling is often the triggering factor of mortality when these conditions are present (Grefsrud et al., 2022; Sommerset et al., 2023).

Occurrences of PD, as well as salmon lice and infectious salmon anemia (ILA), are required to be reported (Grefsrud et al., 2022). PD is linked to poor growth, reduced welfare, and increased mortality (Sommerset et al., 2023). Mortality is more common for fish in later stages of the production cycle, typically between 2-5 kg. Additionally, the possibility of developing CMS increases with days spent at sea. Underlying diseases are commonly not fatal unless stress is also inflicted. Delousing treatments subject the fish to stress, and the combination is considered to be part of the increasing mortality in salmon (Walde et al., 2021).

Occurrence of viruses late in the production cycle leads to a higher economical loss. As opposed to PD, CMS is not required to be reported, leading to a lack of knowledge on the condition. However, it is currently regarded as one of the biggest contributors to mortality in Norwegian salmon, and is present along the entire Norwegian coastline (Grefsrud et al., 2022; Sommerset et al., 2023). HSMI also does not require reporting and is comparatively less impactful in terms of mortality. Both CMS and HSMI are viral diseases, and outbreaks with heightened mortality are often triggered by inducing stress, such as in delousing treatments (Sommerset et al., 2022).

Winter ulcers is the most impactful bacterial disease. The condition becomes increasingly severe and prolonged during cold temperatures. Production zones 11 and 12 are to a larger degree faced with challenges related to bacterial diseases than the rest of the country due to longer winters and colder temperatures. The mortality associated with winter ulcers is considered to be relatively low but poses a challenge in terms of animal welfare. Moreover, farmers can incur economical losses due to downgrading of the products affected by ulceration (Wade & Weber, 2020).

In a survey conducted of fish health personnel for Sommerset et al. (2023), complex gill disease (CGD) was reported as the most important increasing health problem in Norwegian salmon. This condition can be caused by a variety of factors, including water quality, algae, viruses, or bacteria, and can occur in salmon from the fry stage and onwards. CGD is most common in southern production zones, but not subject to mandatory reporting and knowledge on the condition is limited.

Health conditions in diseased salmon often consist of a combination of factors, such as CGD in combination with HSMB and/or CMS. This can cause fish groups to be especially weak and at risk of mortality if subjected to stress. Sommerset et al. (2023) finds that individual diseases often do not lead to mortality itself, but that a combination of underlying diseases can be present in stock, and mortality can be caused by delousing operations as a triggering factor.

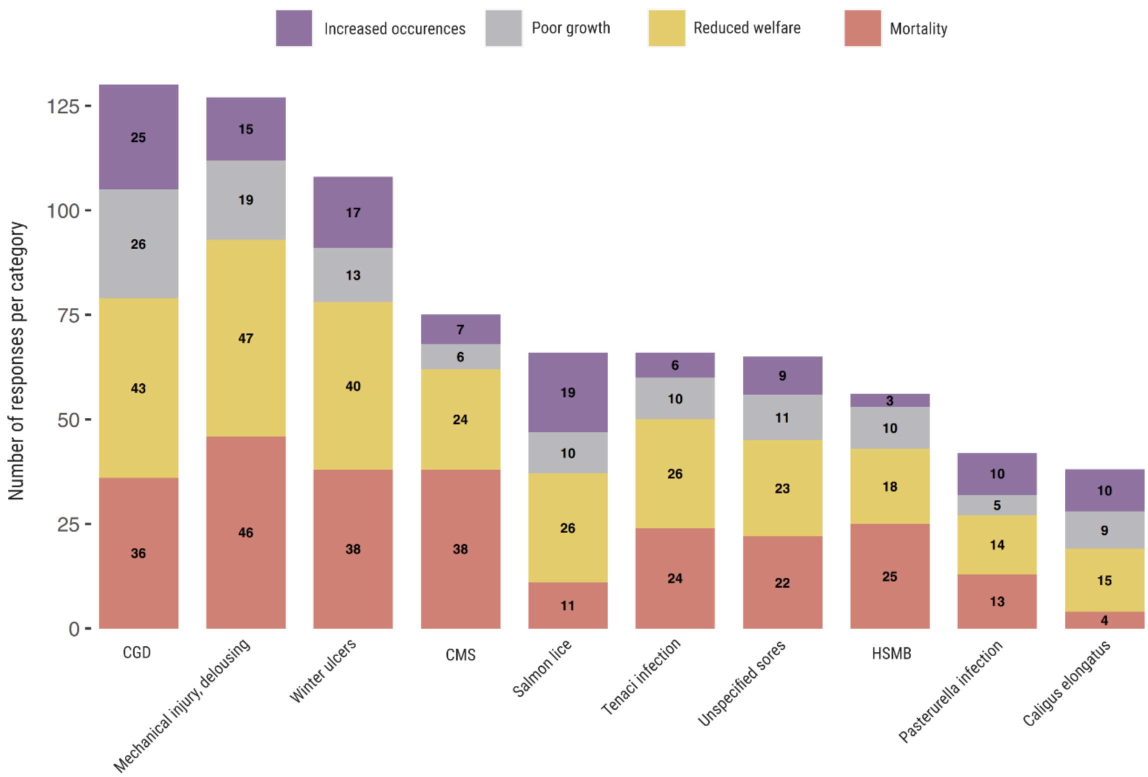

Figure 17: Ten most important health problems in farmed salmon. According to survey of 74 fish health personnel and inspectors from the Norwegian Food Safety Authority for Norwegian Fish Health Report 2022. Adapted from (Sommerset et al., 2023).

5.3. Escapes

As discussed in Chapter 4, escaped fish contribute to a small amount of total loss numbers. However, escapes remain a problem due to the threat to biodiversity and are one of many causes of loss that should be prevented. Thorvaldsen et al. (2015) identifies the prevailing challenge in preventing escapes to be human errors. Based on interviews with operators involved in escape incidents, it was found that three operations were particularly risky in terms of escapes: Handling of nets and sinker tubes (part of aquaculture cage designs), delousing treatments, and wellboat operations (Thorvaldsen et al., 2015).

These operations puts the net at risk of tearing due to various technical factors, subsequently allowing the escape of fish. Føre and Thorvaldsen (2021) found that in the period 2010 to 2018, 76 % of all escape incidents from farms at sea were directly linked to holes in the net. Bad weather is also identified as a significant factor contributing to escapes. This can occur either due to wear and tear on nets, resulting in the formation of holes, or because of adverse weather conditions negatively impacting workers' performance, potentially leading to mistakes that would not have occurred under normal circumstances. It was estimated that 27 % of fish lost to escapes had escaped during bad weather and storms (Føre & Thorvaldsen, 2021).

5.4. Spatio-Temporal Mortality

Bang Jensen et al. (2020) investigated the influence of stocking time, harvesting time, and production site location on mortality patterns (spatio-temporal mortality) in the Norwegian salmon farming industry. 23,523 monthly mortality reports for 1,474 cohorts (production cages) in 703 locations, harvested in the period from 2014 through 2018 were analyzed. Mortality rate and mortality risk (probability of a fish dying during a given month) was calculated for each month a cohort spent at sea. Mortality in relation to time of first stocking, harvesting time, and geographical location was examined.

It was found that the month of first stocking, the year of harvest, production zone, and number of months at sea were all statistically significant factors in determining mortality. Mortality varied between months and monthly mortality patterns varied between production zones. Large variations in average mortality were found between production zones.

Mortality risk was highest in the first month after stocking, when fish size is the smallest. Mortality risk decreased significantly in month 2 and was the lowest in months 3-4. A gradual increase occurs from month 5 and gets steeper around month 10. Mortality risk stabilized around month 15, but this could be a result of farmers choosing to harvest stock with high mortality. The period from month 10 to 15 coincides with a phase of production associated with elevated risks of disease, which can be part of the explanation for the increased mortality risk.

The highest average mortality was observed for production zone 3, which had the highest density of producing farms. Cohorts in this area were therefore associated with a higher risk of disease transmission from nearby producers. The second and third highest mortalities were however observed in production zones 2 and 12, where density of producing farms were low. This suggests that farm density is one of several factors impacting mortality.

Production zones 5-7, located in the middle of the country, exhibited patterns of seasonal mortality; increases were observed during both spring and fall. In production zones 9-12, located north, seasonal mortality included an increase only during spring. Production zones 2-4, located south, did not exhibit seasonal patterns. Production zones 1 and 13 were excluded from the study due to having few commercial producers.

An increase in mortality was observed for cohorts harvested 2016-2018 compared to cohorts harvested 2014-2015, resulting in average mortality increasing from 14.3 % in 2014 to 16.8 % in 2018. A possible explanation for this can be the widespread shift to non-medicinal delousing treatments in 2015.

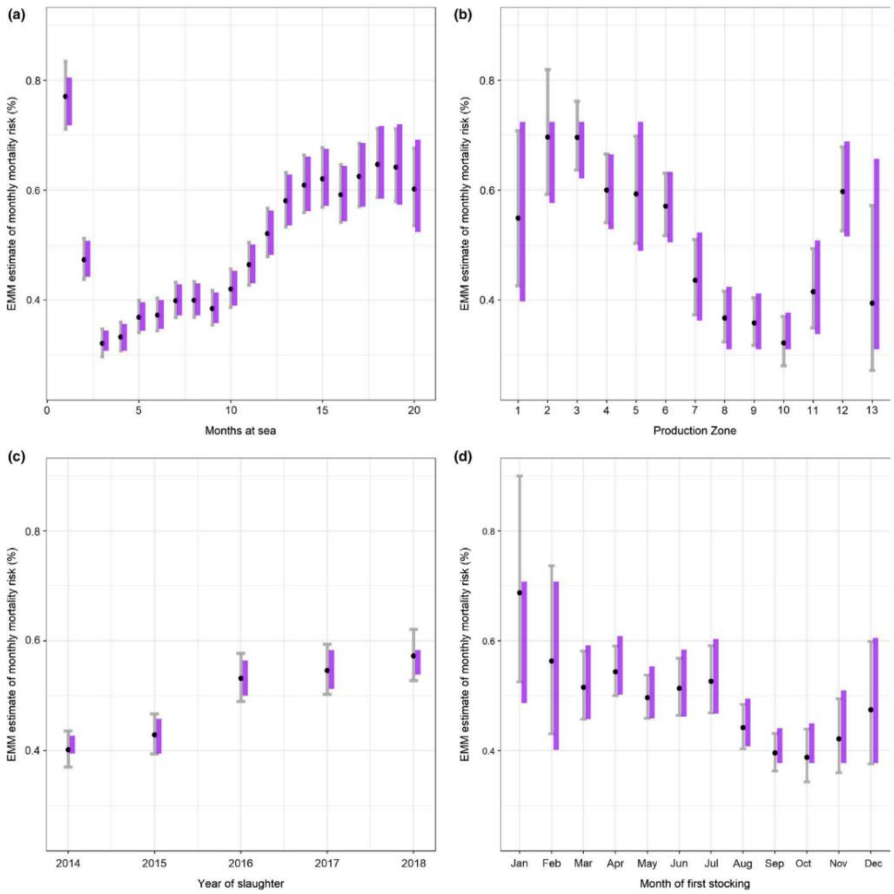

Figure 18: Monthly mortality risk modelled using estimated marginal means (EMM) (Bang Jensen et al., 2020). Grey bars mark 95 % confidence intervals. Purple "comparison bars" mark statistical significance of pairwise differences between two levels of the variable. Non-overlapping bars indicate statistical difference at the 5% level. In figure b, production zones 1 and 13 show large variation due to having few farms. In figure d, winter months show large variation due to stocking in these months being uncommon.

5.5. 2014 Food Safety Authority Study

Bleie and Skrudland (2014) investigated causes of loss during the sea phase for farmed Atlantic salmon and rainbow trout in Norway. The study investigated generations stocked autumn 2010, spring 2011, and autumn 2011, and included approximately 80 % of all fish stocked in Norway for these periods. The study was conducted retrospectively post harvesting, based on daily reports from producers submitted during production. The data included reports from 1,066 cohorts from 318 individual farms and was divided into three intervals: From initial stocking until and including three months at sea, from four months until and including 10 months at sea, and from 11 months at sea until harvesting. Atlantic salmon represented 988 of the 1,066 cohorts studied, rainbow trout represented the remaining 78.

Average registered loss was 16.3 % for salmon and 18.3 % for rainbow trout, where 100 % represents the total amount initially stocked. Unregistered loss was calculated based on harvest data and varied from 1.3 % to 2.3 % for the different stocking periods. Large variations were observed for both cohorts and localities. A small number of cohorts were found to significantly affect the average loss. By excluding the top 20 % of cohorts with the highest amounts of losses, it was estimated that average losses would be reduced by 5.3 percentage points.

Table 5 shows that the greatest losses occur for different reasons depending on location. Infections and hatchery fish cause high losses in some cohorts in all locations but have overall lower means. The highest cohort loss is registered in Mid-Norway at 71.5%, caused by mechanical injuries. Max losses for this category in other locations are significantly lower, and mean values are low compared to other categories.

Table 5

Loss percentages by cause and locations (Bleie & Skrudland, 2014).

	South-west Norway		**Mid-Norway**		**North-Norway**	
Cause:	Mean	Max	Mean	Max	Mean	Max
Miscellaneous	4.2%	15.9%	2.9%	16.9%	4.1%	22.7%
Environmental	0.3%	6.7%	0.3%	13.5%	0.4%	13.9%
Mechanical injury	1.0%	9.6%	2.1%	71.5%	1.3%	11.9%
Infections	6.9%	43.5%	5.0%	24.6%	7.2%	41.1%
Hatchery fish related	2.1%	29.2%	5.8%	47.5%	2.9%	52.6%

For salmon, average losses based on time intervals varied from 4.3 % to 5.3 %. In the interval 0-3 months at sea, quality of hatchery fish was found to be the top contributing factor. In the interval

4-10 months at sea, infections were found to be the top contributing factor. In the interval 11 months until harvest, losses were to a larger degree caused by various factors, but infections remained a top contributing factor. For losses caused by infections, Pancreas disease (PD) and winter ulcers were found to be top contributing factors, where the occurrence of the diseases varied depending on location.

It should be noted that at the time of the study, medicinal treatments for lice control were dominating in the industry (Sommerset et al., 2023). Mechanical and thermal treatments were introduced as delousing methods in later years, and the industry shifted at large from medicinal to non-medicinal treatments around 2016 (Bang Jensen et al., 2020). Recent publications indicate that in later years, losses can to a larger degree be attributed to delousing methods (Bang Jensen et al., 2020; Sommerset et al., 2023; Walde et al., 2023).

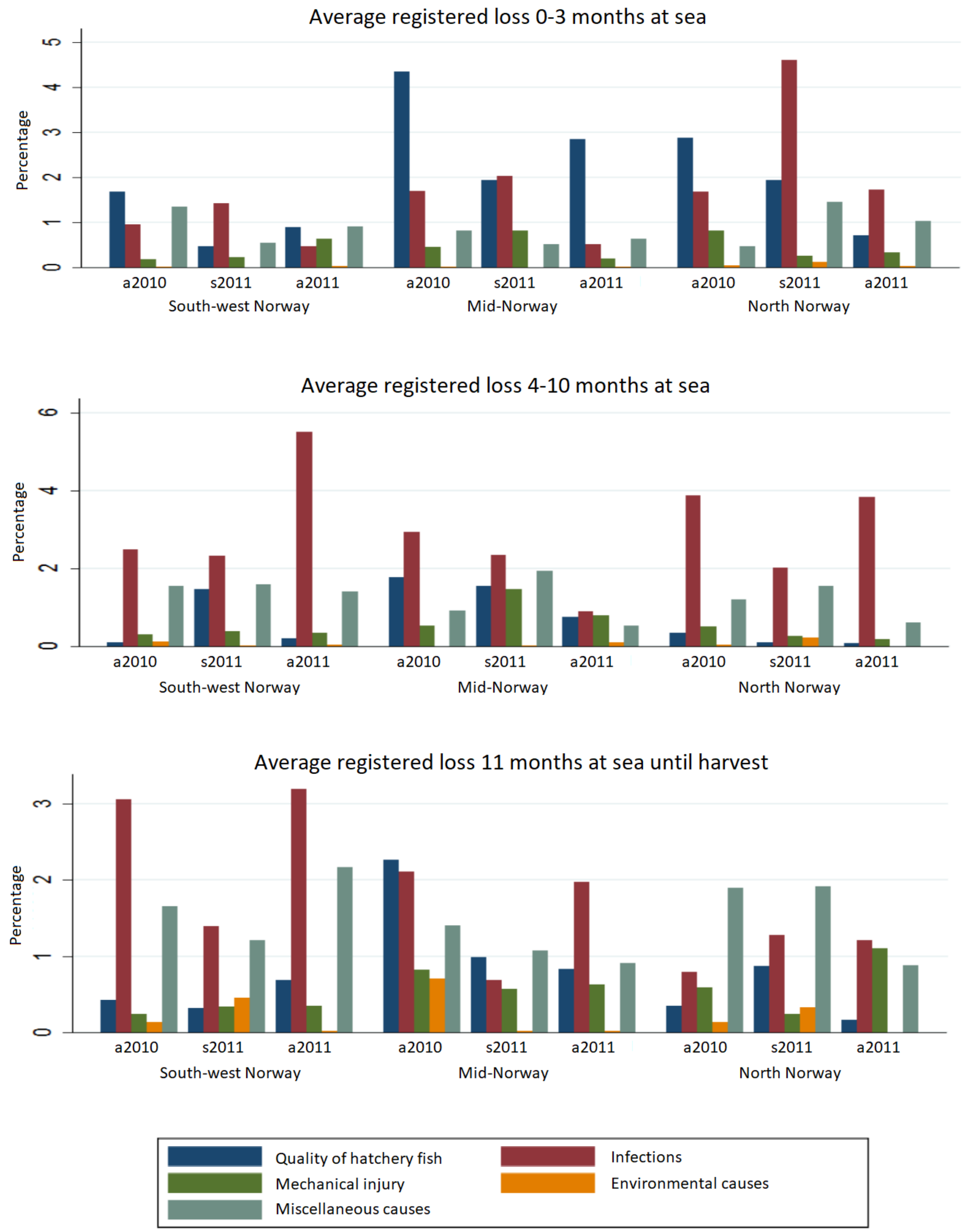

Figure 19: Causes of loss for intervals at sea, location, and generation. Adapted from (Bleie & Skrudland, 2014). 100 % represents the total amount of fish initially stocked. The data in this figure is based on reports for both Atlantic salmon and rainbow trout, where Atlantic salmon represents the majority of cohorts (988 of 1,066).

6. Discussion

Salmon farming is an intensive and complex process consisting of several stages. Multiple factors can impact losses, biomass- and quantity control over the course of production. Individual farmers have developed different operation practices and can face different challenges depending on the location of production sites. This variation and complexity make it challenging to investigate the causes of losses in salmon aquaculture.

The quantity obtained during vaccination of juvenile fish provides the only certain measurement of stock size before the fish is harvested after 1-2 years at sea. During the sea phase, there is no immediate method of obtaining the number of fish present in a cage. The size of the stock is managed by daily removal and recording of dead fish, based on numbers from the initial stocking. However, because of the large quantities often present in a cage, even small increases in mortality rates can make individual handling of losses unfeasible, subsequently requiring quantity estimation by weight.

Furthermore, losses can occur entirely without being collected by the loss collection system. Operations involving wellboats can provide opportunities to count the stock and update the registered quantity, but these measurements are associated with uncertainty and must be weighed against the quantity recorded by the production management system. Improving the precision of measurements by wellboats requires keeping fish under stressful conditions for extended periods of time, potentially causing negative health effects, as well as incurring increased costs related to labor hours. Transferring stock using wellboats is therefore often done at rates above what counting equipment can manage.

In the absence of precise quantity measurements and potential for imprecise and incomplete loss recording, it follows that as sea cage progresses, the exact size of the stock present in a cage becomes increasingly uncertain as time passes. Feed consumption can be used as an indication for errors in the registered stock size, but due to variations in feed consumption and feed conversion, this is only true for extended periods of time and/or larger errors. Studies at the cohort and cage level, and statistics at the county and national level show that farmers' reports of stock sizes are associated with significant uncertainty.

The increasing use of delousing treatments involves increased handling of the fish in the sea phase and can serve as opportunities to perform counting and measurement of the stock. However, it is usually desirable to perform these operations quickly, resulting in doing transfers at rates above what counting equipment can manage. With delousing treatments themselves being a stressor to the fish, a farmer may be opposed to the extra stress exposure counting operations can entail, especially when considering the lack of precision and uncertainty associated with such measurements.

Considering the distribution of salmon farms along the Norwegian coastline and variations in mortality across production zones, it is likely that farmers will encounter different challenges relating to loss management and quantity control. Rough weather as a limiting factor on time frames allowing safe operations is one example. Available statistics and reports show that loss quantities vary depending on locations, and that high mortality incidents can occur for different reasons depending on location.

Bjelland et al. (2012) finds that farmers successful in biomass- and quantity control maintains an active and thoughtful approach to measurement and management. It is reported that these farmers point to experience and competency, but also gut feeling as necessary success criteria (Bjelland et al., 2012). Transfer of knowledge between producers and personnel, establishment of procedures, and further development of technology is therefore warranted in the industry.

Losses at the processing stage consist of fish that for various reasons are not suitable for human consumption. By having made it all the way to the processing stage, it is implied that considerable resources have been invested into these fish. These losses could be reduced either by prevention; making sure that the fish remain suitable for consumption throughout the production process, or by earlier removal to make sure that production resources are not being wasted. Fish being discarded due to ending up on the floor during processing make up the most convincing example. However, if death and injury occurred due to factors such as handling during harvesting, losses could be reduced by altering procedures. Further investigations into harvesting procedures and discards would be beneficial here.

Estimating discard numbers based on mean weight of the harvested stock has a possibility of negatively impacting the quality of statistics. For example, if discards consist mainly of low-weight runt fish and this quantity is estimated based on the weight of harvest-sized fish, the recorded number of discards will likely be lower than the number of actually discarded individuals. In this scenario, otherwise precise quantity records will at the end of the production chain indicate that fish have gone missing. The same principle will apply for dead fish collected during the daily loss management. It is not unlikely that fish dying because of disease or infection will be of smaller size and weight than the mean in its cage. Further investigation into these losses could therefore improve quantity control and loss statistics.

Few papers have been published on the use and precision of measurement equipment in the industry, and few investigations into the accuracy of biomass- and quantity estimations have been performed. Bjelland et al. (2012) investigated solutions and challenges related to biomass control based on observations in farms and interviews with personnel from different stages of the production chain. The report was published in 2012. Aunsmo et al. (2013) investigated the accuracy and precision of stock estimations in cages at harvest-time. The cages in the study belonged to three major producers located in mid-Norway and were all harvested in 2009-2010. The industry has continued to develop since, and technological advancement in equipment is likely to have occurred since the publication of these papers. Available statistics show some improvement regarding accumulated errors in loss reports in recent years, but errors are still significant and vary for years and counties. Regulations on MAB, and economic aspects of effectively utilizing available production capacity in farms necessitates the maintenance of biomass control in the industry.

When analyzing loss statistics, losses can be quantified by several approaches. It was chosen to present and investigate the development in losses based on quality assured data on the county and national level, and to present losses as a percentage of the number of fish exiting production in a year. With this approach, a decrease in the loss of individuals is observed in the past 15 years. In the past 5 years, it is found that an average of 16.2 % of all fish exiting production is a loss. At the same time, harvested weight and harvested individuals have more than doubled. Harvested individuals have increased at a higher rate than harvested weight, and the average weight of harvested salmon is exhibiting a decreasing trend.

Losses occur for several reasons, and approximately 8 out of 10 losses occur due to mortality. On the national level, 13.8 % of fish exiting production over the last 5 years have been a loss due to mortality. Loss ratios and mortalities vary significantly for years and locations, and increased mortality rates can be caused for different reasons depending on year and location. Individual counties contribute differently to national loss and harvest numbers. Nordland is the leading county in terms of number of harvests per lost individual, and consistently contributes to a higher portion of national harvest numbers than national loss numbers. Vestland exhibits the opposite behavior, and consistently contributes to a higher portion of national loss numbers than national harvest numbers.

Nordland and Vestland are subject to different conditions in terms of environment, diseases, and density of producing farms, but the lack of recent and specific data on mortality causes makes it difficult to draw meaningful conclusions to why these differences exist. Vestland has had the highest number of active production sites over the last 5 years, suggesting that the density of farms can affect losses. However, Nordland has had the second highest number of active production sites and exhibits losses lower than counties with fewer sites.

The decreasing trend in loss of individuals and yearly mortality percentages presented in this thesis are conflicting with mortality rates published in other literature, such as the Norwegian Fish Health Report (Sommerset et al., 2023), due to different approaches of quantification. These approaches have individual benefits and limitations. The benefit of the quantification method presented in this thesis is the utilization of quality assessed data, based on numbers obtained through individual handling of the fish. The limitation is that it is based solely on fish ending its production cycle in a given year. The benefit of Sommerset et al.'s (2023) approach is that mortality rates are calculated based on monthly numbers for losses and average stock size at the cage level. The limitation is that monthly reports are associated with significant uncertainties, and not subjected to quality assessment before publishing. It is important that stakeholders are aware of the limitations in each of the quantification methods when investigating losses and mortalities.

A possible explanation for the apparent decreasing trend in losses is farmers choosing to harvest rather than treat fish groups infested with salmon lice, thereby turning fish at risk of becoming a loss into harvests. The decreasing trend in average weight of harvested salmon supports this explanation. The use of stun-boats to harvest at-risk stock can contribute to limiting losses by salvaging fish that otherwise would have to be processed as silage, but this practice implies harvesting fish before growing to the desired weight. The practice also raises animal welfare concerns, proposing that farmers' willingness to perform risky operations on weak stock may increase (Sommerset et al., 2023). The effect of diverting mortalities to harvesting numbers might cause statistics to misrepresent the state of animal welfare in the Norwegian salmon aquaculture industry.

The increasing use of delousing treatments in the industry can be attributed to several factors. Resistance to treatment regimens can build in lice, and regulations require farmers to keep lice numbers within specified levels. At the same time, the traffic light system incentivizes low lice levels through the promise of MAB increases. This can lead to farmers performing increasingly frequent treatments to obtain higher MAB levels at the expense of increased mortality, or at the expense of decreased harvesting weight through early harvest. Parts of fish groups can have underlying and possibly unknown diseases and health implications, which in conjunction with delousing treatments can lead to high mortality. The frequency of, and mortality increase associated with, delousing treatments make the salmon lice problem an important contributing factor to losses during production.

7. Conclusion

This thesis set out to explore and identify factors contributing to losses in the Norwegian salmon aquaculture industry, and assess how these losses are quantified and measured. Literature on factors affecting health and mortality in salmon, and available reports on specific causes of loss have been discussed. The different stages of the production process have been explained in detail to describe how and when losses occur, and the challenges related to measuring losses and maintaining precise biomass- and quantity control have been identified. Available statistics on losses and how these are distributed have been investigated and presented. The quality and generation of statistical data in the industry has also been assessed.

It is found that loss in the industry is generated by a complex set of mechanisms, including environmental, geographical, operational, health, and timing related factors. The majority of losses occur due to mortality during production in the sea. Salmon lice control is a major challenge in the industry, and stress inflicted during required delousing treatments is identified as an important contributing factor to mortality. Different treatment regimens are associated with different mortality increases, and non-medicinal treatments with handling of the stock lead to the highest increases in mortality. These are also the most frequently applied treatments in the industry.

High mortality incidents can occur when delousing treatments are performed in conjunction with underlying health impairments present in the fish, where the stress inflicted during treatment acts as a triggering factor. Norwegian salmon is at risk of contracting a series of diseases and infections, and complex gill disease, cardiomyopathy syndrome, and winter ulcers appear to be the most prevalent in terms of mortality. Health impairments in salmon are often a combination of several conditions. Industry regulations require reporting of some disease incidences, but currently no widely adopted system for linking mortality to diseases exist in the industry. A recommendation to aid in the generation of statistical data in the industry is therefore to implement a system to record disease incidents and related mortalities.

Losses occur with high variation between years within counties, and significant variations are seen in the ratio of harvested individuals to lost individuals within and between counties. Some counties have consistently lower numbers of losses than others, but available data do not allow making specific conclusion as to why. A system for reporting mortality causes would here too be beneficial for understanding specific drivers of losses.

On a national basis, loss numbers in the industry are exhibiting a decreasing trend. Approximately 16 % of fish is lost during production every year. However, the average size of harvested individuals is decreasing. This is likely linked to farmers performing early harvests to minimize the risk of mortality.

During production in the sea, stock size is managed based on numbers from the initial stocking and updated based on daily loss management. Losses are counted manually when occurring in small amounts, but due to the size of aquaculture cages, small increases in mortality can lead to losses being estimated by weight. Monthly reporting of stock size and losses is required by regulatory bodies, but these reports are associated with significant uncertainty. Comparison of statistics based on monthly reporting and quality assured data based on post-harvest reports reveals significant errors in reports. Existing technology for counting and measuring stock during production is both imprecise and can have negative health impacts in fish.

The industry would benefit from both increased data generation on causes of loss and mortality, and improved measurement technology for managing stock size and loss numbers. A recommendation for future research is to investigate drivers of loss through surveys or interviews with aquaculture personnel. In order to implement effective remediative measures in the industry, a solid knowledge base on specific factors driving losses is necessary.

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