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Estimated effectiveness of treatments against salmon lice in marine salmonid farming

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ABSTRACT

We here estimate the effectiveness of ten types of salmon lice treatments currently used in the salmonid industry by analysing daily and cage-wise data from 90 full production cycles from farms spread along the Norwegian coast. The calculations are based on a stage-structured population model for salmon lice and accounts for the structure of the data, including the uncertainties that arise from the weekly counting of lice on a subset of the fish. Results suggest that the most commonly used treatment methods in the data set, i.e. thermal, mechanical and freshwater treatments, kill 70–80% of the lice in average, but with high variability. Feed treatments with emamectin benzoate are also commonly used, but are only estimated to kill around 35% of the lice in average. Bath treatments with hydrogen peroxide are estimated to kill around 74% and pyrethroids 50% of the lice in average. The other medicinal treatments were infrequently used in the data set and the estimates are therefore more uncertain. Of note is that the recently licenced bath treatment with imidacloprid is estimated to kill more than 99% of sessile and 98% of pre-adult and adult lice in average. The estimated effects of hydrogen peroxide, pyrethroids and azamethiphos, here based on data from 2017–2020, are lower than estimates from a previous analysis of production data from 2011–2014, possibly because of resistance development. In contrast, there is no indication of reduced effects of thermal, mechanical or freshwater treatments compared to previous analyses of production data from 2013–2018. These results allow comparing the effectiveness of the different treatment methods in a consistent and comprehensive way, hence enabling fish farmers and authorities to better balance the expected benefits of the treatments in terms of lice control against the economic costs, fish welfare and risk of resistance development.

1. Introduction

Salmon farming has become a large and economically prosperous international industry over the last decades. Norway holds a leading position as a producer of farmed salmonids with an annual production above 1.4 million tonnes, which is roughly half of the worldwide production (FAO, 2022). Further growth in the production of salmonids is in demand (Anonymous, 2015), but this will come at the cost of increasing risks of pathogen propagation and transmission. Of special concern, is the spread of the salmon louse, *Lepeophtheirus salmonis*, which is perceived as a major threat to wild salmonid populations and if not controlled; also a threat to the health of farmed salmonids (Grimnes and Jakobsen, 1996; Wagner et al., 2008; Taranger et al., 2015; Vollset et al., 2015; Forseth et al., 2017).

Salmon lice have traditionally been controlled using anti-parasitic medicines, as either in-feed or bath treatments. Frequent treatments with medicines containing active substances from relatively few chemical classes have led to resistance development towards almost all available anti-parasitics (Aaen et al., 2015; Helgesen et al., 2015). Several non-medicinal treatment methods against salmon lice have therefore been developed in the last decade, e.g. exposing the lice-infested fish to freshwater, heated seawater or removing the lice through brushing or flushing (Overton et al., 2019; Jensen et al., 2020). The non-medicinal methods have, however, shown worse side-effects than medicinal treatments through injuries and increased mortality of the treated fish (Oliveira et al., 2021; Walde et al., 2021; Moltumyr et al., 2022). These treatments are therefore entailing increased costs, both in terms of the welfare of the farmed fish and the economic costs for the fish farmers. There is furthermore a concern that the salmon lice may be developing resistance against non-medicinal treatment methods (Groner

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et al., 2019). This concern is fueled by indications of variation among salmon lice families in their tolerance to heated or low-saline water (Ljungfeldt et al., 2017). However, it is not known whether genotypes conferring high tolerance towards these two treatments are spreading in the lice populations.

The effectiveness of the different treatment methods is evaluated by fish farmers as well as by regulatory authorities. The goals of the evaluations can be to measure effectiveness against maximum permitted lice numbers and/or to evaluate the ethical and economical sides of the treatments. Every treatment has welfare and financial costs, which need to be balanced against the assumed benefits of the treatments in terms of controlling the lice abundance. Reliable effectiveness results are important for finding the optimal balance between these costs and benefits. However, our knowledge of treatment effectiveness is fragmented and often relying on small-scale studies. Moreover, the knowledge becomes rapidly outdated. For example, while it is well documented that salmon lice have become less sensitive to medicinal treatments due to the spread of resistant genotypes (Kaur et al., 2017; Fjørtoft et al., 2020), less is known about how treatment effectiveness has changed in practice, which also depends on e.g. operating procedures and doses. Knowledge about changes in treatment effectiveness can furthermore possibly be used for early resistance detection, for broad-scale resistance surveillance and for resistance monitoring of methods where no resistance tests are available.The aim of the present paper is to estimate the effectiveness of the types of treatments that are currently used in the Norwegian salmonid industry. This includes medicated feed, medicinal bath treatments and non-medicinal treatments. The effectiveness of each of these treatments is estimated from daily and cage-wise data from 90 full production cycles from stocking to slaughter from marine salmonid farms spread along the Norwegian coast. The calculations are based on an updated version of a mechanistic stage-structured population model for salmon lice developed by Aldrin et al. (2017). This model allows for the complexities inherent in full-scale salmon farming and accounts for the structure of the data obtained from the production system, where salmon lice are counted on samples of fish from separate cages within a farm. The pharmacological differences between the active substances of the medicinal treatments are incorporated in the assumptions taken in the model. In this paper, we focus on the estimates of the treatment effectiveness and relates these results to other knowledge about the treatment use. The model itself is briefly presented in the main part of the paper and described in more detail in the Supplementary material.

2. Lice treatments

We divide the various treatment types into three main groups: medicated feed, medicinal bath treatments and non-medicinal treatments (Table 1). The medicated feeds are typically given over one or two weeks and have a relatively low daily effectiveness, but the effects last over a period. The other treatments are applied over a duration of seconds to minutes, with a more or less immediate effect. Furthermore, some of the treatments have effect on all parasitic life stages of lice (copepodids, chalimi, pre-adults, adults), while others have effect on only some of the stages.

There are marketing authorisations of medicated feed against salmon lice with the active substances emamectin benzoate (EMB), diflubenzuron and teflubenzuron. All of these in-feed treatments have been in ordinary use for several years (Aaen et al., 2015). In addition, medicated feed with lufenuron has been applied against salmon lice in some countries in the later years, however not in Norway (Junquera et al., 2019). EMB is effective against all parasitic life stages and gives a prolonged effect, meaning that it also kills lice that attach to the fish several days after the treatment has ended (Anonymous, 2022a). Diflu- and teflubenzuron are chitin synthesis inhibitors that obstruct with the moulting and are therefore not effective against adult parasites. These substances have no prolonged effect. Hydrogen peroxide (H_2O_2), pyrethroids (deltamethrin and cypermethrin), azamethiphos and imidacloprid are all active substances in medicinal bath treatments against salmon lice. Except for imidacloprid, these treatments have been used extensively for several years, and as a consequence, resistance is widespread (Aaen et al., 2015; Jensen et al., 2020). Ectosan (containing imidacloprid) got market authorisation in Norway in 2021, and was then the first medicinal treatment with an active substance from a new chemical class that was introduced to the Norwegian market for more than twenty years. Pyrethroids have effect on all parasitic life stages, while hydrogen peroxide and azamethiphos have effect on the motile stages (pre-adults and adults, Johnson et al. (1993), Roth et al. (1996), Hart et al. (1997)). Imidacloprid's marketing authorisation holder says that it has effect on motile lice (Anonymous, 2022b). All of the bath treatments only have effect on the lice present when the fish are treated, but for some substances the full effect cannot be seen immediately, as it may take some hours before all moribund lice have fallen off (Kaur et al., 2015; Jensen et al., 2017).

Non-medicinal treatments can be divided into thermal (heated water, up to 34 °C), mechanical (brushing and flushing) and freshwater treatments. These treatments have since 2016 replaced many of the medicinal treatments (Overton et al., 2019).

As a preparation for this study a literature search was performed to be able to answer questions on duration of treatment efficacy and life stages affected by treatments, with the various active substances included in this study. As for duration of treatment efficacy, only emamectin benzoate has effect on lice attaching to the treated fish post treatment, due to slow elimination of the active substance (Kim-Kang et al., 2004; Sevatdal et al., 2005). The Summary of Product

Table 1

Overview over types of lice treatments, assumptions we do in the modelling, number of treatment events, number of farms per treatment type and production areas where the treatment type has been used in our data. Codes: MF = medicated feed, MB = medicinal bath, NM = non-medicinal, Y = yes, N = no, S = sessile (attached copepodids and chalimi), PA = Pre-adults, A = adults. Duration is the assumed number of days with increased mortality.

Treatment name or medical used	Type	Duration (days)	Effect on S	Effect on PA	Effect on A	Number of treatments	Number of farms	Production areas
Emamectin benzoate	MF	60	Y	Y	Y	458	53	2,3,5,6,7,9,10,11,12
Diflubenzuron	MF	*a*	Y[b]	Y[b]	N	27	3	3,9
Teflubenzuron	MF	*a*	Y[b]	Y[b]	N	23	3	2,3
Hydrogen peroxide	MB	1	N	Y	Y	131	15	2,3,10,12
Pyrethroids	MB	7	Y	Y	Y	137	14	2,6,10,12
Azamethiphos	MB	1	N	Y	Y	47	4	11,12
Imidacloprid	MB	1	Y[c]	Y	Y	29	5	2
Thermal	NM	1	Y	Y	Y	948	57	2,3,5,6,7,9,10,11,12
Mechanical	NM	1	Y	Y	Y	640	40	2,3,5,6,7,9,10,11
Freshwater	NM	1	Y	Y	Y	458	19	2,3

[a] Duration until development from PA to A.

[b] Causes excess mortality when developing from S to PA and from PA to A, see Section 4.

[c] It is not known if imidacloprid has effect on sessile lice.

Characteristics (SPC) of the medicinal product containing emamectin benzoate, Slice®, says that efficacy can be expected in up to approximately 60 days (Anonymous, 2022a). A duration of 60 days was therefore taken as the model assumption, although some studies have found efficacy exceeding 60 days (Stone et al., 2000a; Armstrong et al., 2000). The duration of pyrethroids was chosen to be 7 days in this model, since this has been shown in both laboratory and field studies, although most lice have been seen to detach during the first 24 h (Jensen et al., 2017; Hart et al., 1997). The choice of moving from temperature dependent duration as in Aldrin et al. (2017) to fixed duration as the model assumptions, was the lack of literature to support the choice of a temperature-dependent curve. For pyrethroids this has to our knowledge not been studied, while for emamectin benzoate it has been studied to some degree for maximum efficacy, but not duration of efficacy. In addition temperature has varied during each individual study in both the laboratory and in the field (Ramstad et al., 2002; Stone et al., 2000a, b; Armstrong et al., 2000; Gustafson et al., 2007; Stone et al., 1999).

3. Data

The data consists of detailed, daily production data from 90 salmonid (mostly Atlantic salmon, *Salmo salar* L., but also rainbow trout *Oncorhynchus mykiss*) farms from five different salmonid producers (Bremnes Seashore, Bolaks, Salmar Farming, Grieg Seafood and Ellingsen Seafood), with one cohort per farm, that is a full production cycle from sea stocking until slaughter. The coast of Norway is divided into 13 production zones (Fig. 1), and the farms in our data are located in 9 of these (2, 3, 5, 6, 7, 9, 10, 11 and 12). The 90 farms are not picked at random, but we still believe they are quite representative for salmonid farms in Norway. For the set of farms managed by the five companies, we selected the last completed production cycle at each farm, conditioned on fish being stocked in 2016 and later and that there had been no movement of fish between farms. The 90 farms cover 8% of all farms that have been active in the period 2016–2020 in Norway, 12% of the farms in the 9 production areas and between 7 and 30% of the farms within each production area.

Three cohorts were stocked in 2016, 34 in 2017, 37 in 2018 and 16 in 2019, and they were all slaughtered between 2018 and 2020. Each farm had between 2 and 18 cages, and there was on average 8.1 cages per farm (732 cages in total). Fish were sometimes moved between cages, and some cages had fish in only a part of the production cycle.

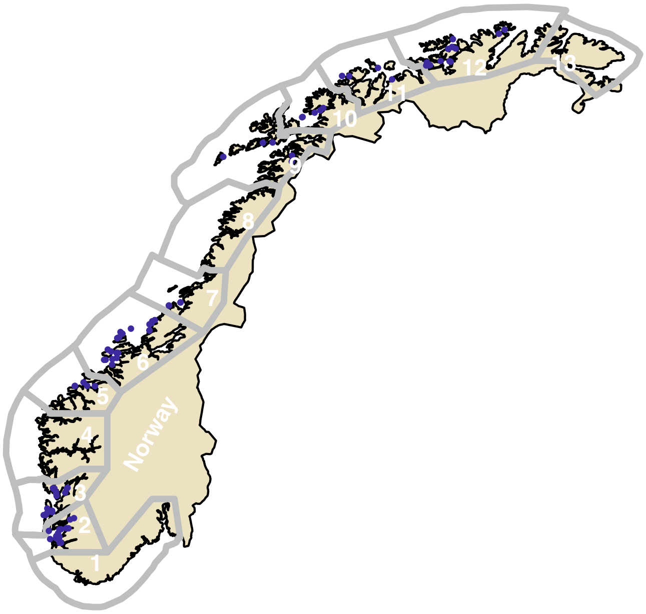

Fig. 1. The 13 production zones along the coast of Norway. Farms in our data set are marked with blue circles.

Weekly seawater temperatures and daily salinities were available at farm level. Temperatures, measured at 3 m depth, were downloaded from Barentswatch.no, and interpolated from weekly to daily time resolution. Average temperature was 9.0 °C, and 95% of the temperatures were between 3.1 and 16.6 °C. Salinity data for 0–3 m depth, computed from the hydrodynamic model NorKyst800, were downloaded from met.no. 95% of the salinity data were between 21.6 and 34.6 practical salinity units (psu), with an average of 31.7 psu.

Data on cage level include daily number of fish and their mean weight per cage, covering 297 538 cage-days with fish. On average, there were 130 000 fish per cage, but more in the beginning and less at the end of a production cycle. The average stocking weight was 145 g and the average slaughter weight was 5.1 kg.

The numbers of lice on fish were manually counted weekly in each cage, giving a total of 40 800 lice counts with around 20 fish investigated in each count. The counted lice were grouped into female adults, other motiles (pre-adults and male adults) and sessile (attached copepodids and chalimi). On average, there were 0.12 sessile, 0.47 other motile and 0.13 adult female lice per fish. The data also contain information on stocking of cleaner fish (day and number of cleaner fish stocked), which were divided into lumpfish (*Cyclopterus lumpus*) and wrasses (usually ballan wrasses, *Labrus bergylta*, or goldsinny wrasses, *Ctenolabrus rupestris*).

Of particular importance in the present study is the information on lice treatments (cage, day of application and type of treatment). We use the term treatment event for each new application of a given treatment in a cage. Medicated feed given for a period of one or two weeks is then regarded as one treatment event. There were 508 medicated feed, 315 medicinal bath and 1717 non-medicinal treatment events, see Table 1 for details. Note that there are only between 23 and 47 treatment events for each of the treatment types diflubenzuron, teflubenzuron, azamethiphos and imidacloprid, and that they only have been applied at 3–5 farms.

In addition to the detailed cage-level data, we have more aggregated data on all other Norwegian marine salmonid farms. For each farm, we know the weekly number of salmonids and the number of adult female lice per fish based on lice counts. We also have the seaway distances between all farms. Based on these data, we calculated a daily external infestation pressure index (Aldrin et al., 2017) for each of the 90 farms with detailed data.

Fig. 2, shows some of the data for one specific cage for each of three farms. The upper panel shows time series of temperature, weight and infestation pressure from neighbouring farms. Vertical lines indicate when the fish were stocked, treatment events (emamectin benzoate, freshwater, imidacloprid and two thermal in this example) and stocking of cleaner fish. The lower panel shows abundances of different lice stages based on weekly manual lice counts. There are no visual effects of the feed treatment by emamectin benzoate, but this does not exclude that it has effect in total over a period, since it may affect the lice for two months (Table 1). The lice counts for all stages seem to decrease immediately after each of the four non-feed treatments. Note also that the second thermal treatment seems to be more effective than the first one, illustrating that there may be large, random variation in effectiveness between different treatments even if they are of the same type. Fig. 3 shows data for one cage at another farm, with lower seawater temperature and infection pressure (upper panel) than at the farm in Fig. 2, and therefore also with few treatments (lower panel). It is not possible to see any effect of the azamethiphos treatment, whereas both the hydrogen peroxide treatment and the feed treatment by teflubenzuron seem to be quite effective. Fig. 4 gives a third example, where the many treatments indicate that it has been difficult to control the lice level. Both the mechanical treatment and most of the thermal treatments seem to have reduced the lice levels shortly after the treatments. A fourth example of data is given in the Supplementary material.

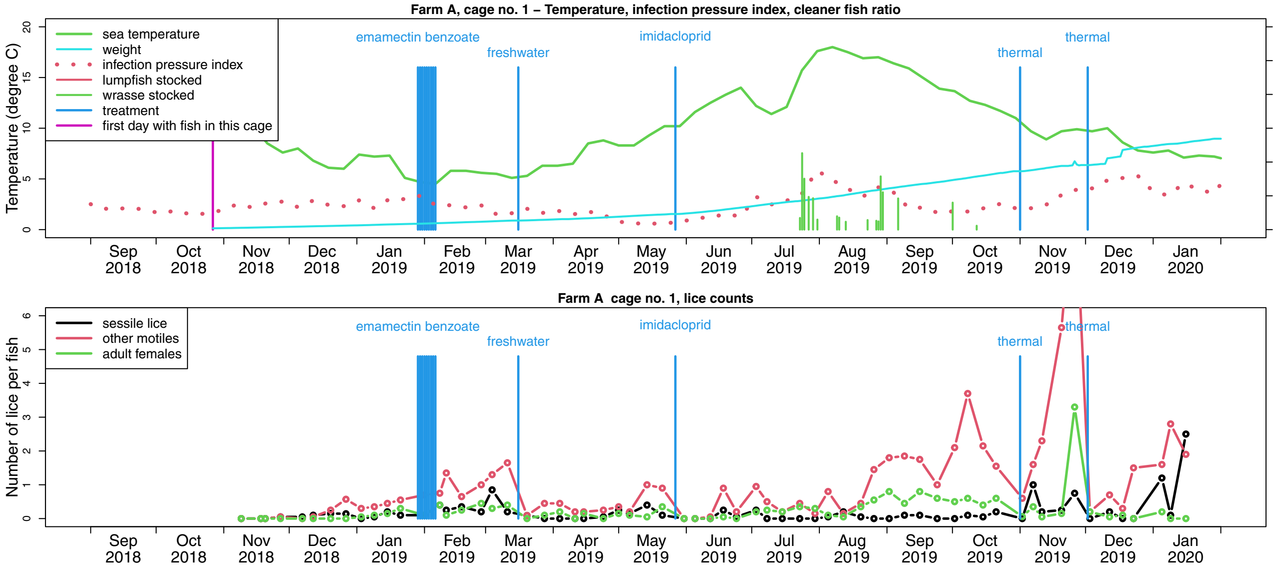

Fig. 2. Data for one cage at farm A. For weight in the upper panel, the y-axis goes from 0 kg to 10 kg, corresponding to 0 and 20\degreeC on the left y-axis. Infection pressure is an index without any unit. Cleaner fish ratio is the number of cleaner fish divided on the number of salmonids.

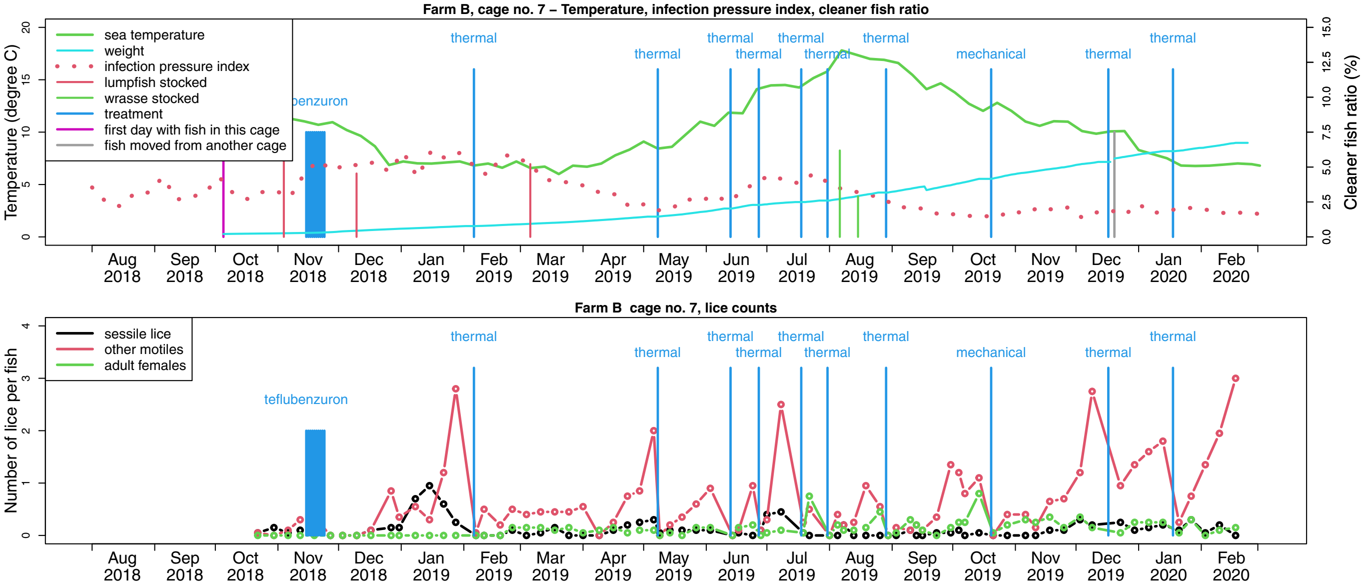

Fig. 3. Data for one cage at farm B. See figure caption for Fig. 2 for more explanation.

4. Population model

The population model for lice is an updated version of a model presented by Aldrin et al. (2017). Here we present the main features of the model, while a more detailed description is given in the Supplementary material. Fig. 5 gives an overview of the model. The model divides lice into five stages, where some of the modelled stages include more than one biological stage. Recruits (R) include eggs and the non-infective nauplii I and nauplii II larvae stages. Copepodids (CO) are infective copepodid larvae in the water, before they have attached to a fish. Sessile lice (S) include copepodids that have attached to a fish and chalimi (chalimus I and II). Pre-adult lice (PA) include lice in the pre-adult I and pre-adult II stages. Finally, adult lice (A) are divided into adult males (AM) and adult females (AF). Adult females reproduce and produce recruits. When salmonid smolts are stocked at sea, they are always free of lice, and the infestation process starts by external infestation of recruits produced by adult females at neighbouring farms. Then, from one day to the next, a louse can either die or survive, and if it survives, it can either develop to the next stage or stay in the stage. Development times depend on temperature; the higher temperature, the shorter it takes to develop to the next stage. The infestation success, i.e. the probability for a copepodid larva to attach to a fish, is also dependent of temperature and increases with the number of fish and their size.

The mortality from one day to another is divided into natural mortality, mortality due to use of cleaner fish and mortality due to lice treatments, where the latter is the focus of this paper. Our assumptions regarding which lice stages that are affected, and the duration of this effect are summarised in Table 1.

Sometimes a treatment of a certain type can be very successful, but other times its effectiveness can be smaller. Therefore, for each treatment event of a given treatment type, we assume that the proportion of lice killed due to the treatment is stochastic with a mean dependent on the treatment type. For imidacloprid, we assume that this mean effect is equal for pre-adults and adults. It is unknown whether imidacloprid has

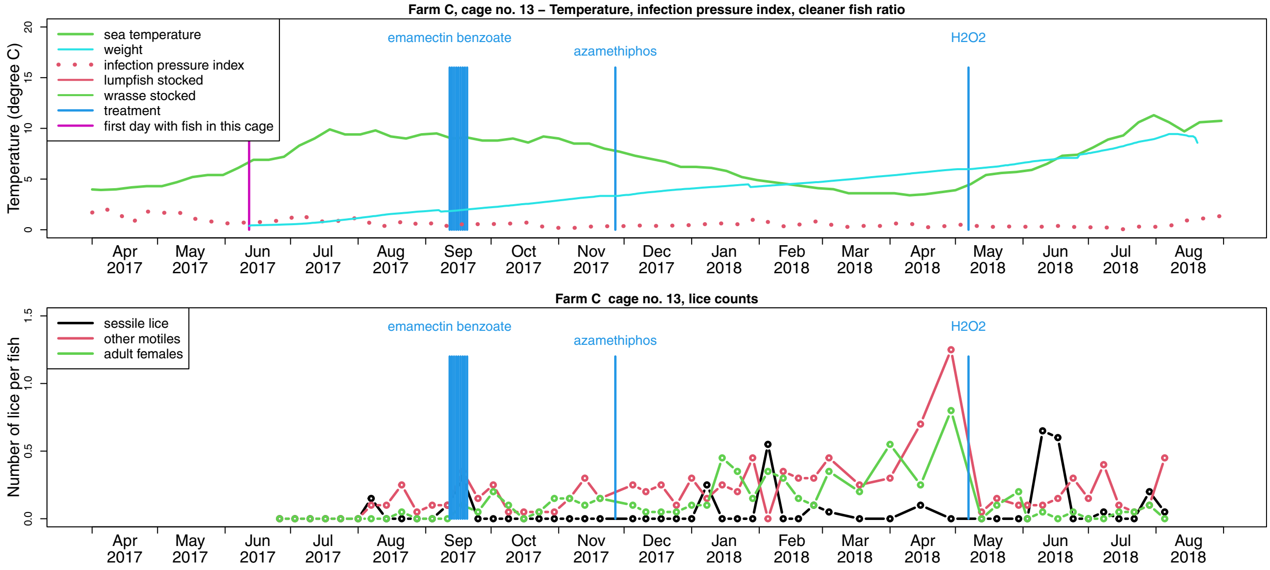

Fig. 4. Data for one cage at farm C. See figure caption for Fig. 2 for more explanation.

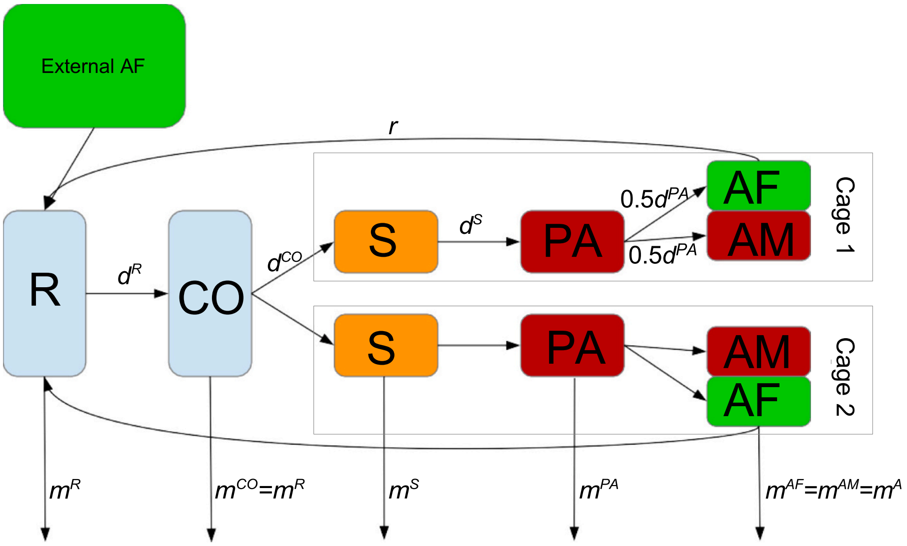

Fig. 5. Overview of the population model for a farm with two cages. The colours indicate the counting groups: R and CO not counted, S counted, PA and AM counted together, AF counted. Other notation: r = recruitment, d = development, m = mortality.

an effect on sessile lice, and we therefore assume a separate effect for this stage. For all other treatment types, we assume that the mean effect is equal for all stages for which the treatment type is assumed to have effect. Furthermore, if the effect of the treatment lasts for several days, we assume an equal treatment mortality each of these days that adds up to a total mortality due to the treatment.

For the medicinal bath and the non-medicinal treatments, we assume that lice that already are attached on the fish at the day of treatment are affected, and that the effect starts immediately. Except for pyrethroids, we assume that the effect lasts for one day, so the full effectiveness can be seen already the day after the treatment. For pyrethroids, we assume that the duration of the effect is seven days. This prolonged duration is not expected to come from a prolonged effect, but from a variation in time from treatment to death.

EMB is typically given for one week. We assume that it results in a daily constant excess mortality in a period from the first treatment day until 59 days after the last treatment day (the duration of the effect is 60 days including the treatment day). We assume that both lice that are attached to the fish at the start of the feeding period and lice that become attached to a fish any time until 59 days after the last treatment day are affected by the treatment.

Diflubenzuron and teflubenzuron are typically given for two weeks. These medicated feeds obstruct with the moulting. When several biological stages are merged into one model stage, the model cannot handle moultings within the model stage. For simplicity we therefore ignore that there are moultings within the S and PA stages, and assume that the treatment results in excess mortality when lice develop from S to PA or from PA to A, but only for lice that become attached to a fish until the last treatment day. See Supplementary material for details on the implementation of these assumptions.

5. Results

Fig. 6 shows the model fit to the lice counts shown in Fig. 2. We see clearly the estimated effects of the freshwater, imidacloprid and thermal treatments. Corresponding figures for the model fits to the lice counts shown in Figs. 3 and 4 as well as estimates of all model parameters are given in the Supplementary material. In the remaining part of this

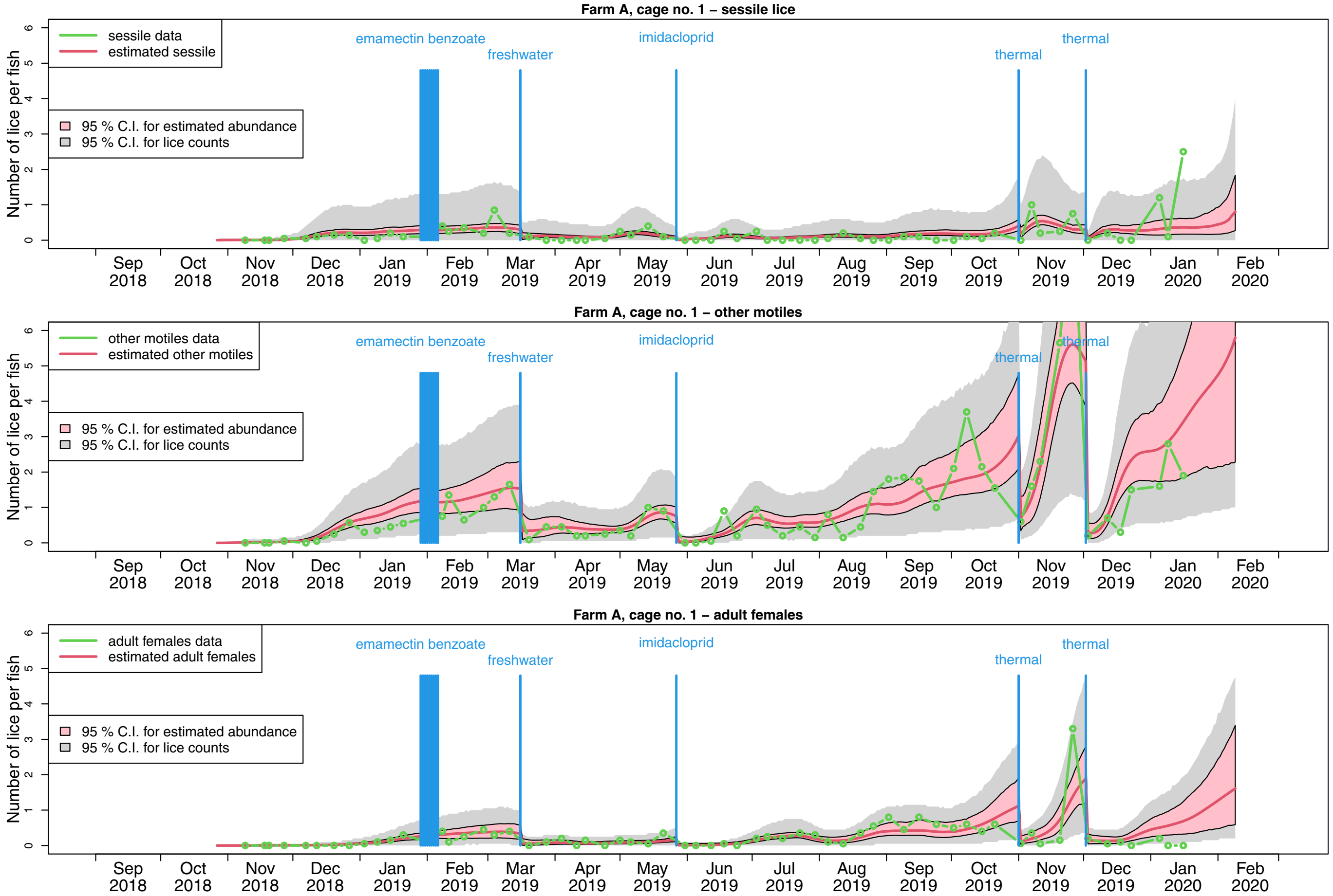

Fig. 6. Model fit for one cage an Farm A.The abundance of sessile lice is shown on the scale of the lice counts, which underestimates the true abundance by a factor of around four according to the model results.

section, we focus on the estimated mortality effect of each treatment type.

The estimated expected total excess (to natural mortality and mortality from cleaner fish) mortality per treatment event for each treatment type is given in Table 2, together with 95% uncertainty intervals. In addition, the table gives the 2.5% and 97.5% percentiles for the distribution of the treatment effectiveness, indicating that 95% of the treatments will have an effect in these intervals. Remember that

Table 2
Estimates (posterior means) of expected total excess mortality (in %) per treatment event for each treatment type, with 95% uncertainty (credible) interval (C.I) for the expected value. This is given for the present study and the previous studies Aldrin and Huseby (2020) (Study 2) and Aldrin et al. (2017) (Study 1). For the present study, the column "95%D.I." gives 95% intervals for the distribution for a random treatment.

Treatment type	Effect on stages	This study. Data from 2017–2020			Study 2. Data from 2013–2018		Study 1. Data from 2011–2014	
		Est.	95%C.I.	95%D.I.	Est.	95%C.I.	Est.	95%C.I.
Emamectin benzoate	S, PA, A	35	31–39	0–100				
Diflubenzuron	PA →A[a]	88	76–96	8–100				
Diflubenzuron	S → PA →A[b]	99	94–100	16–100				
Teflubenzuron	PA →A[a]	79	63–92	2–100				
Teflubenzuron	S → PA →A[b]	96	87–99	3–100				
Hydrogen peroxide[c]	PA, A	74	67–80	5–100	69[e]	59–78	99[e]	97–100
Pyrethroid[c]	S, PA, A	50	43–56	0–100	71[e]	60–80	94[e]	89–98
Azamethiphos[cd]	PA, A	26	13–43	0–94	44[e]	29–59	75[e]	64–86
Imidacloprid	S	99.9	99.6–100	99.6–100				
Imidacloprid	PA,A	98	95–99	79–100				
Thermal	S, PA, A	80	78–81	21–100	76	71–80		
Mechanical	S, PA, A	69	67–71	11–99	56	36–74		
Freshwater	S, PA, A	74	69–78	14–99	68	47–85		

[a] When developing from PA to A.
[b] When developing first from S to PA and then further to A.
[c] Assumptions for delay and duration differ between the present study and the previous studies.
[d] One third of azamethiphos treatments in this study were shortened due to production problems.
[e] At seawater tmeperature 10° and 10 days after treatment.

there are less than 50 treatment events available for estimation of the effects of diflubenzuron, teflubenzuron, azamethiphos and imidacloprid. In addition, each of these treatment types were used on only between three and five farms, and a third of the azamethiphos treatments were shortened due to production problems. One should therefore be more careful when interpreting the results for these treatment types than the others. The table consists of two rows for each of diflubenzuron and teflubenzuron. The first row applies to lice that are in the PA stage when treated, and experience excess mortality when developing from PA to A. The second row applies to lice that are in the S stage when treated, and first experience excess mortality when developing from S to PA, and, if they survive, later experience excess mortality when developing from PA to A. There are also two rows for imidacloprid, one for the estimated excess mortality in the S stage and another for the PA and A stages.

Table 2 also presents estimates for hydrogen peroxide, pyrethroids and azamethiphos from the study by Aldrin et al. (2017). These estimates were based on production data between 2011 and 2014 from 32 farms in production zones 2, 3, 4, 5 and 6. In addition, Table 2 presents estimates from an intermediate study (Aldrin and Huseby, 2020) for six of the treatment types. Those estimates were based on data between 2013 and 2018 from 35 farms in production zone 2. However, note that the assumptions on delay and duration for these treatment types have been updated in the present study compared to the two previous ones (Table 1 in this paper compared to Table 1 in Aldrin et al. (2017)).

6. Discussion

The effectiveness of 10 different treatment methods against salmon lice, seven medicinal and three non-medicinal, have been calculated by applying a salmon lice population model on a data set of cage-wise production data. The effectiveness of each treatment type is stochastic, and may vary substantially between different treatments of the same type. The variation may e.g. origin in lice biology; resistance or natural variation in sensitivity (Roth et al., 1996; Helgesen et al., 2019), in fish biology; e.g. appetite for in-feed treatments (St-Hilaire et al., 2019), or for technical reasons; e.g. treatment dose or temperature and holding time (Roth et al., 1996; Nilsson et al., 2023). Additionally effectiveness is difficult to assess for single treatments due to lice' uneven distribution on fish and that typically small sample sizes are applied for calculation of effectiveness (Jimenez et al., 2012). When treatment effectiveness has been found to decline over time; resistance has been suggested to be the main explanation (Jones et al., 2013; Godwin et al., 2022).

The most effective treatments were medicinal treatments with the active substances imidacloprid and the benzoylureas diflubenzuron and teflubenzuron. Imidacloprid can however not be a sole treatment option since medicinal treatment methods historically have lost effectiveness over time due to resistance (Aaen et al., 2015). Of note is also the limited number of treated cages and farms from which these figures are calculated (23–29 treated cages and 3–5 farms). The high effectiveness of imidacloprid is nonetheless expected, since the product was new to the market in 2021 and other medicinal treatments also showed high effectiveness in their first years on the market (Hart et al., 1997; Ramstad et al., 2002). We also found effect of imidacloprid on sessile lice, which we have not seen documented elsewhere. More surprising is the relatively high effectiveness of diflubenzuron and teflubenzuron, considering that these medicinal treatments have been used since 1996 in Norway. The use has however always been limited, probably since the substances lack effect on adult lice and because of the potential effects on wild crustaceans (Branson et al., 2000; Helgesen et al., 2022).

Treatments with EMB, pyrethroids and azamethiphos as active substances all showed at most 50% mean effectiveness in the current study. Relatively few treated cages with azamethiphos at few farms in the data set again questions the generalisability of this result. The low treatment results when using these three substances coincide with the widespread resistance against the same compounds seen in Norway at least since 2013 (Jensen et al., 2020). Resistance towards pyrethroids and azamethiphos have also been found in lice throughout the Atlantic Ocean (Kaur et al., 2017; Fjørtoft et al., 2020) and towards EMB, also the Pacific Ocean (Godwin et al., 2022). The low effectiveness seen in the current study is of note when assessing if or when these types of treatments should be performed, considering also the medicines' unwanted effects on non-target organisms, their economic costs and the side effects on the fish from the treatment process.

The non-medicinal treatments showed similar mean effectiveness in the range 69–80%. Since equal effect on all attached life stages is assumed in the model for the non-medicinal methods, lower effectiveness on one or more life stage might hide high effectiveness on others. Experimental studies suggest, for example, that except for the effect of handling the fish, thermal treatments have little or no effect on sessile stages (Nilsson et al., 2023), implying that the effects on pre-adult and adult lice may be higher than the estimated mean effect in Table 2. The side effects of non-medicinal treatment methods are both injuries and mortality of the fish (Overton et al., 2019; Moltumyr et al., 2022; Østevik et al., 2022). The exact side effects and their strength vary between methods and the calculated effectiveness from this study can be used when choosing treatment method.

All non-medicinal methods showed indications of increased effectiveness compared to the previous comparable study, as presented in Table 2. This might be because the producers and the operators of these methods have made improvements over time to increase effectiveness. The frequent and increasing use of these methods since 2016 have given the opportunity for selection of resistant parasites (Groner et al., 2019), but the relatively high effectiveness seen in the current study indicates that this has not happened. Only one of the non-medicinal treatment methods (freshwater) is included in the Norwegian resistance monitoring program for salmon lice, making these effectiveness figures even more important for resistance evaluation (Helgesen et al., 2022). The results from the present study hence show the potential for using cage-level farm production and lice monitoring data in resistance monitoring. Today however only farm-level lice data are publicly available in Norway.

For both pyrethroids and azamethiphos, the development in effectiveness has been negative over time as shown in Table 2. Contradictory to this finding, the resistance surveillance program has showed a tendency of reduced resistance since 2016 (Helgesen et al., 2022). Some of the explanation can be the selection of farms for the studies. The inclusion criteria were not equal in the three studies presented in Table 2 as well as not between those studies and the resistance surveillance program. The different assumptions for delay and duration of effect between the present study and the previous studies cannot explain the trend, as preliminary analysis using the previous model assumptions provided similar effect estimates for these substances (results not shown).

Treatments with hydrogen peroxide showed effectiveness at the level of the non-medicinal treatments and contrary to the other bath treatments, a small, non-significant, increase in treatment effectiveness compared to the previous study presented in Table 2. A non-significant increase in estimated effectiveness compared to the previous study was also found in the preliminary analyses using the previous model assumptions (results not shown). The resistance surveillance program has reported lower levels of resistance towards hydrogen peroxide than to the other substances included, and signs of reduced resistance since 2016 (Helgesen et al., 2022). These results coincide with the results of the current study.

A more crude estimation of effectiveness based on comparing lice counts before and after treatments on a subset of the data confirmed most of the model-based results (see Supplementary material). One exception was that the crude estimation only showed around 80% reduction in lice numbers after imidacloprid treatments, which is lower than the model-based estimate of close to 100% effectiveness. Another exception was that the average abundance of sessile lice was reduced after azamethiphos treatments, in contradiction to our model assumption.

We also estimated cleaning effects of wrasse and lumpfish in our model (see details in the Supplementary material). The results showed practically significant effects of wrasse, while the estimated cleaning effect for lumpfish was negligible. Note that the estimated effects are uncertain, particularly as we do not have direct estimates on the number of cleaner fish present. This depends on the unknown mortality rate, which we also have to estimate. Stomach content data clearly show that there is a nonzero cleaning effect of lumpfish (Engebretsen et al., 2022). In order to compare our estimated effects to those implied by stomach contents, it is necessary to combine the stomach content estimates with estimates of evacuation time for salmon lice in lumpfish, which has not yet been done.

The results presented here allow comparing the effectiveness of the different treatment methods currently used in salmonid aquaculture in Norway in a consistent and comprehensive way. Hence, fish farmers and authorities can make better-informed decisions about which methods should be used to control salmon lice under different circumstances, also considering the economic costs involved, fish welfare and the risk of resistance development.

CRediT authorship contribution statement

M. Aldrin: Methodology, Software, Writing-original-draft. **R.B. Huseby:** Methodology, Software, Writing-review-editing. **L.C. Stige:** Methodology, Software, Writing-review-editing. **K.O. Helgesen:** Methodology, Writing-review-editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.aquaculture.2023.739749.

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