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The impact of parasitic sea lice on harvest quantities and sizes of farmed salmon

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ABSTRACT

Sec lice infections are recognized as a primary challenge for both salmon farming and adjacent stocks of wild salmon and sea trout, triggering strict regulations at farm sites and in larger coastal production areas. In 2017 the Norwegian government implemented the Traffic Light System (TLS), where green, yellow, and red lights imply that salmon farmers can raise, maintain, or must reduce production quantities depending on estimated sea lice-induced mortality of wild salmonids. Past research has explored the impacts of sea lice on the growth rate of salmon, indicating a possible link between sea lice numbers and harvest practices. This study evaluates the impact of sea lice on salmon farmers' harvest behavior focusing on production quantities and fish sizes while controlling for market prices of salmon and fish meal. We also investigate whether and to what extent the TLS implementation affects harvest behavior. Our empirical results indicate that farmers tend to harvest marginally faster in response to increasing levels of sea lice and slower during delousing operations. The implementation of the TLS strengthened the negative impacts of delousing operations on harvest quantities. Fish sizes at harvest are negatively associated with sea lice levels and delousing operations, regardless of the implementation of the TLS. Control variables, such as seawater temperature, salmon prices, and fish meal prices, also influence harvest quantities and fish sizes.

1. Introduction

Since the early 1980s, the production of Atlantic salmon (*Salmo salar L.*) has been growing faster than any other aquacultural species. However, salmon farming is highly vulnerable to biophysical shocks such as sea temperature changes, fish diseases, and harmful algal blooms (Asche et al., 2009; Kumbhakar and Tveterås, 2003; Abolofia et al., 2017; Walde et al., 2022; Zhang et al., 2023). Among various diseases, sea louse (*L. salmonis*) infection is the biggest pathogenic threat to salmon farming (Liu and Vanhauwaer Bjelland, 2014; Larsen and Vormedal, 2021; Hjelle et al., 2022). Infestations of sea lice may cause skin erosion, physical damage, and osmoregulatory failure in farmed salmon (Overton et al., 2020), thereby influencing the growth rate and feed efficiency, and ultimately causing death (Bjørn et al., 2001; Walde et al., 2022). This results in substantial costs for salmon farmers (Liu and Vanhauwaer Bjelland, 2014; Abolofia et al., 2017). Cost inefficiency influences sustainable production growth for farmed salmon (Peñalosa Martinell et al., 2020) and other aquacultural products (Hossain et al., 2022), which may further affect the contribution of aquaculture in meeting the goal of the Food and Agriculture Organization of the United Nations: a world without hunger and malnutrition (van Walraven et al., 2021).

Besides their negative impact on fish welfare and the economic results for salmon farming companies, sea lice also affect populations of wild salmon (Johnsen et al., 2021; Torrissen et al., 2013) and other salmonids such as sea trout and arctic char (Bjørn et al., 2001). In response, strict regulations based on the number of sea lice and various delousing treatments are implemented in Norway, the largest salmon farming country in the world (Larsen and Vormedal, 2021; Hjelle et al., 2022) and in other large salmon producing countries such as Chile, Canada, and Scotland (Liu and Vanhauwaer Bjelland, 2014; Luthman et al., 2019; Meyer et al., 2019; Jeong et al., 2023). For example, the level of sea lice per salmon in Norwegian salmon farm sites cannot exceed 0.2 in the spring and summer months and 0.5 in the remaining months, indicating that various delousing treatments are required to control sea lice levels. It has been documented that delousing treatments affect the growth rate of salmon negatively (Barrett et al., 2022; Walde et al., 2022), which may lead salmon farmers to harvest salmon of smaller sizes (Barrett et al., 2022), ultimately indicating poor harvest

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management. In Norway, salmon size at harvest has been steadily decreasing during the last decade (see Fig. 1 below), which may be attributed to sea lice and other biophysical factors.[1]

Apart from harvest quantities, fish size is an important product attribute affecting harvesting decisions for salmon (Forsberg and Guttormsen, 2006) and other aquaculture products (Gasca-Leyva et al., 2008). Interestingly, size heterogeneity is often observed in aquaculture even for fish in the same cohort due to differences in their responses to biophysical factors and feed conversion ratios (Gasca-Leyva et al., 2008; Domínguez-May et al., 2011; Domínguez-May et al., 2020). Fish size directly affects the flesh quality of farmed salmon in terms of concentrations of polychlorinated biphenyl compounds, selected fatty acids, and so on (Ikonomou et al., 2007), thereby influencing salmon prices (Guttormsen, 1999; Asche and Guttormsen, 2002; Bloznelis, 2016) and market performance (Asche et al., 2021).

Despite substantial research efforts documenting the negative impacts of sea lice on the growth rates and general well-being of salmon (Jansen et al., 2012; Larsen and Vormedal, 2021; Barrett et al., 2022; Hjelle et al., 2022; Walde et al., 2022), relatively few studies have investigated the costs and economic losses caused by sea lice outbreaks (Liu and Vanhauwaer Bjelland, 2014; Abolofia et al., 2017). Moreover, little attention has been paid to the impact of sea lice on salmon farmers' harvesting behaviors in terms of the sizes of harvested fish and produced quantities. One notable exception is the study by Barrett et al. (2022), who evaluate the impact of sea lice and delousing treatments on fish size at harvest. However, Barrett et al. do not control for the effects of market conditions on harvest behaviors. This is relevant because changes in salmon prices may influence salmon farmers' responses to sea lice outbreaks.

This study uses farm-site data from 2012[2] to 2021 to evaluate the impact of sea lice and various delousing operations on the quantities and fish sizes of harvested salmon in Norway while controlling for the influence of sea temperature and market prices. Studying salmon farming in Norway is highly warranted as Norway is the world's largest producer of farmed salmon and has the most stringent delousing regulations. In 2017, the Norwegian government introduced a new regulatory regime – the "Traffic Light System" (TLS) – which links changes in allowed production volumes to sea lice levels. We further test whether this TLS implementation has changed the impacts of sea lice on harvest quantities and sizes of farmed salmon. In this way, we gain new insights into the potentially unintended consequences of these tightened regulations.

The outline of the article is as follows. Section 2 briefly reviews the relationship between sea lice and salmon farming and the relevant regulations. Section 3 is devoted to data sources and descriptive analysis. Following the description of the empirical models in Section 4, Section 5 presents the empirical results and Section 6 discusses the main findings. The article ends with the summary and implications in Section 7.

2. Sea lice and salmon farming

The Norwegian government introduced the National Action Plan against salmon lice on salmonids to control sea lice infection on wild salmon and sea trout in 1997 (Heuch et al., 2005). Salmon farmers were required to count sea lice levels and report salmon lice infestations to the Food Safety Authority (NFSA) (van Walraven et al., 2021). Since then, sea lice regulations have been tightened (Larsen and Vormedal, 2021; Osmundsen et al., 2022). In 2013, a new regulation was introduced requiring the number of mature female sea lice per salmon not to exceed 0.5 at a given production site. As of March 2017, all salmon farmers were further required to keep the level of mature female sea lice per salmon below 0.2 in the spring and summer months when wild salmon migrate from fresh water to the open ocean and below 0.5 for the rest of the year. According to the new regulation, salmon farmers should set up a plan for sea lice control that would be approved by NFSA. If the sea lice control plan is not satisfying, the Authority will adopt special regulations, including mandatory delousing, special sea lice limits, forced slaughtering, and extra reporting. In addition to these special regulations, the violation of sea lice limits can cause a temporary reduction in maximum allowed biomass (MAB) as the abundance of sea lice is related to the crowded conditions of sea cages (Jansen et al., 2012).

The TLS system introduced in 2017 aims to link production growth with environmental indicators (Hersoug, 2022). Under this new system, production sites along the Norwegian coast are divided into 13 production areas. An expert committee evaluates the level of sea lice-induced mortality of wild salmonid fish in each production area based on up to seven different empirical assessment methods (Eliasen et al., 2021). According to the evaluation results (e.g., Vollset et al., 2021), salmon farmers may increase, maintain, or reduce production volumes if they are in a production area with a corresponding "acceptable" (green light), "moderate" (yellow light), or "unacceptable" (red light) level of sea lice-induced mortality of wild salmonid smolts.[3]

Stricter sea-lice regulations and the substantial economic losses due to sea louse outbreaks motivate salmon farmers to adopt various delousing operations. The main challenge that salmon farmers face in controlling sea lice outbreaks is to find effective methods with low costs and minimal negative impact on fish and the environment (Hjelle et al.,2022). Delousing operations can increase salmon mortality by 14–31%, depending on the methods (Overton et al., 2019). The main delousing methods are medicinal treatments, mechanical treatments, and cleaner fish.[4] Medicinal treatments are mainly used for small salmon and reduce sea lice at a gradual rate, while mechanical treatments are typically used for large salmon and can achieve a quick delousing effect (Liu and Vanhauwaer Bjelland, 2014; Overton et al., 2019). The increasing sea lice resistance to medicinal treatments and the need to keep sea lice levels within the stricter regulatory limits forced salmon farmers to shift to mechanical treatments (Barrett et al., 2022). Mechanical treatments are highly effective at delousing; however, they may also cause severe injuries to treated salmon, leading to slower growth and increased mortality (Overton et al., 2019; Barrett et al., 2022; Walde et al., 2022). The empirical findings of Walde et al. (2022) indicate that non-medicinally treated fish-groups take longer to return to base-level growth than medicinally treated groups. Releasing cleaner fish that feed on sea lice is another widespread approach used by salmon farmers (Overton et al., 2020; Jeong et al., 2023). Compared to other types of treatments, cleaner fish are more gentle and less stressful to the treated salmon. However, the welfare of cleaner fish is questionable as >40% of cleaner fish die during salmon production cycles (Larsen and Vormedal, 2021; Philis et al., 2022). Furthermore, the transport of cleaner fish across countries may have a negative impact on ecosystems and may spread diseases and parasites (Murray, 2016).

Both outbreaks of sea lice and the subsequent delousing treatments affect salmon growth and biomass. For a typical production area in mid-Norway, the total loss in biomass per production cycle due to average sea-lice infestations was estimated to be between 3.62% and 16.55% in 2011 (Abolofia et al., 2017). The delousing treatments differently

[1] For example, seawater temperature is one of the most important biophysical factors due to its strong impact on feed conversion rates and salmon growth (Thyholdt, 2014) and on the life cycle of sea lice (Larsen and Vormedal, 2021; Nilsson et al., 2023). Investigating drivers of the short-term supply of farmed salmon, Asheim et al. (2011) found that sea temperature is more important than salmon prices for harvest behavior.

[2] 2012 is the first year with available data on sea lice levels and delousing treatments by farm site.

[3] See Larsen and Vormedal (2021) for a detailed review of sea-lice regulations.

[4] Throughout this study, delousing activities/operations refer to medicinal/mechanical treatments and cleaner fish.

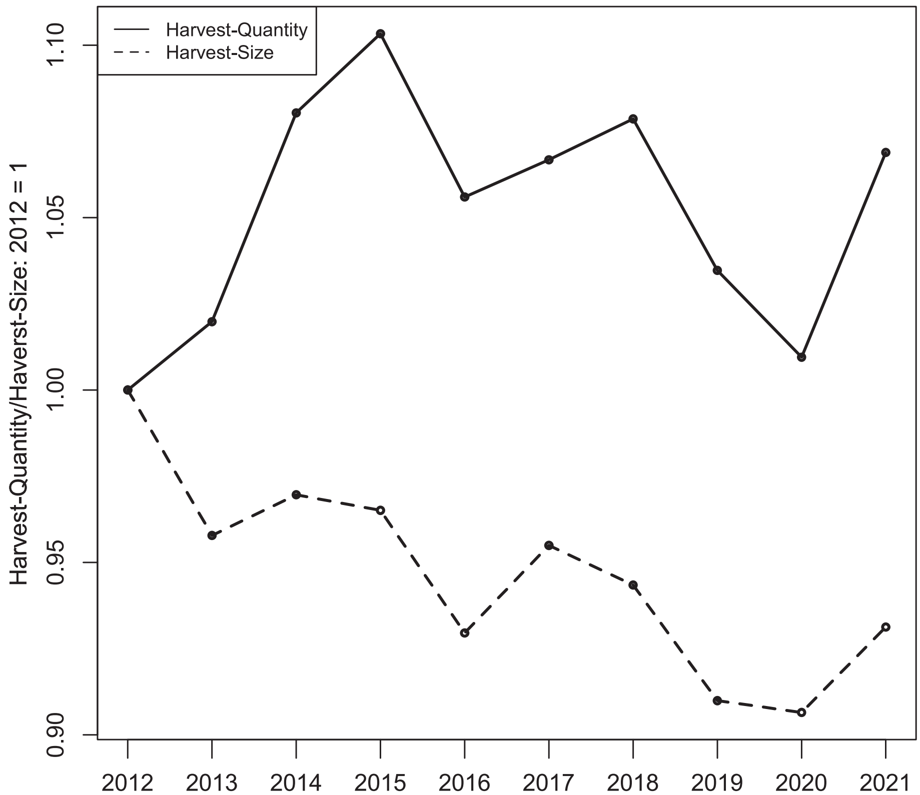

Fig. 1. Average monthly salmon harvest quantity and size, by year (2012 = 1).
Notes: The actual monthly average values of harvest quantity and size in 2012 (the base) are 609,677 kg and 4.96 kg per fish, respectively.

impact salmon growth rates. Non-medicinally treated salmon takes longer to return to a normal growth rate than do medicinally treated salmon (Walde et al., 2022). For individual salmon, the average weight of a salmon harvested in 2021 is 6.6% lower than in 2012, with the smallest average size-at-harvest found during the delousing-intensive spring and summer months (Barrett et al., 2022). One study reveals that an individual non-medicinal treatment event causes a potential decrease in weight gain of about 52 g per fish the week after the treatment compared to a non-treated fish (Walde et a., 2022).

Salmon farmers' economic losses related to sea lice outbreaks and delousing treatments have been further assessed. As summarized in Costello (2009), researchers have estimated the cost of controlling sea lice to be in the range of euro 0.1–0.2 per kg of fish. After estimating the biomass growth-loss resulting from sea lice outbreaks, Abolofia et al. (2017) calculate the economic loss of a typical spring-release production cycle to be between US$ 321,634 and 1,115,091, equivalent to a loss of US$ 0.15 and 0.67 per kg of farmed salmon. The economic losses also depend on delousing treatment strategies. The simulation results in Liu and vanhauwaer Bjelland (2014) indicate that the average cost of various combinations of treatments was in the range between NOK 2.42 and 5.03 per kg of farmed salmon.

Both Abolofia et al. (2017) and Liu and vanhauwaer Bjelland (2014) assume a constant salmon price in their simulation analysis. However, price changes play a crucial role in aquaculture management practices and production planning (Forsberg and Guttormsen, 2006). Recently, Enghagen et al. (2021) incorporate salmon prices in a scenario analysis to study the consequence of biophysical shocks resulting from harmful algal blooms. They document that salmon prices have a profound impact on harvesting decisions when salmon farmers confront biomass uncertainties. Thus, the present study asserts that market prices may affect salmon farmers' harvest management in response to sea lice and delousing efforts.

Quantitative evidence on the impact of sea lice and delousing operations on harvesting strategies is scarce, but limited research is emerging. Recently, Barrett et al. (2022) evaluate the impact of sea lice and delousing treatments on fish size at harvest and the probability of choosing between delousing treatments and harvesting in response to sea louse outbreaks. They document that size-at-harvest was 3.4% smaller in treatment months than in non-treatment months. Moreover, sea lice may affect profitability through their impact on harvest strategies. Abate et al. (2022) find a negative impact of sea lice prevalence on profit for salmon farmers as a whole; however, farmer heterogeneity causes an ambiguous relationship between profit and sea lice level.[5]

3. Data and descriptive analysis

Our data are from different sources with weekly or monthly frequencies at the farm-site level. The sample period covers from 2012 to 2021. We first describe the datasets and then explain how to combine them at the monthly level.

3.1. Harvest and biomass data

Salmon farmers report monthly harvest and biomass data to the Norwegian Directorate of Fisheries, which provided the farm-site data for this study. The farm-site data include harvest quantities in kilograms, the number of fish harvested, and an estimate of the biomass of fish in kilograms in the sea at the end of each month. Dividing the harvest volume by the number of fish yields the average size of fish in kilograms.

The sample with reported harvest volumes comprises 19,622 observations at the farm-site level. To avoid outliers, we follow Barrett

[5] Salmon farming companies' annual accounting data can be used to estimate the impact of sea lice on profitability. However, the aggregated annual values of sea lice level and delousing treatments may not fully reflect salmon farmers' operating strategies.

et al. (2022) and omit observations with harvest volumes or biomass <100 kg and observations with <10 harvested salmon (3894 observations). We also remove observations with fish sizes <1 kg or >10 kg (271 observations). This yields a dataset with 15,457 observations of harvest and biomass data to be combined with other datasets.

The average monthly harvest quantity ranges from a low of 609,677 kg in 2012 to a high of 672,674 kg in 2014. Farmed salmon with the largest average size was harvested in 2012, which was also the year with the smallest average harvest volume. The second smallest average monthly harvest volume occurred in 2020 with 615,477 kg, possibly due to a combination of biological problems (e.g., diseases, sea lice, or harmful algae) and the COVID-19 pandemic (Straume et al., 2022). The year 2020 also had the smallest average fish size (4.49 kg). Fig. 1 illustrates the trend of harvest quantities and fish sizes over time by setting their respective values in 2012 equal to 1. Unlike harvest volumes, fish sizes show a clear downward trend throughout the ten-year period covered by the data.

3.2. Sea lice and delousing data

Data on sea lice and delousing (and seawater temperature) at the farm-site level are extracted from salmon farmers' weekly reports to the Norwegian Food Safety Authority. Since 2018 quantities and species of cleaner fish by month have been reported to the Norwegian Directorate of Fisheries.

We use the weekly sea lice data to obtain the average numbers of sea lice per salmon by month for the period 2012–2021, comprising 69,888 observations. Of these, 13,834 observations contain zero sea lice. The average number of sea lice per fish was 0.169 during the whole sample period, 0.187 between 2012 and 2016, and 0.123 between 2017 and 2021 when the TLS regulation was in place. Between the two subperiods, the average number of sea lice per fish was reduced by 18.2%. As illustrated in Fig. 2, the number of sea lice per salmon started to drop after 2014, increased in 2019, and finally declined in 2020 and 2021.

The weekly data on mechanical and medicinal delousing treatments are aggregated to monthly levels.[6] For cleaner fish, the data on average monthly numbers based on the weekly data for 2012–2017 are combined with the monthly data for 2018–2021. The whole sample for delousing operations includes 26,268 observations, accounting for 37.6% of the observations of the sea-lice data. During the whole sample period and on average, salmon farmers conducted 1.134 delousing treatments per month and released 11,021 cleaner fish per month. Fig. 3 depicts the changes in the number of treatments and released cleaner fish per year and between the two subperiods (before and after 2017). After 2017, farmers relied more on cleaner fish than on treatments to reduce sea lice levels. This indicates that the reduction in sea lice shown in Fig. 2 may be partially explained by the intensive application of cleaner fish (Fig. 3).

We further calculate the ratio of the number of mechanical treatments to the number of medicinal treatments and plot the average values by year in Fig. 4. Before 2015, medicinal treatments dominated but have been steadily replaced by mechanical treatments since then. After 2018, the number of mechanical treatments is >2.5 times greater than the number of medicinal treatments. This may also explain the decline in sea lice levels since mechanical treatments are more effective than medicinal treatments.

When combining the sea lice data with the delousing operation data, missing values for treatments and cleaner fish are set to zero. Thus, the combined dataset has the same number of observations as the dataset for sea lice, a total of 69,888 observations. We further calculate the number of delousing operations (treatments or cleaner fish) per sea lice and plot the monthly average by year in Fig. 5. The figure shows that from 2016 to 2017 the number of cleaner fish per sea lice increased substantially, while the number of treatments per sea lice decreased. After this, the number of cleaner fish per sea lice shows a downward trend, in contrast to an upward trend of treatments per sea lice.

3.3. Combining the harvest and sea-lice data

We set the harvest dataset as the base and combine it with the data on sea lice and delousing operations, resulting in 15,159 observations after deleting missing values for variables in the sea lice data. This dataset is used for the empirical analysis below. The final dataset comprises 864 farm sites.

We further compare harvest volumes and fish sizes with the numbers of sea lice per salmon, treatments, and cleaner fish by plotting them (relative to their respective values in 2012) in Fig. 6. Both treatments and cleaner fish are more volatile than harvest quantities, fish sizes, and the level of sea lice. The huge increase in cleaner fish in 2017 was accompanied by a decrease in mechanical and medicinal treatments. Since 2018, the number of treatments has kept an upward trend, which is associated with the reduced sea lice level.

4. Empirical methods

Using the farm-site monthly data covering the period 2012–2021 described above, we investigate the impacts of the sea lice level and delousing operations on harvest quantities and sizes of farmed salmon. The sea lice level is represented by the number of mature female sea lice per fish (*Number-Sea-Lice*). The numeric variable *Treatments* equals the sum of medicinal and mechanical treatments. *Number-Cleaner-Fish* represents the number of released cleaner fish. The dummy variable *TLS* equals one for the period 2017–2021 and zero for the period 2012–2016.

The above specification yields the baseline model for harvest quantities (*Harvest-Quantity*) and fish sizes (*Harvest-Size*) by including either *Number-Sea-Lice* or delousing operations (*Treatments* and *Number-Cleaner-Fish*). For the harvest model, we follow Asheim et al. (2013) to define control variables, leading to the following baseline model equation (taking *Number-Sea-Lice* as an example):

$$\begin{aligned} log\left(Harvest-Quantity_{i,t}\right) = {} & a_0 + a_1 log\left(Harvest-Quantity_{i,t-1}\right) \\ & + a_2 log\left(Biomass_{i,t-1}\right) + a_3 log\left(Salmon-Price_{i,t-1}\right) \\ & + a_4 log\left(Fish-Meal-Price_{i,t-1}\right) + a_5 Temperature_{i,t} \\ & + a_6 log\left(Number-Sea-Lice_{i,t-1}\right) + a_7 TLS_i + a_i \\ & + Residual_{i,t} \end{aligned} \tag{Model A1}$$

where i and t are indices for farm sites and time (year-months); log is the logarithm function; *Biomass* is the biomass of live fish in kilograms at the end of the month; *Temperature* refers to the seawater temperature in °C; a_i stands for the individual (farm site) fixed effect; the error term, *Residual*, captures any other unobserved factors that may influence the harvest volume.

In Eq. (1), the lagged dependent variable captures market dynamics, i.e., the time farmers take to return to the equilibrium (Asheim et al., 2011; Zhang, 2020).[7] Both price variables and biomass are lagged one month to avoid simultaneity bias.[8]

[6] The data show that medicinal and mechanical treatments are seldom used simultaneously.

[7] The monthly salmon price is represented by the Fish Pool Index from Fish Pool ASA, which is the weighted price of achieved sales prices for exporters (95% and for salmon of 3–6 kg) and export price for fresh salmon (5% of and for all sizes and quantities) reported by Statistics Norway. The fish meal price, obtained from Index Mundi, is Peruvian fish meal/pellets, with 65% protein, CIF, NOK per kg.

[8] Using the lagged variables in the models leads to a smaller sample size used for estimations than the size of the originally cleaned sample (9243 versus 15,159).

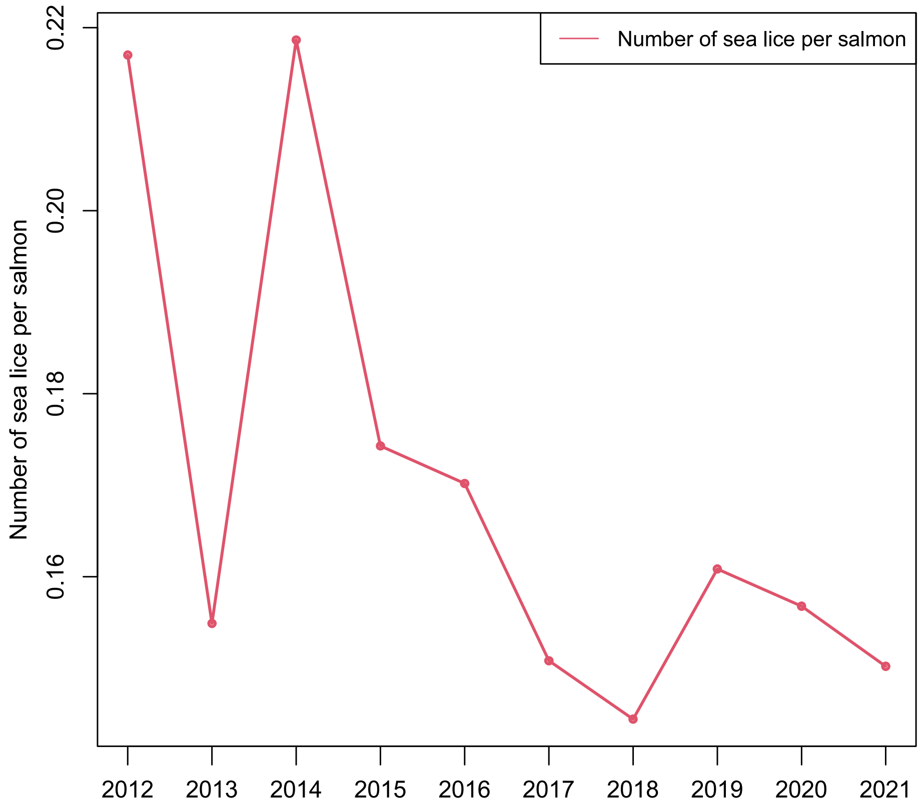

Fig. 2. Average monthly number of female sea lice per salmon, by year.

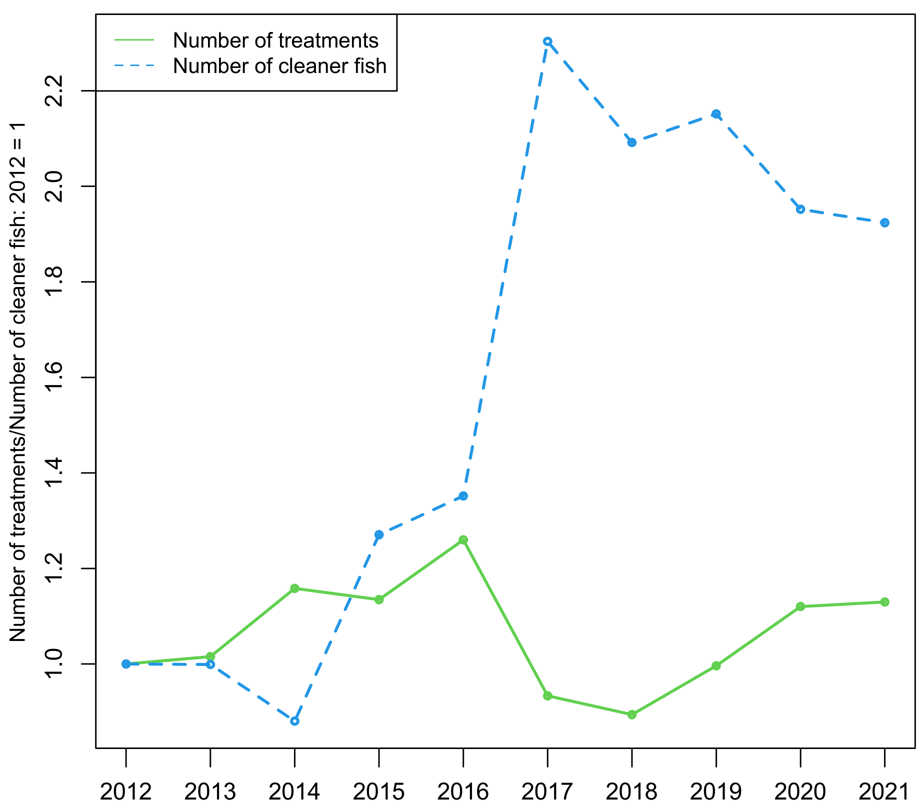

Fig. 3. Average monthly numbers of treatments and cleaner fish, by year (2012 = 1).
Notes: The actual monthly average numbers of treatments and cleaner fish in 2012 (the base) are 1.07 and 6593, respectively.

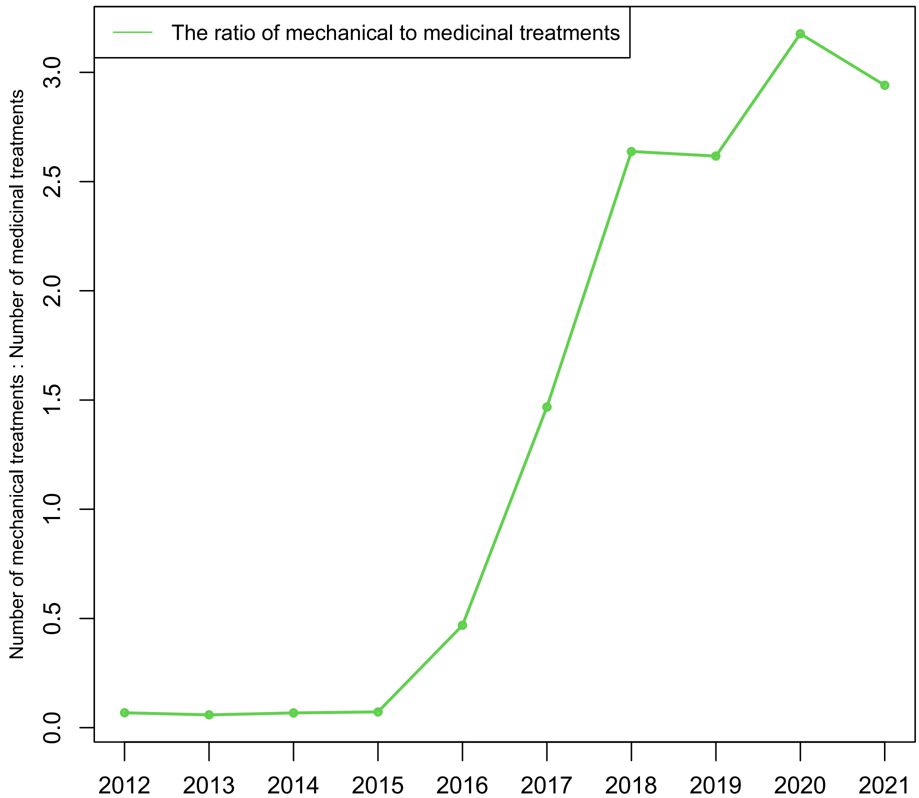

Fig. 4. The average monthly ratio of mechanical treatments to medicinal treatments, by year.

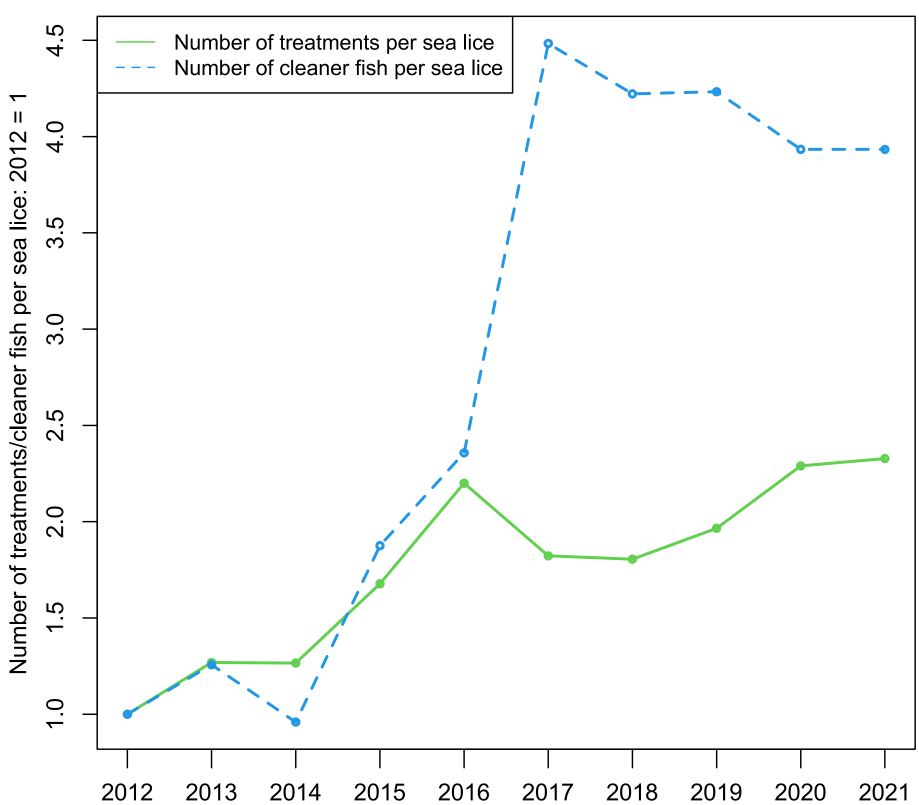

Fig. 5. Average monthly numbers of treatments and released cleaner fish per female sea lice, by year (2012 = 1).
Notes: The actual monthly average numbers of treatments and cleaner fish per female sea lice in 2012 (the base) are 0.32 and 1950, respectively.

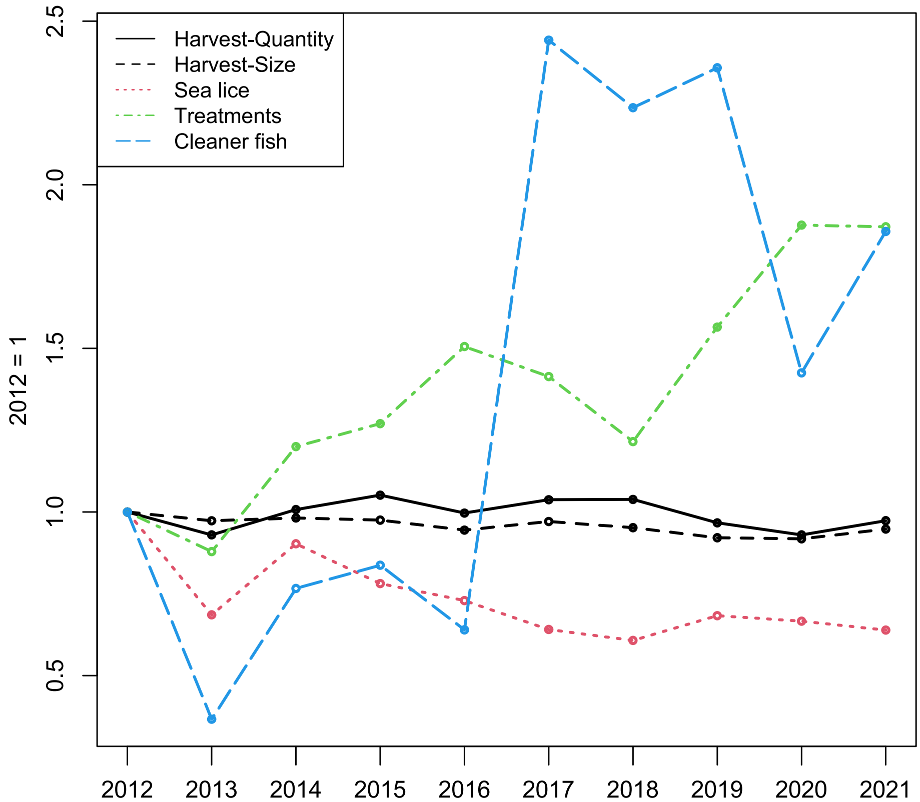

Fig. 6. Average monthly harvest volume and size versus lagged numbers of sea lice, treatments, and cleaner fish, by year (2012 = 1).
Notes: The average monthly harvest volume, fish size, sea lice (lagged), treatments (lagged, and cleaner fish (lagged) in 2012 (the base) are 738,052 kg, 5.04 kg, 0.37, 0.50, and 1352, respectively.

Table 1
Variable definitions and summary statistics.

Variable	Definition	Mean	SD
log (Harvest-Quantity)	Harvest quantity, in kg and logarithm	13.1	1.15
log (Harvest-Size)	Salmon size at harvest, in kg and logarithm	1.55	0.20
log (Biomass)	Biomass of live salmon at the end of month, in kg and logarithm	14.1	0.91
log (Salmon-Price)	Fresh salmon price in NOK per kg, in logarithm	3.90	0.28
log (Fish-Meal-Price)	Fish meal price in NOK per kg	2.46	0.14
Sea-Temperature	Sea temperature (°C)	9.00	3.45
Number-Sea-Lice	Mature female sea lice per salmon	0.30	0.43
Treatments	Number of mechanical and medicinal treatments	0.63	0.94
log (Number-Cleaner-Fish)	Number of released cleaner fish, in logarithm	0.53	2.17
TLS	Dummy variable for Traffic-Light-System (= 1 for 2017–2021 and 0 otherwise)	0.55	0.50
Original variable values (before log transformation):			
Harvest-Quantity	Harvest quantity in kg	730,111	623,794
Harvest-Size	Salmon harvesting size in kg per fish	4.81	0.91
Biomass	Biomass of live salmon at the end of month, in kg	1,866,903	1,256,117
Salmon-Price	Salmon price in NOK per kg	51.1	13.2
Fish-Meal-Price	Fish meal price in NOK per kg	11.8	1.49
Number-Cleaner-Fish	Number of released cleaner fish	1174	7376

The dummy variable, *TLS*, in Eq. (1), may capture the impact on farmers' harvest behavior of the 2017 delousing regulation starting, or of other factors such as the COVID-19 pandemic in 2020 and 2021 (Straume et al., 2022). Accordingly, we further modify Eq. (1) by adding an interaction term between *Number-Sea-Lice* and *TLS* (Model A2), which reveals the different impacts of sea lice on harvest quantities between the two subsample periods: 2017–2021 and 2012–2016. Replacing *Number-Sea-Lice* in Models A1 and A2 with *Treatments* and *Number-Cleaner-Fish* gives rise to Models A3 and A4, respectively.

Following the same modeling strategy, we have four regression models for *Harvest-Size*, with the following baseline specification (taking *Number-Sea-Lice* as an example):

$$log(Harvest-Size_{i,t}) = \beta_0 + \beta_1 log(Harvest-Quantity_{i,t}) + +\beta_3 log(Salmon-Price_{i,t-1}) + \beta_4 log(Fish-Meal-Price_{i,t-1}) + \beta_5 Temperature_{i,t} + \beta_6 Number-Sea-Lice_{i,t-1} + \beta_7 TLS_i + \beta_i + Residual_{i,t} \quad \text{(Model B1)}$$

Modifying Model B1 by including an interaction term between *Number-Sea-Lice* and *TLS* leads to Model B2. Again, replacing *Number-Sea-Lice* in Models B1 and B2 with *Treatments* and *Number-Cleaner-Fish*

Table 2
Estimation results of Model A for *Harvest-Quantity*.

Variable	Model A1	Model A2	Model A3	Model A4
log (Harvest-Quantity)-lag	0.2762***	0.2762***	0.2746***	0.2723***
	[0.0193]	[0.0193]	[0.019]	[0.0189]
log (Biomass)-lag	0.6478***	0.6481***	0.6630***	0.6620***
	[0.0296]	[0.0296]	[0.0301]	[0.0300]
log (Salmon-Price)-lag	0.1404***	0.1412***	0.1145**	0.1009**
	[0.0472]	[0.0473]	[0.0472]	[0.047]
log (Fish-Meal-Price)-lag	−0.1943**	−0.1955**	−0.1660**	−0.1617**
	[0.0845]	[0.0845]	[0.0848]	[0.0851]
Sea-Temperature	0.0168***	0.0168***	0.0220***	0.0222***
	[0.0048]	[0.0048]	[0.0048]	[0.0048]
Number-Sea-Lice-lag	0.0462*	0.0437*		
	[0.0250]	[0.0239]		
Treatments-lag			−0.0529***	−0.0239**
			[0.0104]	[0.0127]
Log (Number-Cleaner-Fish)-lag			−0.0178***	−0.0095*
			[0.0039]	[0.0056]
TLS	−0.1123***	−0.1164***	−0.0937***	−0.0399
	[0.0238]	[0.0315]	[0.0236]	[0.0267]
TLS * Number-Sea-Lice-lag		0.0155		
		[0.0843]		
TLS * Treatments-lag				−0.0566**
				[0.0220]
TLS * log (Number-Cleaner-Fish)-lag				−0.0131*
				[0.0076]
Individual effect	Yes	Yes	Yes	Yes
Within R-Squared	0.1290	0.1290	0.1333	0.1345
Between R-Squared	0.8691	0.8697	0.8692	0.8715
Overall R-Squared	0.3825	0.3825	0.3868	0.3884
p-value of F test	< 0.01	< 0.01	< 0.01	< 0.01
Observations	9243	9243	9243	9243

Notes: *, **, and *** Stand for the significance level of 10%, 5%, and 1%, respectively. Robust and clustered standard errors are in brackets.

Table 3
Estimation results of Model B for *Harvest-Size*.

Variable	Model B1	Model B2	Model B3	Model B4
log (Harvest-Quantity)	0.0600***	0.0600***	0.0592***	0.059***
	[0.0027]	[0.0027]	[0.0027]	[0.0027]
log (Salmon-Price)-lag	−0.0337***	−0.0339***	−0.0359***	−0.0371***
	[0.0124]	[0.0124]	[0.0123]	[0.0123]
log (Fish-Meal-Price)-lag	−0.0767***	−0.0765***	−0.0697***	−0.0694***
	[0.0231]	[0.0232]	[0.0231]	[0.0232]
Sea-Temperature	−0.0092***	−0.0092***	−0.0082***	−0.0082***
	[0.0010]	[0.0010]	[0.0010]	[0.0010]
Number-Sea-Lice-lag	−0.0152**	−0.0147**		
	[0.0059]	[0.0061]		
Treatments-lag			−0.0080***	−0.0053**
			[0.0020]	[0.0028]
log (Number-Cleaner-Fish)-lag			−0.0041***	−0.0026*
			[0.0008]	[0.0014]
TLS	−0.0047	−0.0040	−0.0012	0.0046
	[0.0068]	[0.0078]	[0.0068]	[0.0078]
TLS * Number-Sea-Lice-lag		−0.0028		
		[0.0165]		
TLS * Treatments-lag				−0.0052
				[0.0042]
TLS * log (Number-Cleaner-Fish)-lag				−0.0022
				[0.0016]
Individual effect	Yes	Yes	Yes	Yes
Within R-Squared	0.1407	0.1407	0.145	0.1454
Between R-Squared	0.8692	0.8693	0.8692	0.8715
Overall R-Squared	0.3825	0.3854	0.3868	0.3884
p-value of F test	< 0.01	< 0.01	< 0.01	< 0.01
Observations	9243	9243	9243	9243

Notes: *, **, and *** Stand for the significance level of 10%, 5%, and 1%, respectively. Robust and clustered standard errors are in brackets.

yields Models B3 and B4, respectively.

In Model B, we include *Harvest-Quantity* to test the impact of total harvest on fish size composition. Since harvest quantity is directly related to biomass, we exclude the *Biomass* variable in Model B. We also argue that salmon prices, fish meal prices, temperature, sea lice levels, and delousing activities affect both harvest quantity and fish size.

Table 1 reports the descriptive statistics for the variables used in the models. Over the sample period, the monthly average harvest quantity and fish size are 730,111 kg and 4.81 kg, respectively. The coefficient of variance (CV), a standardized measure of the dispersion of the numeric variables, is 0.85 for harvest quantity and 0.19 for harvest size, indicating a more fluctuating harvest quantity. Additionally, the value of the CV is greater for harvest quantity than for biomass (0.85 versus 0.67), indicating the impact of market conditions on harvest behaviors. Due to zero values, both the numbers of treatments and cleaner fish have a great degree of fluctuations, with CV values of 1.49 and 6.28, respectively.

5. Estimation results

Tables 2 and 3 report the estimation results for *Harvest-Quantity* and *Harvest-Size* with variables for sea lice levels or delousing operations, respectively. The robust and clustered standard errors (at the farm-site and year-month dimensions) are reported for inferences. For the two series of models, the within R^2 values are about 0.13–0.14 and the between R^2 values are approximately 0.87. Thus, while these models explain a small share of variation in the harvest patterns within farm sites, they capture most of the variations in the harvest patterns between farm sites.

5.1. Harvest quantity model

As shown in Table 2, for the harvest quantity model, the coefficient of the lagged *Harvest-Quantity* is significant in the four regressions with a value of about 0.27, indicating that salmon production is a dynamic activity. Salmon farmers spend approximately 1.37 months (= 1/(1–0.27)) to fully adjust to changes in the equilibrium supply. Our estimate of the lagged *Harvest-Quantity* (0.27) is smaller than the one in Asheim et al. (2011) (0.358), which may be due to different sample periods and model specifications used in Asheim et al. and this study.

The individual variable *Number-Sea-Lice* is significant in Models A1 and A2. The magnitudes of the coefficients indicate that the harvest volume increases by approximately 0.4% when the number of sea lice per salmon increases by 0.1 unit (equivalent to a 33% increase over the mean of the sea lice; see Table 1).[9] Thus, sea lice levels do not significantly impact harvest plans. The interaction term between *Number-Sea-Lice* and *TLS* is not significant in Model A2, implying that the TLS implementation does not affect harvesting responses to sea lice levels.

For delousing operations, both the individual *Treatments* and *Number-Cleaner-Fish* in Models A3 and A4 and their interaction with *TLS* in Model A4 are significant. As such, the TLS implementation has affected salmon harvesting volumes in response to delousing operations. The estimates of Model A3 indicate that, during the whole sample period, one additional treatment reduces the harvest volume by 5.29%, while one percentage point increase in the number of cleaner fish reduces the harvest volume by 0.018%, implying that harvest volumes are more sensitive to mechanical/medicinal treatments than to cleaner fish. The more severe impact of mechanical/medicinal treatments on salmon may explain the reduction in harvest volumes following those treatments.

The significant and negative coefficients of the interaction terms in Model A4 indicate that harvest volumes respond more negatively to delousing operations after the TLS implementation than prior to this regulation, namely 8.05% versus 2.39% for mechanical/medicinal treatments and 0.022% versus 0.0095% for cleaner fish.

In Models A1, A2, and A3, the coefficient of the *TLS* dummy is significant and negative. On average, the monthly salmon harvest was smaller in 2017–2021 than in 2012–2016. According to Model A1, the introduction of the TLS is associated with a significant reduction of 9.15% in harvest volume per month. However, *TLS* is insignificant in Model A4. Thus, the differences in harvest volumes during the two periods are probably attributed to the changed response of harvest volumes to delousing operations.

For control variables in Table 2, the four regression models provide similar estimates, especially regarding the level of significance. Biomass is positively associated with harvest quantities, as expected. A one-percent increase in salmon prices leads to an increase in harvest quantities by 0.10%–0.14% the following month, depending on the model specification. In contrast, a higher fish meal price shifts the supply curve inward. Our results further indicate a positive impact of sea temperature on harvest volumes. A positive (negative) deviation from the mean temperature during our sample period would increase (reduce) harvest volumes, which could be attributed to the relationship between seawater temperature and salmon growth rate, feed intake, or mortality (Asheim et al., 2011; Falconer et al., 2020).

5.2. Harvest size model

Table 3 reports the estimation results for *Harvest-Size*. The individual *Number-Sea-Lice*, *Treatments*, and *Number-Cleaner-Fish* are significant and negative in the four models, while none of the interaction terms are significant. Moreover, none of the *TLS* dummy and its interactions with sea lice levels or delousing operations is significant in the four models. Increasing numbers of sea lice and delousing operations affect harvest size negatively, regardless of the implementation of the TLS. In addition, the size of harvested salmon is not substantially different between the two subperiods distinguished by the TLS implementation, holding other factors constant. Since the interaction terms in Models B2 and B4 are not significant, we rely on Models B1 and B3 to further explain the estimation results.

The coefficient of *Number-Sea-Lice* in Model B1 is −0.0147, indicating that a 0.1 increase in the sea lice level leads to a 0.147% reduction in fish size. In response to a 0.1 increase in the number of treatments, fish size decreases by 0.08%. A one-percent increase in the number of cleaner fish causes a 0.0041% reduction in fish size. Although our estimation results reveal a negative relationship between sea lice levels or delousing operation and harvest sizes, in line with the findings in Barrett et al. (2022), the impacts are marginal. The margin effects of the sea lice and delousing operation variables are probably attributed to the small variation of fish sizes over the sample period (see Table 1). This is also reflected by estimates of other control variables. For example, a one-percent increase in salmon prices and fish meal prices only leads to an approximately 0.03% and 0.07% reduction in fish sizes, respectively. However, the positive relationship between harvest quantity and fish size, despite its small magnitude, is associated with good harvest management practices.

Comparing the estimation results of Models A and B further reveals the impact of sea lice levels and delousing operations on harvest management strategies. In general, the TLS implementation has changed the responses of salmon farmers' harvest volumes to sea lice and has had no impact on the relationship between the numbers of sea lice and harvest sizes. This indicates a direction for salmon farmers to respond to stricter sea lice regulations since a combination of harvest volumes and fish sizes reflects better harvest management. During the entire sample period, sea lice positively impact harvest quantities and negatively impact fish size at harvest. On the contrary, delousing activities negatively impact both harvest volumes and fish size at harvest. Salmon farmers may consider biomass and harvesting as well as sea lice levels when deciding to implement delousing operations. In response to increasing sea lice levels, salmon farmers harvest faster but with reduced fish sizes. However, when they conduct delousing treatments, they harvest more slowly despite small fish size at harvest, indicating flexible harvesting strategies.

Finally, we estimate the models without price variables to explore how those variables affect the impact of sea lice on harvest volumes and fish sizes. The results are reported in Tables A1 for Model A and A2 for Model B in the Appendix. For Model A, the estimates of the dummy for TLS are less negative than their counterparts in the main results. In addition, the impact of sea lice levels on harvest quantities in Model A2

[9] For a log-level regression, the coefficient of the level variable, for example a_6 for *Number-Sea-Lice*, means that the dependent variable changes by $100{\cdot}a_6$ percent given a one-unit increase in the level variable.

becomes negative. For Model B, unlike the main results, the dummy for TLS is significant in all regressions, indicating the spurious results due to excluding price variables in the model regressions. This applies to the interaction term between TLS and the number of cleaner fish in Model B4. Collectively, salmon farmers' harvesting strategies in response to sea lice levels and delousing activities are subject to market demand as reflected by salmon prices.

6. Discussions

This study evaluates the impact of sea lice and delousing activities on quantities and fish sizes of harvested salmon. Harvest quantities and fish sizes are crucial elements of harvesting strategies, indicating that important managerial implications can be derived from our empirical results.

In contrast to traditional aquaculture, salmon farming uses intensive rearing methods (Landazuri-Tveteraas et al., 2023), providing salmon farmers with wide control over harvesting strategies, including harvest timing, quantity, and fish size. Fish size may affect the flesh quality of farmed salmon (Ikonomou et al., 2007), influence processing and final consumer product opportunities, and affect salmon market prices (Asche and Guttormsen, 2002; Bloznelis, 2016). Our empirical results indicate that the impact of sea lice and delousing operations affect harvesting quantities and fish sizes, indicating adjusted harvesting strategies.

However, sea lice and delousing operations affect harvesting strategies in different ways. The empirical results show that harvest quantities are positively associated with sea lice levels and negatively associated with delousing activities. In response to increased sea lice levels, farmers accelerate harvest. This is consistent with Engehagen et al.'s (2021) proposition that salmon farmers adjust harvesting strategies when med with biophysical shocks. An early harvesting strategy is probably attributed to a temporary reduction in MAB due to continuous increases in sea lice levels, while the negative relationship between delousing activities and harvesting quantities may indicate a better-informed decision.

Changes in the sizes of harvested fish further reveal how salmon farmers adjust their harvest strategies in response to sea lice levels and delousing activities. Ideally, farmers should harvest fish of large sizes due to their higher prices, thereby generating more revenue from natural resources (Barrett et al., 2022). Our empirical results indicate that harvest sizes are negatively associated with sea lice level and delousing activities, in line with Oglend and Soini (2020). Pettersen et al. (2015) document a positive impact on economic performance of a disease-triggered prescheduled harvest given an average salmon weight of 3.2 kg or larger. For size-heterogenous farmed fish such as tilapia, an optimal harvest strategy is to keep the fish in the farm for a longer time as compared to results obtained from size-homogenous species (Gasca-Leyva et al., 2008). Thus, sea lice-induced early harvesting, accompanied by reduced fish sizes, may indicate that the adjusted harvest strategies in response to sea lice level are economically inefficient. However, the negative impact of delousing activities on harvest volumes may reduce the economic inefficiency tied to smaller fish size at harvest.

The TLS system, introduced in 2017, may alter the relationship between sea lice prevalence and salmon harvesting behaviors. The empirical results indicate that this is not the case as the TLS implementation did not change the response of salmon harvest quantities and fish sizes to sea lice levels. However, both delousing treatments and cleaner fish more negatively affect harvest quantities post TLS implementation, while their impacts on fish size remain the same. Salmon farmers have relied more on cleaner fish and mechanical treatments than medicinal treatments since 2017 (Fig. 4). Mechanical delousing methods are quite successful in terms of reducing sea lice prevalence, yet they may also severely stress and harm treated fish, increasing mortality (Barrett et al., 2022; Walde et al., 2022). The moribund fish due to risky treatments are probably harvested before they reach an optimal size for harvest, leading to reduced total harvest volumes. In addition, if moribund fish cannot be harvested before they die, harvest quantity may consequently decline.[10]

7. Conclusion

This study evaluates the impact of sea lice levels and delousing operations on Norwegian salmon farmers' harvest behavior regarding harvested fish sizes and volumes. Fish size is an important quality attribute reflected in higher market prices for larger fish, which is also found for other species such as Atlantic cod (Asche et al., 2015). A harvest strategy is a process of combining harvest quantities, fish sizes, costs, and market conditions. The negative impacts of sea lice and regulations on harvest quantities and fish sizes indicate economic losses for salmon farmers. However, stringent regulations may also motivate salmon farmers to innovate (Afewerki et al., 2023), leading to more effective delousing technologies and harvest strategies that may eventually raise profitability.

The present study combines datasets on sea lice, delousing activities (medicinal or mechanical treatments and cleaner fish), and harvest, resulting in 9243 monthly observations at the farm-site level from 2012 to 2021. Econometric models are applied to the empirical data to investigate the impact of sea lice on salmon farmers' harvesting strategies, which further reveal relationships between environmental and financial performances. Thus, the present study addresses the call made by Peñalosa Martinell et al. (2020) for aquaculture research to apply econometric models to explore the interdependence between any of the three pillars of sustainability in the aquaculture industry.

Our empirical results indicate that sea lice levels are positively associated with harvest quantities and negatively associated with fish size. The opposite impacts of sea lice levels on harvest quantities and fish sizes can likely be attributed to uncertainty regarding the consequences of sea lice levels, indicating that reliable information on biomass is important for optimal harvesting strategies (Engehagen et al., 2021). Regarding delousing activities, the results show that both medicinal/mechanical treatments and cleaner fish have a negative effect on harvest quantities and fish sizes.

This study investigates the relationship between sea lice and salmon harvest behavior while also considering the influence of salmon and input prices. We provide new insights into the negative impact of sea lice and delousing operations on harvest strategies, which can be further used to evaluate how sea lice influence economic performance of salmon farming. Since salmon prices vary across size groups, the impact of sea lice and delousing activities on quantities and fish sizes implies a channel through which sea lice affect economic performance. This further indicates a direction for salmon farmers to improve profitability while simultaneously responding to environmental sustainability concerns and regulations. For example, the TLS implementation is associated with a more negative impact of delousing activities on harvest volumes, yet it does not affect fish size at harvest.

We need a better understanding of relationships between environmental sustainability concerns, new regulatory innovations responding to these concerns, and farmers' harvesting strategies and economic performance. TLS is a regulatory instrument that may not directly restrict short-run harvesting decisions. Still, we find an overall negative relationship between the TLS implementation and salmon farmers' harvest volumes, and changes in interactions between environmental mitigation actions and harvest volumes. This may affect economic performance, and regulatory innovations responding to emerging environmental sustainability issues, such as the TLS, should therefore motivate further studies.

[10] Only damaged or moribund salmon that are slaughtered before they die are categorized as having been harvested in the statistics (Sommerset et al., 2021).

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CRediT authorship contribution statement

Dengjun Zhang: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Geir Sogn-Grundvåg:** Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Ragnar Tveterås:** Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

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Data availability

The authors do not have permission to share data.

Appendix A

Table A1
Estimation results of Model A for *Harvest-Quantity*, without price variables.

Variable	Model A1	Model A2	Model A3	Model A4
log (Harvest-Quantity)-lag	0.2767***	0.0600***	0.2749***	0.2725***
	[0.0194]	[0.0027]	[0.019]	[0.019]
log (Biomass)-lag	0.6471***	−0.0339***	0.6628***	0.6617***
	[0.0296]	[0.0124]	[0.0302]	[0.0301]
Sea-Temperature	0.0158***	−0.0765***	0.0213***	0.0216***
	[0.0049]	[0.0232]	[0.0048]	[0.0048]
Number-Sea-Lice-lag	0.0431*	−0.0092***		
	[0.0246]	[0.001]		
Treatments-lag			−0.0541***	−0.0236*
			[0.0104]	[0.0127]
log (Number-Cleaner-Fish)-lag			−0.0179***	−0.0099*
			[0.0038]	[0.0056]
TLS	−0.0915***	−0.0147**	−0.0771***	−0.0257
	[0.0187]	[0.0061]	[0.0184]	[0.0222]
TLS * Number-Sea-Lice-lag		−0.004		
		[0.0078]		
TLS * Treatments-lag				−0.0596***
				[0.0222]
TLS * log (Cleaner-Fish)-lag				−0.0125*
				[0.0075]
Individual effect	Yes	Yes	Yes	Yes
Within R-Squared	0.128	0.129	0.133	0.134
Between R-Squared	0.877	0.878	0.877	0.879
Overall R-Squared	0.434	0.403	0.407	0.409
p-value of F test	< 0.01	< 0.01	< 0.01	< 0.01
Observations	9243	9243	9243	9243

Notes: *, **, and *** Stand for the significance level of 10%, 5%, and 1%, respectively. Robust and clustered standard errors are in brackets.

Table A2
Estimation results of Model B for *Harvest-Size*, without price variables.

Variable	Model B1	Model B2	Model B3	Model B4
log (Harvest-Quantity)	0.0599***	0.0599***	0.059***	0.0589***
	[0.0027]	[0.0027]	[0.0027]	[0.0027]
Sea-Temperature	−0.0092***	−0.0092***	−0.0082***	−0.0082***
	[0.001]	[0.001]	[0.001]	[0.001]
Number-Sea-Lice-lag	−0.0112*	−0.011*		
	[0.0061]	[0.0063]		
Treatments-lag			−0.0084***	−0.007**
			[0.002]	[0.0028]
log (Number-Cleaner-Fish)-lag		−0.0041***	−0.0023*	
			[0.0008]	[0.0014]
TLS	−0.0275***	−0.0273***	−0.0238***	−0.0197***
	[0.0056]	[0.0067]	[0.0056]	[0.0065]
TLS * Number-Sea-Lice-lag		−0.0009		
		[0.0167]		
TLS * Treatments-lag				−0.0028
				[0.0041]
TLS * log (Cleaner-Fish)-lag				−0.0027*
				[0.0016]
Individual effect	Yes	Yes	Yes	Yes
Within R-Squared	0.134	0.134	0.139	0.14
Between R-Squared	0.134	0.134	0.192	0.211
Overall R-Squared	0.177	0.177	0.182	0.183

(*continued on next page*)

Table A2 (*continued*)

Variable	Model B1	Model B2	Model B3	Model B4
p-value of F test	< 0.01	< 0.01	< 0.01	< 0.01
Observations	9243	9243	9243	9243

Notes: *, **, and *** Stand for the significance level of 10%, 5%, and 1%, respectively. Robust and clustered standard errors are in brackets.

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