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The economic impact of decreased mortality and increased growth associated with preventing, replacing or improving current methods for delousing farmed Atlantic salmon in Norway

Cecilie Sviland Walde [a,*], Britt Bang Jensen [a,b], Marit Stormoen [c], Frank Asche [d,e], Bård Misund [f], Jostein Mulder Pettersen [g]

[a] Norwegian Veterinary Institute, Elizabeth Stephansens vei 1, Ås 1433, Norway
[b] National Institute of Aquatic Resources, Technical University of Denmark, Denmark
[c] Faculty of Veterinary Medicine, Norwegian University of Life Sciences, Elizabeth Stephansens vei 1, Ås 1433, Norway
[d] School of Forest, Fisheries and Geomatics Sciences and Global Food Systems Institute, University of Florida, Gainesville, FL, USA
[e] Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway
[f] Department of Economics and Finance, University of Stavanger Business School, Stavanger, Norway
[g] PHARMAQ AS, Industrivegen 50, Overhalla N-7863, Norway

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ABSTRACT

Impacts of salmon lice is a major concern for a sustainable production of farmed Atlantic salmon in Norway. Most treatment methods for removal of salmon lice have associated increased mortality and decreased growth in a period after delousing, which affects the profitability of the farmer, and causes poor welfare and sustainability. In addition, the variance in mortality and growth, especially after non-medicinal treatment methods, is high, which makes it hard for a farmer to decide which control measure to apply to keep lice levels below the legal limit. In this study, we have applied a stochastic partial budget approach to assess the economic impact of reducing mortality and increasing growth of farmed Atlantic salmon by preventing, replacing and improving current delousing methods in Norway. We have simulated a production cycle of two different smolt-groups to find the outcome (harvested biomass, average end weight of the salmon, number of dead fish and feed consumption) of production cycles without or with two, three or four delousing treatments in the on-growing phase at sea. The results suggest that accounting for the biological losses associated with lice treatments is important when making choices of delousing strategies. The biological costs of increased mortality and decreased growth associated with especially non-medicinal treatments are expected to be high, but varies substantially. Therefore, the economic benefit of preventing or improving can also be high. The calculations imply that salmon producers could invest a considerable amount in measures for prevention or improvement of thermal treatments before break-even. For example could a farmer use on average 535,313 €/cage/ 1-yearling production in measure to prevent four thermal treatments before it is no longer economical beneficial. Depending on the performance of the four thermal treatments a farmer could use from 319,196–737,934 €/cage/ 1-yearling production on measures of improvement. Replacing one thermal treatment with another immediate treatment method has a minor economic benefit. The results further shows that sales value and feed consumption constitutes the largest share of the change in profit between different treatment regimes. The results from this study also show that not taking into account the risk of mortality and reduced growth associated with the different treatment methods of delousing, could lead to underestimating the benefit of improving, preventing and replacing treatments.

1. Introduction

There are considerable concerns regarding the sustainability of Norwegian production of Atlantic salmon, limiting growth in a highly profitable industry (Osmundsen et al., 2022; Sikveland et al., 2022). Impacts of salmon lice is one of the main concerns and is now the

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* Correspondence to: Norwegian Veterinary Institute, Thormøhlensgate 53C, 3. Floor, Bergen 5006, Norway.
E-mail address: cecilie.walde@vetinst.no (C.S. Walde).

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defining element of the regulatory system in terms of whether production will increase, remain constant or decline in each of 13 production areas (Osmundsen et al., 2020). Managing the salmon lice challenge lead to significant costs to the farmer due to lost biomass as a consequence of reduced growth and increased mortality associated with treatment (Walde et al., 2021; Walde et al., 2022), possible negative effect of treatment on the filet quality causing down-grading or reclaims, direct treatment costs such as equipment, labour and energy, as well as costs of control and prevention (Abolofia et al., 2017; Costello, 2009; Iversen et al., 2020; Iversen et al., 2017).

Production of salmon takes 2 ½– 3 years from hatching of eggs until harvest. The fish spend the first 10–16 months of their life in a land-based freshwater facility. Subsequently, groups of 150,000–200,000 salmon are transferred and stocked in open net-cages at seawater sites for an on-growing period for the remaining 14–22 months. Fish transferred to sea in the fall the same year they hatch are commonly referred to as 0-yearling, while fish transferred the spring the year after they hatched are referred to as 1-yearling. Since production at sea occur in open net cages, the salmon are exposed to seasonal environmental changes such as fluctuating water temperatures, light and salinity, in addition to different pathogens in the water column, including salmon lice.

Following its commercial breakthrough in the early 1970 s, salmon farming has developed rapidly from an owner-operated small-scale sector to a large-scale intensive production process operated by multinational companies (Asche et al., 2022). This is partly due to a number of innovations that has reduced production cost and improved competitiveness (Afewerki et al., 2023; Asche, 2008) and increased the scale of each site (Asche et al., 2013), as well as dynamic regulatory system that has facilitated this growth (Hersoug, 2021).

As in other biological production processes, salmon aquaculture is affected by different diseases. Many of the diseases are detrimental to the production as they reduce growth rates and in worst case induce mortality, thereby reducing health and welfare, increasing production cost and reducing profitability (Iversen et al., 2020). However, production losses also create economic incentives to prevent or treat the diseases, and a rapidly increasing knowledge base has improved the industry's ability to do so (Afewerki et al., 2023).

As production has increased, so has the salmon biomass along the Norwegian coast. In turn, this has increased the number of hosts for different pathogens, causing a challenge to the salmon industry itself as well as an externality to wild salmon occupying the same waters (Dean et al., 2021). The most important challenge is the ectoparasite salmon lice, *Lepeoptheirus salmonis,* which due to its potential impacts on wild salmon is the main factor in the regulatory system in terms of determining the industry's production growth (Osmundsen et al., 2020). The regulations of lice in farmed salmonids aim to protect both the farmed salmon and reduce the spill-over effect of infestation to wild stocks (Forskrift om lakselusbekjempelse, 2016; Jeong et al., 2023). In Norway, salmon producers are obliged by law to maintain lice levels below a legal maximum limit (Forskrift om lakselusbekjempelse, 2016). If the number of lice increases beyond the salmon's ability to compensate, it can cause pathology and eventually death (Pike and Wadsworth, 1999).

For many years, the infestation pressure of lice was kept under control by different medicinal feed or bath treatments. However, during 2000–2012 the lice developed resistance against most of these active substances (Myhre Jensen et al., 2020). From 2015, the dominating treatment practice thus shifted from medicinal treatments to non-medicinal treatments involving heated baths (thermal treatment) and flushing or brushing the lice of the fish (mechanical treatment) (Overton et al., 2018). While a variety of methods exist for the management of salmon lice, including the utilization of cleaner fish, the implementation of preventative measures such as semi-closed and submerged cages, and geographical management strategies, there is often a requirement for one or several immediate treatments (Barrett et al., 2020). Currently, the control of salmon lice consists of a mixture of several different preventive measures and immediate treatments, mostly non-medicinal.

An important part of the salmon lice challenge is high mortality due to handling and subsequent treatment of the salmon, especially in the last period of the on-growing phase at sea (Aunsmo et al., 2023; Bang Jensen et al., 2020; Oliveira et al., 2021; Overton et al., 2018; Persson et al., 2022; Pincinato et al., 2021; Tvete et al., 2023; Walde et al., 2021). The mortality experience after the non-medicinal treatment methods is shown to be many times higher compared to the medicinal treatment methods (Walde et al., 2021).

Another important part of the salmon lice challenge is the lost growth potential of the farmed salmon due to a period of feed withdrawal prior to treatment and appetite drop after treatment (Walde et al., 2022). It has been argued that the focus on lice in the regulatory system and treatments against salmon lice are some of the reasons for the observed declining size at harvest in Norwegian salmon aquaculture (Barrett et al., 2022; Oglend and Soini, 2020). In addition, delousing treatments may have negative effects on filet quality due to injuries and wounds caused by the delousing operation (Gismervik et al., 2019; Thompson et al., 2023).

The increase in mortality and decrease in fish growth affects the profitability of the farmer as it reduces production (Abolofia et al., 2017). However, there is a large variability in the experienced mortality after different delousing treatments, and the effect on growth can vary substantially between the different delousing treatments (Walde et al., 2021; Walde et al., 2022). The uncertain effect on mortality and growth from a delousing treatment can therefore make it hard for a farmer to decide which control measure to apply to keep the levels of lice below the legal maximum limit.

The objective of the present study is to describe the impact on profits over a single production cycle of salmon, from either 1) preventing treatments; 2) replacing treatments with other treatment methods; or 3) improving treatments by including the biological losses of increased mortality and decreased growth associated with different delousing treatments.

2. Material and methods

2.1. Bio-economic modelling

In the present study we apply a stochastic partial budgeting approach. Partial budgeting is a well-known economic tool to support decision-making processes in different areas of animal production (Aunsmo et al., 2010; Pettersen et al., 2016; Pettersen et al., 2015; Rushton, 2009). This tool quantifies the economic consequences of a specific change in the production procedure by comparing the negative and positive impacts to find the economic net benefit of the change. This analysis does not describe the profitability of a production cycle, but rather how profits are affected by choice of treatment method against salmon lice.

For the partial budgeting analysis, we applied a bio-economic model that consisted of several scenarios, where a scenario was defined as the comparison of a single production cycle of either a 1 or 0-yearling with different delousing treatment regimes. The biological input variables were based on distributions from two datasets, one describing mortality and the other describing production and growth of salmon from stocking until harvest. The biological output variables from the simulated production cycles and economic input variables were used to calculate the economic positive and negative impacts of changing a treatment regime. The main output of interest was the economic net benefit of a scenario, expressed as the change in profit.

The bioeconomic model was built in Excel (Microsoft Corporation) with the Monte Carlo simulation add-in tool @Risk (Palisade Corporation, NY, USA) which enables risk analysis by substituting single point estimates of uncertain inputs with distributions sampled randomly by several iterations per simulation.

2.1.1. Data/material

Norwegian salmon farming companies record data of their production, such as number of stocked fish, average fish weight, feeding (type and amount), mortality, treatments, environmental data etc. at the cage-level (NFD, 2008). The dataset in this study is based on daily data from three large Norwegian Atlantic salmon farming companies (companies operating more than 20 sites) and has previously been applied in Walde et al. (2021) (dataset I) and Walde et al. (2022) (dataset II). The dataset includes cage-level historical production data related to production and salmon lice treatments.

The dataset applied in Walde et al. (2021) (dataset I) describe estimated distributions of change in mortality rate after 4,644 delousing operations. This change was calculated by subtracting the mortality rate seven days after delousing with the mortality rate seven days before delousing. Walde et al. (2021) describes the equation for calculating the change in mortality rate, and the background for choosing a seven-day interval (briefly; choosing a seven day interval before and after the treatment minimises the risk of introducing effects of other diseases or treatments, while still providing a sufficiently long period for single-day variations to not influence the results too much). In the current study an additional 165 treatments were excluded from the dataset described in Walde et al. (2021) due to missing values for change in mortality rate seven days after treatment. The final dataset I consisted of 4,479 treatments of 1,756 fish-groups from four year-classes, 2014–2017, and 158 sites. The estimated distributions of change in mortality rate (Δmortrate) stratified on treatment method was used as stochastic input variable in the bio-economic model.

Walde et al. (2022) (dataset II) estimated the short-term effect of different delousing methods on growth. The dataset applied in this study contained the same source of data as the one applied in Walde et al. (2021) (dataset I), however only those groups of fish that could be traced from the time of stocking until harvest were included in the study. The growth rate was expressed as the thermal growth coefficient (TGC) (Cho, 1992). This was calculated by subtracting the seven-day mean of daily TGC after delousing by the five-day mean of daily TGC before delousing. Walde et al. (2022), describes the calculation of change in growth rate and the background for the choice of time interval. In the current study, an additional five fish-groups were excluded due to production length shorter than 200 days. In addition, 21 fish-groups only had treatments against amoebic gill disease (AGD) during the production cycle, and these were also excluded. The final dataset II consisted of 609 fish-groups, 302 1-yearlings and 307 0-yearlings. These came from four year-classes, 2014–2017, and 94 different sites. They were treated a total of 2,281 times. The estimated distributions of change in average daily growth rate (ΔTGC) stratified on treatment method was used as stochastic input variable in the bio-economic model in addition to other biological variables describing production.

2.1.2. Delousing treatments

The treatment methods used were thermal, mechanical, hydrogen peroxide bath, freshwater bath and medicinal bath. Table 1 shows the different categories applied and number of delousing operations within each category. The medicinal treatments were combined in one treatment category, as there were too few treatments for each compound to include them separately. Handling is assumed to be the main driver of mortality during medicinal delousing, regardless of active substance used. However, it was not possible to categorise delousing as treatment in cage or well-boat, as this information was not consistently recorded (Walde et al., 2021; Walde et al., 2022).

Table 1
Categorization (n = 5) of the immediate treatment operations of farmed Atlantic salmon in three Norwegian companies from 2014 to 2019.

Categories of treatment operations	Description of category of delousing operation
Thermal	Non-medicinal treatment using heated seawater. Includes all treatments using: a. Optilice ® b. Thermolicer c. Heated seawater
Mechanical	Non-medicinal treatment using brushing or flushing. Includes all treatments using: a. FLS Avlusersystem b. Hydrolicer c. SkaMik d. Flushing or mechanical treatment
Hydrogen peroxide	Hydrogen peroxide (H2O2) bath in cage or well boat against salmon lice
Freshwater bath	Freshwater bath in cage or well boat against salmon lice
Medicinal bath	Medicinal bath in cage or well boat using one of the following active substances: a. Azametiphos b. Cypermethrin c. Deltamethrin d. Imidaclorid e. Other f. Cohorts treated with two different combinations of active substances a-e or hydrogen peroxide and one of the active substances a-e

2.1.3. Biological input parameters

The biological input variables in the model were: number of stocked salmon, number of production days, estimated average weight at stocking, month of stocking, average monthly seawater temperature at 3 m depth, baseline monthly mortality (%), baseline monthly growth rate (expressed as TGC), days of feed withdrawal prior to treatment, biological feed conversion ratio (bFCR), change in mortality rate (Δmortrate) and change in growth rate (ΔTGC) (Table 2).

The input values for change in mortality (Δmortrate) and growth (ΔTGC) was made stochastic by representing these inputs as distributions (Table 2). This was done by applying the observations of Δmortrate (dataset I) and ΔTGC (dataset II) for each treatment method. Distributions for Δmortrate and ΔTGC were fitted based on the observations using the function "Fit" in @Risk. The distribution fit with the lowest Akaike information criterion value was preferred. To avoid unreasonable values and heavy tails, each distribution was truncated at the minimum and maximum values in the respective datasets after the distributions were fitted. Correlation between the input variables Δmortrate and ΔTGC (n = 2 281) was calculated using the "correlate" command in Stata (StataCorp, 2017). The distributions were sampled randomly by 10,000 iterations per simulation.

The value for the deterministic biological input variables; number stocked, weight at stocking, month of stocking, length of production and days of starvation were chosen based on descriptive statistics of dataset II. The deterministic input value for each of these variables was chosen based on the most representative measure of the underlying distribution, which was either the approximate mean or the approximate median value. The average monthly temperature was estimated by averaging the monthly temperatures for observations in year 2017 and 2018. The 1-yearlings had a mean stocking weight of 133 g and the 0-yearlings of 109 g. In the model, the stocking weight for both smolt types was set to 100 g for ease of comparison of the two smolt types. The baseline mortality percent ($\text{mort}_{\text{baseline}}$) and growth rate ($\text{TGC}_{\text{baseline}}$) defined mortality and growth in months without treatments. The mean growth rate from stocking until first treatment was close to normally distributed, with a mean of 2.9. However, the value of 2.8 was chosen as the baseline in the model to ensure that harvested weight between both smolt types was within the same weight category. The biological feed conversion (bFCR) ratio varied according to the inbound weight of the fish each month. All the monetary values were recorded as Norwegian kroner (NOK), but converted to Euro (€), where 1 € = 10.104 NOK (yearly average 2022).

2.1.4. Biological output parameters

The biological output parameters from the different production

Table 2
Overview of the variables used in partial budget model. The variables are equal for both 0 and 1-yearling unless otherwise is specified. D=deterministic, S=stochastic. All prices are expressed as 2022-NOK.

Variable	Value used in model	Source	Type	Distribution (value from data)
Number of stocked	150, 000	Dataset II	D	Mean (158,909)
Production days	488	Dataset II	D	Mean (483 days)
Average weight at stocking	100 g	Dataset II	D	Median (104 g)
Month of stocking 1-yearling/0-yearling	April/August	Dataset II	D	Mean (April/August)
Temp per month (°C)	Jan.= 6.2, Feb.= 5.1, March= 4.2, April= 5.2, May= 8.2, June= 9.9, July= 12.0, Aug= 14.7, Sept= 13,9, Oct= 12.3, Nov= 9.8, Dec= 7.5	Dataset II	D	Mean month temp 2017 and 2018
Days of increased mortality/decreased growth after treatment	7	Walde et al. (2021) Walde et al. (2022)	D	
Baseline monthly mortality	0.2%	Oliveira et al. (2021)	D	
Baseline monthly growth	2.8	Dataset II	D	Mean (2.9)
Days of feed withdrawal prior treatment	5	Dataset II	D	Mean (5.6)
Biological feed conversion ratio (bFCR)	Skretting's Relative Growth Index Table	(readimage.aspx (skrettingguidelines.com)	D	
Change in mortality rate (Δmortrate) seven days after treatment				
Thermal	0.000766	Dataset I	S	Laplace Truncated (−0.0169, 0.0347)
Mechanical	0.000646	Dataset I	S	Loglogistic Truncated (0.0075, 0.0706)
Hydrogen peroxide	0.000727	Dataset I	S	Loglogistic Truncated (−0.0054, 0.0637)
Freshwater	0.0000905	Dataset I	S	Loglogistic Truncated (−0.0032, 0.0265)
Medicinal	0.0000105	Dataset I	S	Laplace Truncated (−0.0054, 0.0266)
Change in growth rate (ΔTGC) seven days after treatment				
Thermal	-0.95581	Dataset II	S	Normal Truncated (−3.9846, 2.9028)
Mechanical	-0.92332	Dataset II	S	Logistic Truncated (−3.5377, 1.8403)
Hydrogen peroxide	-0.56656	Dataset II	S	Logistic Truncated (−3.4213, 1.8779)
Freshwater	-0.88385	Dataset II	S	Pert Truncated (−2.6792, 1.1462)
Medicinal	-0.36908	Dataset II	S	Logistic Truncated (−3.7493, 4.3831)
Feed prices (p_{feed})	14.60 NOK/kg dryfeed	Intrafish.no Ilaks.no	D	
Handling dead cost (p_{mort})	2.12 NOK/kg round weight	Pettersen et al. (2015)	D	
Harvesting cost (p_{harv})	4.05 NOK/kg round weight	(Pettersen et al., 2015)	D	
Treatment cost (p_{treat})	NOK/kg live weight			
Thermal	0.37	Iversen et al. (2017)	D	
Mechanical	0.26	Iversen et al. (2017)	D	
Hydrogen peroxide	0.50	Iversen et al. (2017)	D	
Freshwater	1.33	Iversen et al. (2017)	D	
Medicinal	0.37	Iversen et al. (2017)	D	
Sales price (p) per weight class	NOK/kg head on gutted (HOG) week 47, 2022	NASDAQ NASDAQ Salmon Index (nasdaqomxtrader.com)		
3–4	76.53		D	
4–5	79.90		D	
5–6	85.72		D	
6–7	96.00		D	
7–8	99.31		D	
8–9	100.86		D	
9 +	101.99		D	

cycles were the harvested weight (Eq. 1.1) and biomass (1.5), and accumulated amount of feed used (Eq. 1.6) at the end of each production cycle.

The weight gain in a non-treatment month was calculated by setting the TGC in Eq. 1.3 equal to $TGC_{baseline}$ the entire period of the month. The weight gain (wg_t) during a treatment month was calculated in three steps:

1) During feed withdrawal ($wg_{t\ starv}$): A treatment is initiated by a period of feed withdrawal. During this period, the TGC in Eq. 1.3 would be equal to zero, thus the weight gain ($wg_{t\ starv}$) would also be zero.
2) Post treatment ($wg_{t\ post\ treat}$): The weight gain seven days ($t = 7$) after a treatment ($wg_{t\ post\ treat}$) was calculated by substituting TGC in Eq. 1.3 with $TGC_{post\ treat}$ (Eq. 1.4).
3) For the remaining part of the month ($wg_{t\ rem}$): After the period of feed withdrawal and post treatment period ($t = 14$), the weight gain

in the remaining part of the month ($wg_{t\ rem}$) was calculated by setting the TGC in Eq. 1.3 equal to the $TGC_{baseline}$ and t = number of remaining days within the treatment month. This implies an assumption of no compensatory growth after a treatment.

$$weight_{harvest} = weight_{stocking} + \sum_{T=1}^{n=17} (wg_{t\ starv} + wg_{t\ post\ treat} + wg_{t\ rem}) \tag{1.1}$$

$$weight_{T} = weight_{T-1} + wg_{t\ starv} + wg_{t\ post\ treat} + wg_{t\ rem} \tag{1.2}$$

$$wg_{t} = weight_{t-1} - \left\{ weight_{t-1}^{\left(\frac{1}{3}\right)} + \left(\frac{TGC}{1000} x\ temp_{T} * t \right)^{3} \right\} \tag{1.3}$$

$$TGC_{post\ treat} = TGC_{baseline} + \Delta TGC \tag{1.4}$$

T = month, t = days, n = number of months, wg= weight gain, with withdrawal period default = 7 days, post treatment period default = 7 days, temp = average monthly temperature, post treat = post treatment, rem = remaining (weight gain remaining period).

The mortality rate, Δmortrate, was transformed to an incident risk (Toft et al., 2004) and the monthly inbound number of fish (N_T) was calculated by subtracting the baseline mortality and the number of dead seven days after a treatment from the inbound number of fish the previous month (N_T-1) (Eq. 1.5). In no-treatment month Δmortrate would be equal to zero. It was assumed that the treatments occurred in the beginning of the month, initiated by the pre-treatment feed withdrawal period of five days. This generated a small bias in number of dead, as both the baseline mortality and the treatment mortality was calculated from the inbound number at the start of the month. However, the accumulated effect from four treatments was minor and consistent across all scenarios, and the bias thus regarded of unimportant to the modelled outcome.

$$N_T = N_{T-1} - (mort_{baseline} \times N_{T-1}) - (N_{T-1} \times e^{-\Delta mortrate \times t}) \tag{1.5}$$

$$aB = \sum_{T=1}^{n=17} (N_T \times weight_T) \tag{1.6}$$

aB= accumulated biomass, n = number of months

$$aFeed = \sum_{T=1}^{n=17} \left(\frac{wg_T}{1000} \times bFCR \right) N_T \tag{1.7}$$

aFeed= accumulated amount of feed in kg, bFCR= biological feed conversion ratio

$$aBDead = \sum_{T=1}^{n=17} \left[weight_T ((mort_{baseline} \times N_T) + (N_T \times e^{-\Delta mortrate \times t})) \right] \tag{1.8}$$

aBDead= accumulated biomass of dead, n = number of months

$$aBTreat = \sum_{T=1}^{n} (weight_T \times N_T) \tag{1.9}$$

aBTreat = accumulated treated biomass, n = number of treatments.

2.1.5. Economic input parameters

The price components in the model were: feed (p_{feed}) handling of dead fish, (p_{mort}), harvesting, (p_{harv}), and treatment (p_{treat}) (Table 2). The feed prices were expressed as NOK /kg dry feed. The handling of dead fish and harvesting prices were expressed as NOK/ kg produced round weight (Pettersen et al., 2015). Price of different treatment methods per kg treated fish (p_{treat}) were obtained from Iversen et al. (2017). These estimates included the cost of mortality per kg treated fish, and were equal for thermal, mechanical and freshwater treatments, 0.17 NOK/kg treated. The cost of mortality was subtracted from these numbers since treatment specific mortality was retrieved from dataset I (Table 2). All the prices were adjusted for inflation to 2022 NOK using the monthly consumer price index reported by Statistics Norway. The price increase from 2015 and 2017–2022 was 22.8% and 16.4%, respectively.

Since the objective was to estimate the economic benefit (ΔΠ) of a change, only variable costs from delousing operations were included in the model and it was assumed that fixed costs would not change between different treatment methods or production cycles of same length.

Salmon prices for different weight classes were provided from Nasdaq (NASDAQ Salmon Index (nasdaqomxtrader.com)). The Nasdaq Salmon indices consists of 11 individual price indices for weekly reported sales prices of Norwegian farmed salmon of the highest quality classification called superior quality (Table 2). Nine of the indices are prices for nine different weight categories (1–2, 2–3, 3–4, 4–5, 5–6, 6–7, 7–8, 8–9 and 9 + kilograms), while the other two are weighted average prices across all, or a selection of the most sold (3–6 kilos), weight categories. In the model, the sales price (p) was made dependent on harvested weight, using the Nasdaq price categories for different weight categories. The spot sales prices for week 47, 2022 was used as input in the model (Table 2).

2.1.6. Economic output parameters

The cost of handling dead fish (M_{cost}), harvesting cost (H_{cost}), feed cost (F_{cost}) and treatment cost (T_{cost}) were calculated by Eqs. 1.10–1.13. The harvested weight and biomass, and accumulated biomass of dead fish was converted to head on gutted (HOG) or round weight as appropriate, by using a conversion factor of 1.067 or 1.2, respectively (Directorat of Fisheries, 2019). The main output variable of interest, the difference in profit (ΔΠ) (Eq. 1.14) was calculated for each scenario.

$$M_{cost} = \frac{aBDead}{1.07} \times p_{mort} \tag{1.10}$$

$$H_{cost} = \frac{aB}{1.07} \times p_{harv} \tag{1.11}$$

$$F_{cost} = aFeed \times p_{feed} \tag{1.12}$$

$$T_{cost} = aBTreat \times p_{treat} \tag{1.13}$$

$$\Delta\Pi_{scen\ n} = \left\{ \left(\mathrm{p} \times \frac{\mathrm{aB}}{1.2} \right) - (M_{cost} + \mathrm{H}_{\mathrm{cost}} + F_{cost} + T_{cost}) \right\}_{prod\ x} - \left\{ \left(\mathrm{p} \times \frac{\mathrm{aB}}{1.2} \right) - (\mathrm{M}_{\mathrm{cost}} + \mathrm{H}_{\mathrm{cost}} + F_{cost} + \mathrm{T}_{\mathrm{cost}}) \right\}_{prod\ y} \tag{1.14}$$

Scen = scenario, n = scenario number, prod = production cycle.

We assumed the entire harvested biomass to be classified as “superior” quality, the harvested weight of each fish within the fish-group to be the same as the average weight of the fish-group, and the weight of the dead fish to be the same as the average weight of the fish-group the month of death. We further assumed that the (bFCR) was not affected by the treatments.

2.1.7. Modelled production cycle and baseline treatment regime

The number of treatments during a production cycle, when they occurred, the time elapsed between treatments and the type of treatments was defined as a treatment regime. The treatment regime was selected by descriptive statistics of dataset II. In dataset II, the most common type of treatment in the recent year classes (2016 and 2017) was thermal treatments, and the fish groups were on average treated four times during the production cycle. For both smolt types, half of all treatments were performed 20–40 days apart, and number of days from last treatment until harvest was positively skewed with a mode of 31 days. The occurrence of the treatments, however, differed between the smolt types (Fig. 1). The temperature ranged from the lowest temperature in March of 5.3°C to a peak in August of 14.4°C. The highest occurrence of treatments for the 1-yearling is in April (n = 129) and for the 0-yearling in September (n = 202). The selected baseline treatment regime in the model was therefore four thermal treatments that occurred in the second year in sea for both smolt types (Fig. 1). The 1-yearling was treated in April, May, June and July and harvested one month later (Fig. 1). The 0-yearling was treated in August, September, October and November and harvested one month later (Fig. 1). The production at sea lasted for 488 days for both smolt types, and both were treated for the first time 365 days after stocking. The weight of the 1-yearling ranged from 2.5 kg to 3.4 kg and for the 0-yearling 2.3 –3.8 kg in the treatment months.

2.1.8. *Scenarios*

A production cycle with the baseline treatment regime was compared with a production cycle where one or several of the thermal treatments were either prevented, replaced or improved. In scenario 1 the baseline treatment regime was compared with a production cycle without treatments. In addition, we also compared four mechanical treatments to a production cycle without treatments (scenario 2). In scenario 3 and 4, two out of four thermal treatments were prevented, either the first and second or the third and fourth. In scenario 5 and 6 one out of four thermal treatments was prevented, either the first or the fourth. In scenario 7–10 the first thermal treatment was replaced with either a mechanical (scenario 7), hydrogen peroxide (scenario 8), freshwater (scenario 9) or medicinal bath (scenario 10). In scenario 11–13 we looked at the variance in profit if four thermal treatments were within the 5% worst performing treatments with respect to mortality and growth of the salmon, compared to an expected performance (scenario 11), expected compared to 5% best (scenario 12) and 5% worst compared to 5% best (scenario 13). Altogether, this created 13 different scenarios listed in Table 3.

2.2. *Sensitivity analysis*

To assess the effect from varying the values of the deterministic input variables on the output value, sensitivity analyses were performed on the following input variables: baseline growth rate, baseline mortality, days of feed withdrawal, and feed and sales prices. The range of the low and high input values for the variables in the sensitivity analyses was based on the descriptive statistics of dataset II and literature. Baseline growth rate was assumed to be normally distributed in the sensitivity analysis, with 5th and 95th percentiles set to 2.3 and 3.2 for TGC. Monthly mortality was assumed a uniform distribution with a minimum of 0.1 and a maximum 1.0%. Days of feed withdrawal had a uniform distribution with minimum four and maximum seven days of feed withdrawal. Feed prices were assumed a triangular distribution with + /- 20% min/max, and sales prices were assumed a triangular distribution with + /- 40% min/max. The regression coefficients of the input variables were compared in a Tornado chart by applying the function for sensitivity analysis in @Risk.

In dataset I and II, there were < 14 observations of thermal treatments in the year 2014. We suspected that these might have an effect on the expected output, as the mortality after these treatments was quite high. We therefore compared the output with and without these

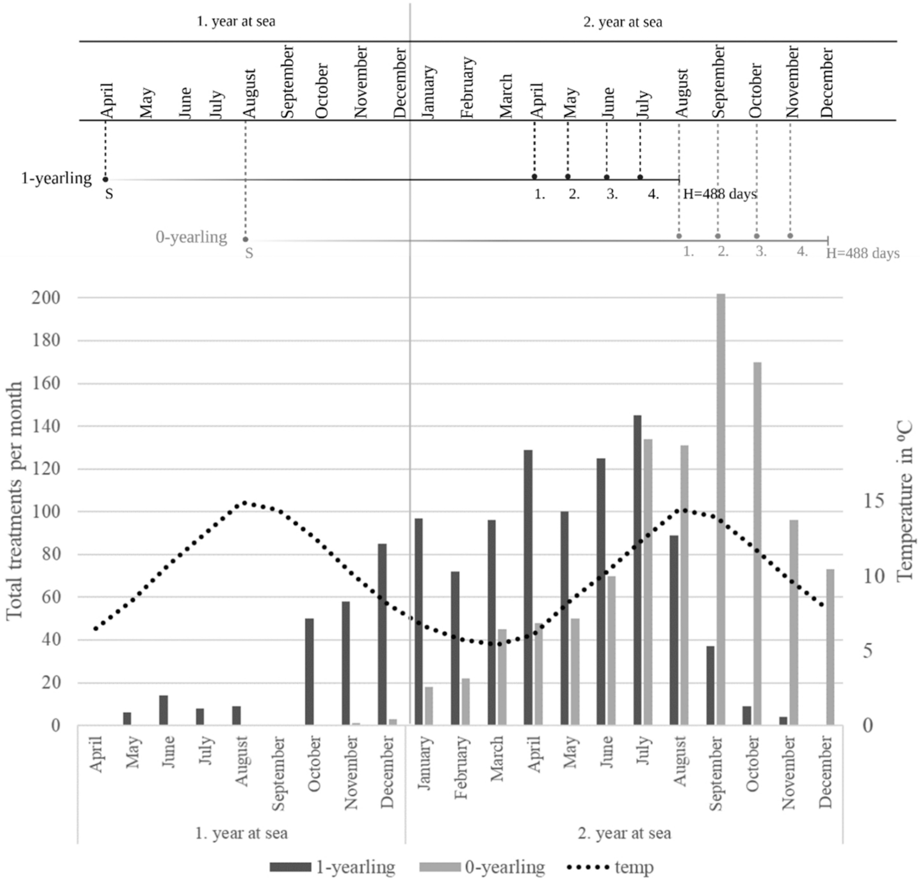

Fig. 1. Shows the modelled production cycle of the two smolt types with month of stocking (S), treatment months (numerated 1–4), and month of harvest (H), in addition to description of the seasonal change in temperature in Celsius degrees (dotted line) and the total number of treatments per month categorised by smolt types (bar graph) from dataset II. Created with BioRender.com.

observations.

Table 3

The different scenarios (n = 13) for both 1 and 0-yearling. Scenario 1, and 3–10 are compared with the baseline scenario that involves four thermal treatments. In contrast, Scenario 2 is compared with four mechanical treatments. The scenarios are categorised based on three criteria: prevention, replacement or improvement. Finally, the improvement scenarios (11–13) specifically compares the 5% worst, expected, and 5% best outcomes derived from the Monte Carlo simulation.

	Description of scenario	Scenario number
Prevent	No treatments (All four thermal treatments removed)	1
	No treatments (All four mechanical treatments removed)	2
	First two (2/4) thermal treatments removed	3
	Last two (2/4) thermal treatments removed	4
	First (1/4) thermal treatment removed	5
	Last (1/4) thermal treatment removed	6
Replace	First (1/4) thermal treatment replaced with one mechanical treatment	7
	First (1/4) thermal treatment replaced with one hydrogen peroxide bath	8
	First (1/4) thermal treatment replaced with one freshwater bath	9
	First (1/4) thermal treatment replaced with one medicinal bath	10
Improve	4/4 thermal treatments, 5% worst compared to expected	11
	4/4 thermal treatments, expected compared to 5% best	12
	4/4 thermal treatments, 5% worst compared to 5% best	13

3. Results

3.1. *The economic benefit (ΔΠ) of changing delousing treatment regime*

For all scenarios, except scenario 9, the most important driver for the expected economic benefit of a change in treatment regime, is the increase in revenue, followed by increased feed costs in scenario 1–6 (Table 4). For scenario 9 (replacing a thermal treatment with a freshwater treatment), the increase in treatment cost is the most important driver. The higher feed cost in scenario 1 and 2 is a result of reduced mortality and higher growth rate, which result in increased feed consumption and subsequently a larger biomass at the time of harvest.

The change in profit for most measures are slightly higher for the 0-yearling compared to the 1-yearling (Table 4).

The economic benefit of changing the delousing treatment regime varies, especially regarding the prevention of four thermal treatment (Fig. 2).

The measures ranged by positive economic benefit are prevention, improvement and replacement.

3.1.1. *Prevention*

The model does not include the direct costs of various preventive measures because of the uncertain effect on reduction in number of immediate treatments as well as the direct costs. The economic benefit would therefore indicate how much a farmer could use on preventive measures per cage before it is no longer economical beneficial. Preventing or avoiding thermal and mechanical treatments has a large expected economic positive benefit (Table 4, scenario 1–6). For instance, the expected increase in profit by preventing four thermal treatments is 535,313 €/cage/production cycle for a 1-yearling and 692,346 for a 0-yearling (Table 4).

For 1-yearlings, preventing the last or the last two treatments (scenario 6 and 4) have a greater effect than preventing the first or the first two treatments (scenario 5 and 3) (Table 4 and Fig. 2). For the 0-yearling, this is opposite; preventing the first or the first two treatments have a greater effect than preventing the last or the last two treatments (Table 4).

3.1.2. *Replacement*

For both smolt types, the model shows that replacing the first thermal treatment with another treatment measure has a minor expected economic positive benefit, compared to the other measures of preventing or improving (Table 4, scenario 7–10). In fact, replacing a thermal treatment with a freshwater treatment (scenario 9) has a modelled expected negative benefit (Table 4).

Table 4 shows, that for the 1-yearling replacing the first thermal treatment with a mechanical treatment has a modelled greater positive impact compared to replacing it with a hydrogen peroxide treatment. This is the opposite for the 0-yearling where replacing the thermal treatment with a hydrogen peroxide treatment has a greater positive impact on profit change compared to replacing it with a mechanical treatment.

3.1.3. *Improvement*

The direct cost of improving treatments is not included in the model, thus the economic benefit of improving indicates what could be spent per cage per production cycle before break even. Improving treatments have a high economic impact, especially if the farmer is able to improve the baseline treatment regime of four thermal treatments from being

Table 4

Shows the expected total change in costs, revenue and profit for the different scenarios in Euro (€). Scenario 11–13 are not included as they reflect the variance in scenario 1. A negative sign indicates a decrease in cost or revenue.

€ total	1-yearling									
Scenario no	1	2	3	4	5	6	7	8	9	10
Costs										
Feed	152,708	150,369	60,445	94,835	26,151	49,003	574	2,005	- 137	5,117
Treatment	- 53,552	- 43,588	- 22,427	- 29,272	- 10,702	- 8,828	- 2,165	6,725	37,154	2,171
Slaugther	38,244	37,073	14,741	22,541	5,966	12,068	265	538	- 175	1,946
Mortality	- 1,839	- 1,542	- 749	- 849	- 354	- 549	- 63	- 15	74	- 339
Revenue	670,874	650,322	258,585	395,409	104,647	211,696	4,650	9,446	- 3,070	34,134
Profit *(ΔΠ)*	535,313	508,011	206,574	308,153	83,586	160,002	6,039	193	- 39,985	25,239
€ total	0-yearling									
Scenario no	1	2	3	4	5	6	7	8	9	10
Costs										
Feed	211,795	209,332	121,728	83,367	62,284	35,665	819	5,360	526	10,008
Treatment	- 57,460	- 46,790	- 20,271	- 33, 231	- 8, 073	- 17,682	- 1,991	6,440	34,570	2,335
Slaugther	51,066	49,804	28,217	21,170	14,365	9,641	334	1,388	- 15	3,222
Mortality	- 1,959	- 1,636	- 663	- 1,160	- 254	- 620	- 61	- 5	75	- 322
Revenue	895,786	873,654	494,974	371,364	251,981	169,119	5,851	24,353	- 271	56,518
Profit *(ΔΠ)*	692,346	662,944	365,963	301,218	183,659	142,115	6,751	11,169	- 35,426	41,275

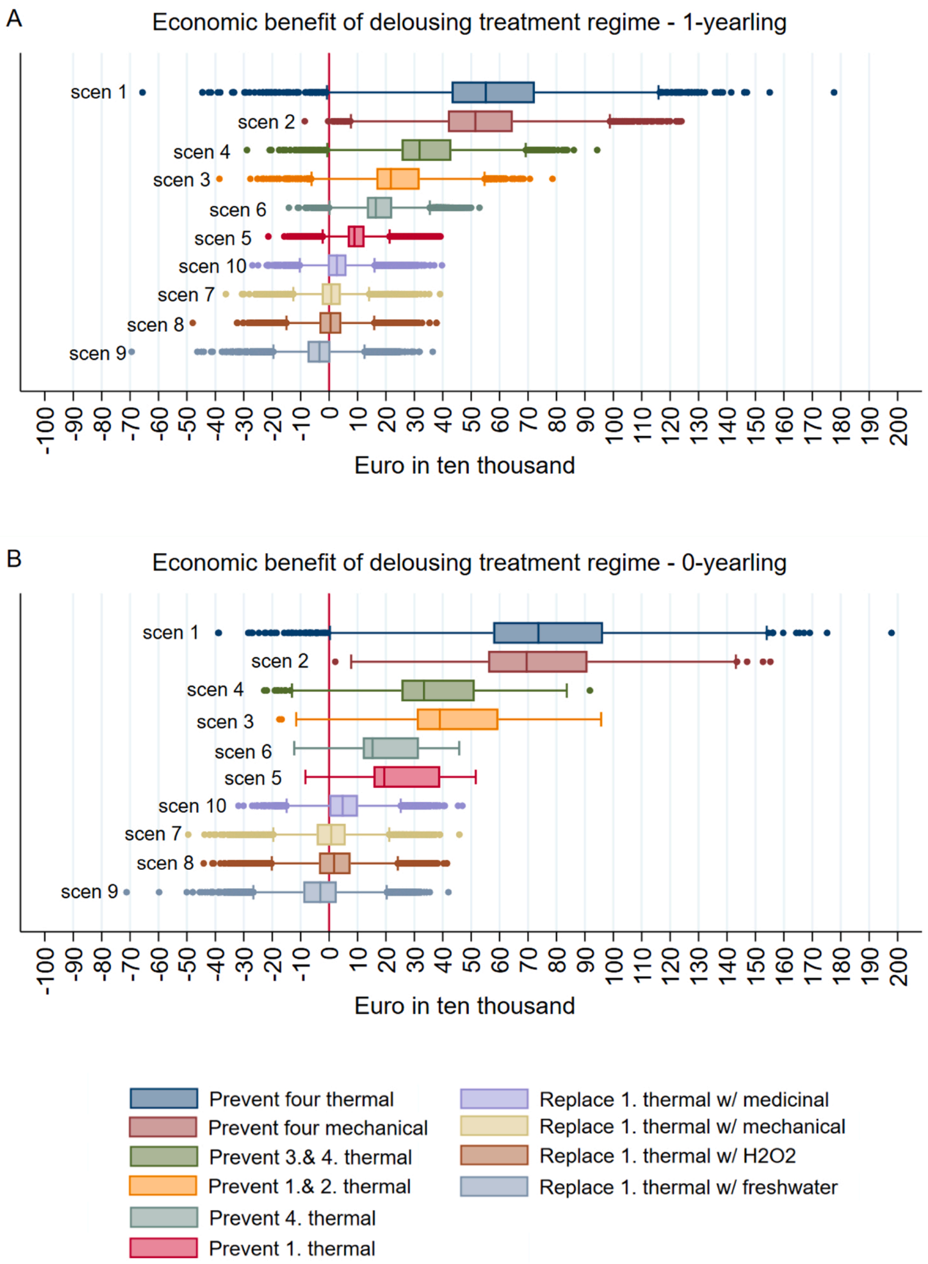

Fig. 2. Shows the variance in profit change for the 1-yearling (A) and 0-yearling (B) measured in ten thousand €/cage/production cycle. The scenarios are ranged by the median increase in profit for the 1-yearling. The red reference line indicates no change in profit by changing delousing regime. A positive change in profit indicates a positive economic impact of changing delousing regime.

among the 5% worst to the 5% best performing (Fig. 2 and supplementary table). The modelled economic benefit of improving four treatments from the 5% worst to expected, expected to 5% best and from worst to best performing has an economic benefit of 319,196, 418,738 and 737,934 €/cage for a 1-yearling and 355,761, 476,703 and 832,464 €/cage for a 0-yearling (supplementary table, scenario 11–13).

3.2. Sensitivity analysis

The sensitivity analysis of the input variables; baseline growth rate ($TGC_{baseline}$), baseline mortality ($mort_{baseline}$), mortality rate after treatment (Δmortrate), growth rate after treatment (ΔTGC), period of feed withdrawal, sales price and feed price, shows that for scenario 1–6 the model is most sensitive to baseline growth rate and the length of the period of feed withdrawal (scenario1, 2, 4, 5) following mortality rate after treatment or sales prices dependent on the scenario (Fig. 3). The economic loss increases with increasing baseline TGC, starvation period and sales prices. For all scenarios, decrease or increase in baseline mortality and feed prices are of lesser importance. The most important factor in scenario 6–10 is the treatment mortality, followed by the growth rate after treatment.

Removing the 14 thermal treatments from 2014 had no effect on the simulated output, they were therefore kept in the distribution.

4. Discussion

Our results suggest that accounting for the biological losses associated with lice treatments is important when making choices of delousing strategies. The biological costs of increased mortality and decreased growth associated with especially non-medicinal treatments are

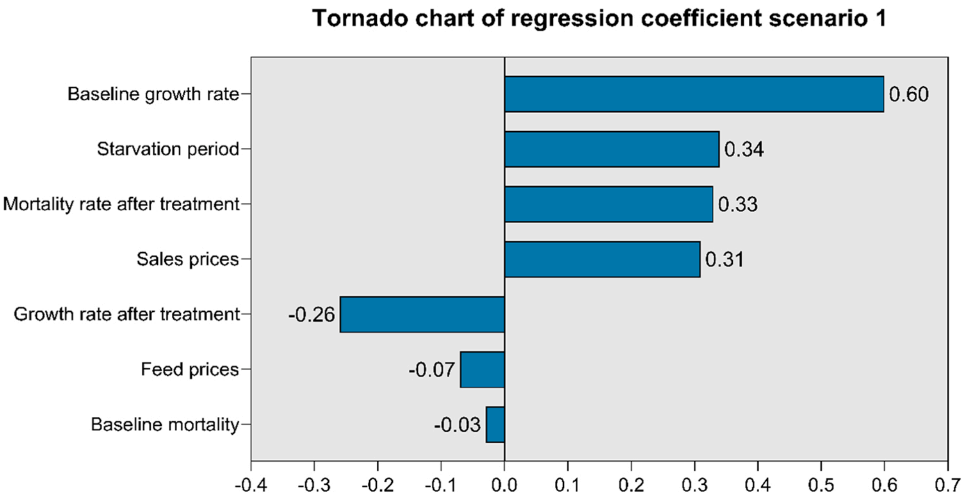

Fig. 3. Tornado plot of sensitivity analysis showing the ranking of the regression coefficient of the selected input variables comparing a production cycle with four thermal treatments (baseline) to a production cycle without any treatments (scenario 1).

expected to be high, but varies substantially. Therefore, the economic benefit of preventing or improving can also be high. Salmon producers could thus invest a considerable amount in measures for prevention or improvement of thermal treatments before break-even. Replacing one thermal treatment with another immediate treatment method has a minor effect. The results further shows that changes in sales value and feed consumption constitute the largest share of the change in profit between the scenarios.

Feed and sales prices are the two most important drivers for the outcome of a change in treatment regime. Increased revenue is due to decreased mortality and increased growth, which means harvesting more and larger salmon. The increased harvest weight might also shift more salmon into a higher weight class, thus extra price premium will give additional revenue. As feed constitutes about 50% of the production costs (Iversen et al., 2020; Misund et al., 2017), most of the increased production cost when preventing treatments is due to increased total amount of feed used in the production cycle. This increase is explained by avoiding either, or both, periods of pre-treatment feed withdrawal and decreased appetite after treatment. In addition, mortality after treatments is avoided, thus a larger number of fish needs to be fed. The cost of harvesting and handling of dead fish are minor compared to feed and sales prices, and do not affect the profit change to the same degree as feed costs and revenue.

Overall, the modelled economic benefit for the different scenarios is higher for the 0-yearling compared to the 1-yearling (Table 4). This can be explained by higher seawater temperatures in the treatment months for the 0-yearling (9.4–14.7 °C) compared to the 1-yearling (5.2–12.0 °C) (Fig. 1). Preventing treatments thus leads to a larger reduction in growth loss for the 0-yearling compared to the 1-yearling, which ultimately leads to a difference in harvested biomass. The model accordingly indicates that preventing treatments in the months with the highest seawater temperatures, would be more beneficial than preventing treatments in months with lower temperatures, because the potential growth loss is reduced. However, an exception to this general observation has been reported for thermal treatments, in which sea water temperatures in the lower ranges are associated with negative impact on growth rates, possibly due to the larger interval between treatment- and sea water temperature (Walde et al., 2022). The pressure of lice is higher in the months with higher seawater temperatures, thus treatments in these months could be harder to avoid. In addition, mechanical treatments at low seawater temperatures are associated with a higher risk of winter-wounds (Andrews et al., 2015; Sommerset et al., 2022). The model does not account for the possible interaction between growth rate and temperature, nor increased risk of secondary diseases.

Not surprisingly, preventing all four non-medicinal treatments, especially poorly executed thermal treatments, has the largest modelled economic benefit (Table 4, scenario 1–2). A recent study demonstrated that combining different preventive measures could reduce the number of delousing events by 25% during a production cycle (Oldham et al., 2023). In our model, this would be equivalent to preventing one thermal treatment. Table 4 shows that if preventing the first thermal treatment (scenario 5) a farmer could justify using 83,586 (1-yearling) or 183,659 (0-yearling) €/cage, as long as the preventive measures do not affect the mortality nor the growth of the salmon.

In Iversen et al. (2017) the cost of a thermal treatment is estimated to be 0.054 € per kg salmon treated, including a mortality cost of 0.017 € per kg treated fish. However, in their estimations the economic value of a dead salmon is equal to the production cost per kg, whereas in our estimations the cost of mortality also includes opportunity cost associated with revenue loss, in addition to growth loss which would be equivalent to 0.14–0.30€/kg. This shows that not including the risk of mortality and growth loss associated with delousing treatments, in addition to the alternative cost of lost revenue could lead to underestimating the cost of a thermal treatment.

In practice, it is challenging to prevent all treatments during a production cycle, and the current control of delousing normally consists of a mixture of preventive and immediate treatment measures (Barrett et al., 2020). Scenario 11–13 (supplementary table) highlight the importance of improving the quality of thermal treatments, showing that the greatest potential effect on profits comes from improving from the 5% worst to the 5% best performing treatments. However, the direct cost of improving treatments is not included in the model because there is little research done identifying potential risk factors related to increased mortality and decreased growth after thermal and mechanical delousing. As in the case of prevention, the model therefore indicates what could be spent per cage per production cycle on improving the treatments. The variation in mortality and growth within the different treatment categories is large, especially within thermal treatments (Walde et al., 2021; Walde et al., 2022). An important factor explaining this could be farmers apply the methods in varying designs. Regarding the thermal treatments, the model shows that it would be economical justifiable to use up to 740,000 €/cage (1-yearling) or 830,000 €/cage (0-yearling) (supplementary table, scenario 13) to improve four poor performing thermal treatments to be among the best performing. Thus, there is a substantial economic incentive for prioritising research on identifying factors related to issues such as handling procedures, the treatment rig, prior health status of the fish, and timing of the treatment, etc. to improve thermal treatments by reducing mortality and ensuring good growth after treatment.

Replacing one thermal treatment with other treatments such as mechanical, hydrogen peroxide, medicinal bath or freshwater bath has a minor modelled economic benefit. For instance, replacing one thermal treatment with one freshwater treatment has a negative net benefit. The reason for this is that the direct cost of freshwater treatments are much higher compared to thermal treatments (Iversen et al., 2017), while the impact on mortality and growth is approximately the same. However, alternating between different treatments is an important part of an integrated pest management strategy to prevent resistance (Myhre Jensen et al., 2020), and this benefit has not been accounted for in our model. The model also assumes that the effect of removing the salmon lice is the same for all treatments, which would not be the case, especially regarding medicinal treatments due to resistance (Aldrin et al., 2023; Myhre Jensen et al., 2020).

Replacing a thermal with a hydrogen peroxide or mechanical treatment has opposite effects on the two smolt-groups. For the 1-yearling, the harvest weight and biomass are slightly higher in a production where a thermal treatment is replaced by a hydrogen peroxide instead of replacing it with a mechanical treatment. However, the cost of the hydrogen peroxide treatment is greater than a mechanical treatment. This means the gain of increased biomass is outweighed by the cost of the treatment for the 1-yearling. For the 0-yearling, the increased weight gain is larger compared to the 1-yearling when replacing the thermal treatment with a hydrogen peroxide treatment instead of a mechanical treatment. This larger increase in weight gain outweighs the larger cost of hydrogen peroxide bath compared to the cost of a mechanical treatments. This example illustrates the fact that deciding between measures of delousing can be different for the 1-yearling and 0-yearling, and be difficult since direct and indirect costs can turn out to be unequally important to the modelled net economic benefit.

The sensitivity analysis shows that profitability is very sensitive to small changes in baseline growth, suggesting that ensuring good appetite and growth of the salmon during production and treatment is perhaps the most crucial measurement for increasing profits. The applied growth rates in the model are based on TGC values calculated from Dataset II. In these calculations, a modelled bFCR is applied, which could lead to an underestimation of growth as described in Walde et al. (2022). The model is not very sensitive to changes in baseline mortality. A monthly mortality of less than 1% is defined as non-extreme in a study from 2018 (Overton et al., 2018). Baseline mortality in the model is thus low, and would perhaps affect the model to a greater extent if above 1%. However, if baseline monthly mortality is higher than 1%, the relative importance of treatment mortality would decrease, and there may be other challenges in addition to salmon lice that needed to be prioritised to decrease overall mortality.

We used the year-classes of 2016 and 2017 to choose different treatment scenarios because these were the year-classes closest to reflecting the current treatment regimes. The technical solutions in aquaculture of Atlantic salmon in Norway progresses quickly, and treatment procedures may have improved since 2016–2019. This implies that the current economic benefit might be smaller than stated here, however delousing operations are still regarded as the second most important single cause of mortality (Sommerset et al., 2022).

There are several constraints in this model, some of them already mentioned. For instance, it is assumed that no compensatory growth occurs between the treatments, and the farmer cannot extend the production length to compensate for the growth loss since the production length is fixed in the model. In addition, the model does not account for the possible additive negative effect of repeated treatments on mortality and growth, nor possible negative effect of treatment on filet quality due to physical damage and wounds potentially causing downgrading or refund claims. In the model, the treatments occur monthly, and it seems realistic to assume that the salmon do not have time to compensate the growth loss between the treatments based on a prior study by Hvas et al. (2022). If the time interval between the treatments or the time from last treatment until harvest was extended, it might be reasonable to include the possibility of compensatory growth in the model. However, as described in Holan et al. (2017) farmers report minor flexibility for adapting the production, for instance by increasing the time interval of production to compensate for growth loss.

In addition, the model does not account for the fact that the production in Norway is regulated by a maximum allowed biomass (MAB) (Hersoug, 2021). Prolonging the production cycle might also increase the risk of another delousing operation. The production length could be affected if we put a MAB constraint into the model. Farmers normally partially harvest sites to ensure optimal use within the biomass constraint, which might prolong the production time at the site. Since this study is described at the cage level, the MAB constraint was not included, however at a site level this would be relevant. The economic gain of decreasing mortality and increasing growth would also be related to a shorter production time and perhaps more flexibility both in planning the production and having a harvestable weight ready when price is high. This flexibility or real option also has a value, which is not incorporated in this bio-economic model.

To the authors knowledge this is the first bio-economic model that incorporates biological risk (mortality and growth) related to delousing treatments using estimated distribution from high-resolution production data. Both the baseline scenario, and the various alternatives are all simplifications of a complex reality. The data showed a varying number and type of treatments, days between treatments, and combinations with other measures for controlling salmon lice. However, the chosen scenarios have been based on the most common traits in the dataset for the various input parameters. Although the present model is a simplification, by comparing one choice with an alternative, it catches some of the complex dynamic between the indirect (biological) costs, direct costs and environmental factors (temperature). It also reflects the fact that some of the choices are not very intuitive. An example of this could be in the case when the benefits of increased growth and decreased mortality are only slight and thus outweighed by the cost of implementing the measure for doing so. It is apparent that assessing the entire complexity of the production of Atlantic salmon, along with its risks and uncertainty, in a single model is neither feasible nor advisable. However, there is a need for both simple and more complex bio-economic models that incorporates risk and uncertainty by the use of high-resolution production data and epidemiological research to aid well founded decisions.

Salmon lice have become a complex, political and expensive problem. It is central to the public regulation of the growth of salmon aquaculture industry in Norway, and influence many parts of the on-growing production and planning of the production of Atlantic salmon at sea (Forskrift om kapasitetsjusteringer, 2022; Forskrift om lakselusbekjempelse, 2016; Produksjonsområdeforskriften, 2017). Several studies have shown the enormous monetary cost associated with salmon lice, and thus highlighted the importance of prioritising the problem both at a macro and microeconomic level (Abolofia et al., 2017; Costello, 2009; Iversen et al., 2020; Liu and Bjelland, 2014; Mustafa et al., 2001; Olaussen et al., 2015). Salmon lice control is a cost to both society, the farmer and the salmon. In addition, there is a cost to the salmon of reduced health and welfare, which manifests as an indirect cost to the farmer in the form of a lower output/biomass. As our model shows, it is important to include the large variance in the indirect costs related to mortality and growth when assessing the economic benefit, as it shows that improving the current non-medicinal treatments have a great positive economic benefit, and therefore identifying risk factors related to improving non-medicinal treatments should be prioritized.

5. Conclusions

In this study the economic benefit of different treatment regimes against salmon lice has been modelled using a partial budgeting approach and a unique high-resolution (cage level) dataset that captures the variance in biological losses of increased mortality and reduced growth due to treatments.

The models show a substantial economic incentive for both preventing and improving the current non-medicinal treatment methods by securing good animal health and welfare. Importantly, it also shows that it is possible to improve factors leading to poorly executed thermal treatment methods.

Declaration of Competing Interest

Jostein Mulder Pettersen is affiliated with Pharmaq AS, a pharmaceutical company supplying products to salmon production.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.prevetmed.2023.106062.

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