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Faculty of Applied Ecology and Agricultural Sciences

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Master thesis

Possible underestimation of salmon lice (*Lepeophtheirus salmonis*) abundance using sentinel cages.

Master's in applied ecology

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Abstract

One of the biggest challenges related to salmon lice today is to get an accurate estimate of lice in its infectious life stage. A standard method to quantify this is to use sentinel cages with salmon smolts. In this study I compare the infestation levels on smolt in time series of sentinel cages from 2012-2017 with a lice infestation model developed at the Norwegian Veterinary Institute. In addition, in 2017 I did a comparative study between the sentinel cages and newly developed method involving towing a cage, to better mimic the natural behavior of the wild salmonids. Finally, the effect of depths was measured in a subset of 3 sentinel cage locations, where replicated cages were placed 3 meters apart at the surface, while also placing 2 cages at greater depths (4 meter and 7 meter). In general, the lice infestation model predicting the number of lice in sentinel cages well at low densities but underestimated at higher densities. In 2012, the model estimated about 1 lice less then what was observed per sentinel cage. In the other years the average number of lice per cage was less than 1. In 2017, a fish from the mobile smolt cages had on average 0.06 lice after one tow (duration of about 6 hours). Scaling up to one week, a smolt from mobile cages would on average have 2.65 lice, compared to only 0.08 lice in the sentinel cages and infestation model. In 2017 the salinity, temperature and placement of the cages did not show any effect on the number of lice on the smolts. This study shows that the relationship between salmon lice density and infestation might be more dependent on the mobility of the fish, and consequently the volume sampled, rather than the time spent at a given location.

Sammandrag

Ein av dei største utfordingane tilknytt lakselus i dag er å få nøyaktige estimat på tettleiken av dei smittsame livsstadia til lusa. Ein standard metode for å måle dette er å bruke faststående smoltbur med laksesmolt. I dette studie har eg samanlikna talet lakselus på smolt frå smoltbur, med ein risikomodell som estimerer talet lakselus på smolt i tidsperioden 2012 – 2017. I tillegg har eg samanlikna talet lus på smolt frå smoltbur med talet lus på smolt frå ein nyutvikla metode som sleper eit bur med smolt, for å etterlikna ein frittlevande laksefisk. Til slutt har eg sett på effekten av djupn, ved å plassere 2 bur i overflata, med om lag 3 meter mellomrom, eit bur på 4 meters djup, og eit bur på 7 meters djup. Generelt så estimerte risikomodellen talet lus bra ved låg tettleik, men underestimerte ved høg tettleik. I 2012 estimerte modellen om lag ei lus mindre enn kva som var observert i gjennomsnitt i bura. Medan gjennomsnittet dei andre åra var ikkje over 1. I 2017 ville ein fisk frå det bevegande buret i snitt ha 0.06 lus etter eit slep (om lag 6 timar). Gonga opp til ei veke ville fisken frå det bevegande buret ha 2.65 lus per fisk, medan fisk frå smoltbura og estimata ifrå risikomodellen hadde 0.08 lus. I 2017 hadde salinitet, temperatur og plassering på buret ingen effekt på talet lus. Dette studiet syner at forholdet mellom lakselus tettleik og smittepress kan væra meir avhengig av bevegelsen til fisken, og ikkje tida fisken er i sjøen.

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1. Introduction.

Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*) have played a key role in many local communities all over the Norwegian coast throughout history. They have been harvested both trough fishing in the fjords, as well as in rivers. Salmon have always been an important source of food. Today the fish farms are a common sight along the Norwegian coast. The first salmon farms in Norway appeared in the 1970s, and in 2016 Norway exported 840 000 tonnes of farmed salmon (Statistisk sentral byrå 2018). The expansion of the fish farms has also caused some challenges for the wild salmonid populations. Some of which are lowered fitness, and lowered survival trough hybridisation between wild and farmed salmon (McGinnity *et al.* 2003; Krkošek, Lewis & Volpe 2005; Forseth 2017). It can also affect the wild populations by spreading diseases, such as infectious salmon anaemia (Nylund, Wallace & Hovland 1993), and parasites due to the high densities of host fish. In Norway the most problematic parasite is *Lepeophtheirus salmonis*, also known as salmon louse (Forseth 2017).

The salmon louse is a small crustacean that lives in saltwater, and taxonomically it belongs to the copepod group. However, it has evolved to become an ectoparasite on marine salmonids. It feeds on blood, mucus, and skin tissues (Kabata 1974). Salmon lice can cause mechanical damage which can lead to infections, increased cortisol levels (Finstad *et al.* 2000), as well as making the host struggle with its osmosis regulation (Wootten, Smith & Needham 1982). This can cause lower growth, and fecundity. It can also lead to death for the most infected individuals (Wootten, Smith & Needham 1982). Salmon lice is estimated to be one of the most severe threats to wild salmonids in Norway today (Forseth 2017; Vitenskapelig råd for lakseforvaltning 2018). It is also estimated to be one of the biggest causes of economically loss in salmon farms (Rae 2002).

Salmon lice has an egg stage, as well as 10 other life stages (Wootten, Smith & Needham 1982). The egg hatches into a free-living nauplius, consisting of two stages, before it moults into a copepodite. As a copepodite it has limited capability of movement, but it can move vertically in the water column. The lice will move towards the surface during the day, and sink to deeper depths during the night, where the salinity is higher (Heuch, Parsons & Boxaspen 1995). It is in this life stage that the lice will seek out a suitable host. The lice detects vibrations in the water (Heuch & Karlsen 1997), and jumps towards what causes the vibrations (Heuch, Doall & Yen 2007). The lice can also detect chemical trails in the water, left by salmonids

(Ingvarsdottir *et al.* 2002). After finding a host, the lice move around on the fish looking for a suitable place to attach itself (Bron *et al.* 1991). It will then stay there until it moults into its chalimus stages. It has four moulting stages as chalimus, where it is stationary on the host while it is feeding. At this stage, it only causes minor damage to the host. Once the lice reach its two pre-adult stages it becomes mobile and will move around on the fish, and usually find places with low drag, such as behind the dorsal or adipose fin. At this stage the lice can inflict substantial damage to the host if the density of lice gets high enough (Finstad *et al.* 2000). After its two pre-adult stages it will become an adult salmon louse and will start reproducing. The generation time of the salmon lice is dependent on the salinity and temperature (Johnson & Albright 1991). If the salinity drops below 15 ppt (points per thousand) the eggs will have trouble developing into nauplius (Johnson & Albright 1991).

One of the biggest challenges related to salmon lice today is to get an accurate density estimate of the lice in its planktonic stages, which is the infectious state. This is because the density of lice plankton is relatively low compared to other kinds of zooplankton (Costelloe *et al.* 1998). This has led to the development of several different methods to measure the density of sea lice. The most direct method is probably to tow plankton nets, and count the lice (Penston *et al.* 2004). However, this require advanced microscopes and experts to distinguish the different species in the sample (Schram 2004). The analyses of the samples acquired from the plankton tow is also time consuming (á Norði *et al.* 2015). Another commonly used method is to place smolts (the lifestage where the salmon adapts to a life in saltwater) in keep nets, or sentinel cages, and distribute the cages around a given geographical area (Sandvik *et al.* 2016). After the cages have been in the sea for 2-3 weeks, they are brought back up and the number of lice is counted. However, this method has been criticized for not correctly mimic the natural encounter rate between a swimming fish, and the planktonic sea lice. Salmon lice are also monitored directly on the wild sea trout and salmon smolts. However, it is difficult to detect the place where the sea trout, and salmon smolts, have encountered the lice it is carrying. Moreover, lice might fall off when releasing fish from the nets. This method can also give biased results, either by selective capture of certain sizes of fish, or by removing the lice when the fish gets tangled in the net (Forseth 2010). In recent years, surveillance of salmon lice on wild sea trout has been conducted mainly by using trap nets. This method lowers the risk of losing lice while handling the fish, and increases the size range of caught fish, compared to gill nets (Barlaup *et al.* 2013). However, both nets and traps efficiency depend on the fish to be moving. Thus lowering s the catch rate of the heaviest infested individuals, because lice

negatively affects the hosts swimming performance (Wagner, Fast & Johnson 2008). This might give biased results (Revie *et al.* 2009).

In 2017 the Norwegian government ratified a management system that will regulate the admissible biomass of farmed salmon according to the estimated parasite induced mortality on wild salmonids (Vollset *et al.* 2017). In this system, several models and surveillance methods are used to estimate the percent of wild salmon and sea trout that succumb to sea lice. One of these methods uses female lice counts and temperature to calculate the local infestation pressure from fish farms (Kristoffersen *et al.* 2017). The model described in Kristoffersen *et al.* (2017) is a risk assessment model that estimates an expected number of lice on salmonids in a given area. The model includes lice counts at fish farms and temperature to estimate the spatial distribution of planktonic salmon lice densities, with a dropping density as the distance from the fish farm increase. The density is then combined with an estimated infestation rate of salmon lice on wild salmonids. This infestation rate is based on the correlation between lice in sentinel cages and estimated sea lice density, in 4 regions from 2013 - 2016.

In 2011, Uni Research developed a new method for sampling sea lice abundance on salmon, the *smoltsimulator*. The method involves towing a cage with salmon smolts over a certain amount of time and then counting the number of copepods on the fish. The *smoltsimulator* method is supposed to simulate migrating smolts to a higher degree than smolts in sentinel cages. The *smoltsimulator* was tested in 2011 and 2012, both giving promising results (Barlaup 2013).

The main goal of this study was to evaluate whether the encounter rate of salmon lice with salmon smolt in sentinel cages correlates with the encounter rate of salmon lice from the *smoltsimulato*r. This was done by first comparing the model by Kristoffersen *et al*. (2017) to a series of 105 sentinel cages from 2012-2017 in the fjords around Bergen, to evaluate if the model correctly predicts encounter rates of salmon lice in sentinel cages in this region. In 2017, I conducted parallel studies using 25 sentinel cages and 6 *smoltsimulator* tows, while simultaneously measuring various environmental variables. In a subset of 3 locations, replicated cages were placed 3 meters apart at the surface, while also placing 2 cages at greater depth (4meter and 7meter). By using the model by Kristoffersen *et al.* (2017), I could then evaluate whether the model over- or underestimated encounter rates in the different cage setups and *smoltsimulator* tows. My main hypothesis is that the sentinel cages and the model described in Kristoffersen *et al.* (2017) will get fewer lice than the *smoltsimulator*. This is

based on the model validation by the relationship between planktonic salmon lice densities and the number of lice in sentinel cages (Kristoffersen *et al.* 2017), compared to smolts that move constantly in the *smoltsimulator*.

2. Material and methods

2.1 Study area

This study was conducted in Hjeltefjorden and Herdlefjorden, northwest of Bergen (UTM 33, E -49410, N6756982) in Norway (Figure 1). The data was collected in May and June, every year from 2012 to 2017. This is a coastal area, with many islands. It is also an area with complex current systems, due to variation in depth, being close to the ocean, and many fjord outlets. Further east of the study area is Osterøy, with the surrounding fjords Osterfjorden, Veafjorden, and Sørfjorden. There are six major salmon rivers entering these fjords; Moelva, Daleelva, Ekso, Arnaelva, Loneelva, and Vosso. The large freshwater influx causes the water in the fjords to have a clear salinity gradient, causing big local variations of the salinity in the study area. Out-migrating smolts from the rivers will pass through the study area. In Vosso, which is the largest of these rivers, there is an ongoing rescue operation to restore the Vosso salmon (Barlaup 2013). The present study area, which is a part of the migration route of the Vosso smolts, has become an important location for salmon lice monitoring, where Uni research has carried out salmon lice monitoring annually since 2011. The data has been collected in May and June because this is when the post-smolts migrate from their rivers and head towards the sea (McCormick *et al.* 1998). This is also an area with relatively high density of salmon farms, and there are 17 fish farms within the study area (Fiskeridirektoratet 2018a). In the new traffic light management plan for salmon farms in Norway, this area is a part of production area 4, which is classified as category red (Fiskeridirektoratet 2018b). The category “red” means that the production of salmon has to be lowered, because the salmon lice induced mortality on the wild salmonids is too severe to consider the activity sustainable (Nærings- og fiskeridepartementet 2017).

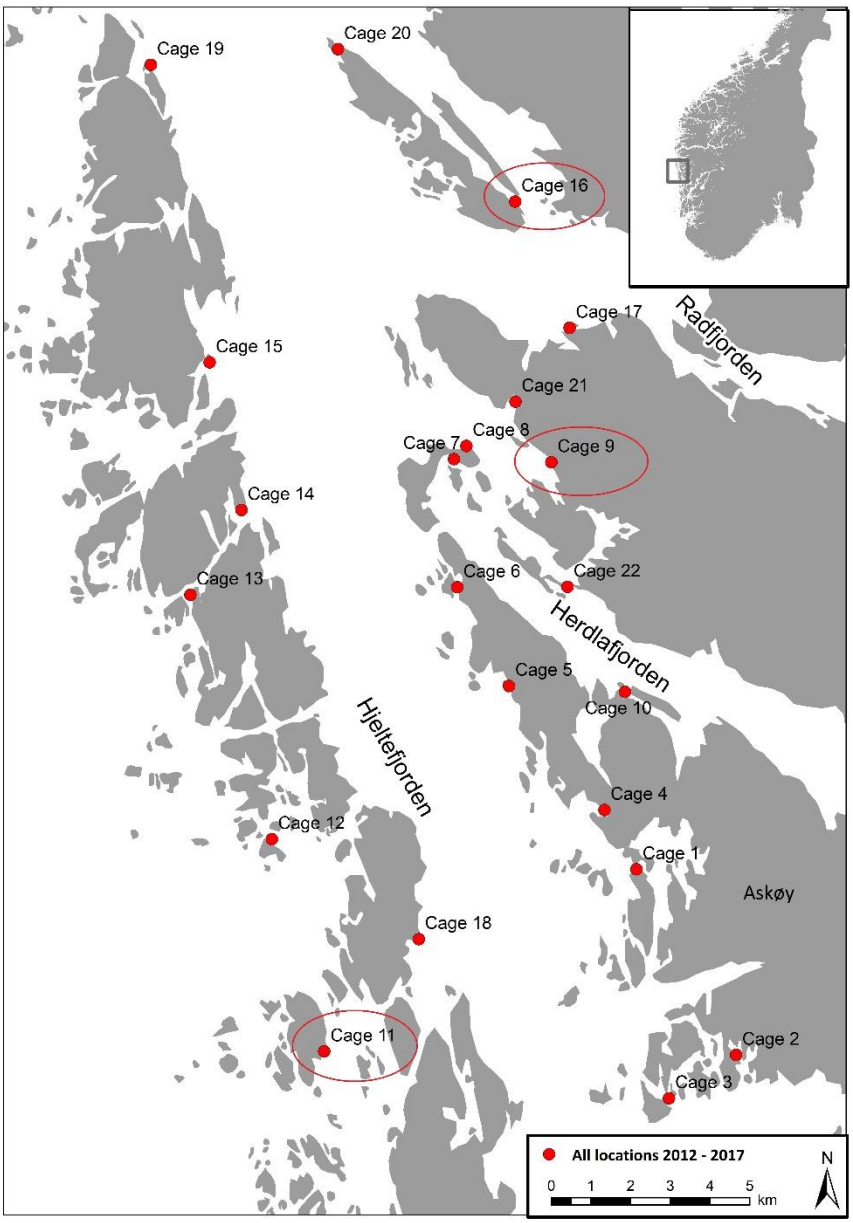

Figure 1 The study area in Nordhordland, northwest of Bergen in western Norway. Each dot represents a cage location that has been used at least once in the period from 2012 to 2017. Circled locations represent the clusters in 2017. Further details on which year the different locations have been used is described in appendix: Table 8.

2.2 The Veterinary Institute model

The Norwegian Veterinary Institute model quantifies the salmon lice infestation, and lice induced mortality on migrating post smolts. The number of female lice is counted on a representative sample of fish on the fish farms, and the average per fish is estimated. Then this average is multiplied by the number of fish on the farm. Using knowledge on how the salmon lice reproduction is affected by temperature (Stien *et al.* 2005) an estimation is made on how many eggs are produced per fish farm per day. The spatial distribution of planktonic salmon lice is then estimated, with a decreased density with an increased distance from the fish farm (Figure 2). Kristoffersen *et al.* (2017) evaluated the relationship between lice density, and number of lice found on smolts from sentinel cages. These cages were located in southern Hordaland, Møre og Romsdal, and Sør- and Nord- Trøndelag, from 2013 to 2016. Using the function between the infestation rate and expected density it is then possible to estimate the expected number of lice found on smolts at one location during a given time period (Kristoffersen *et al.* 2017: Table 6 and Figure 6). Kristoffersen *el al.* (2017) describe further details on this model.

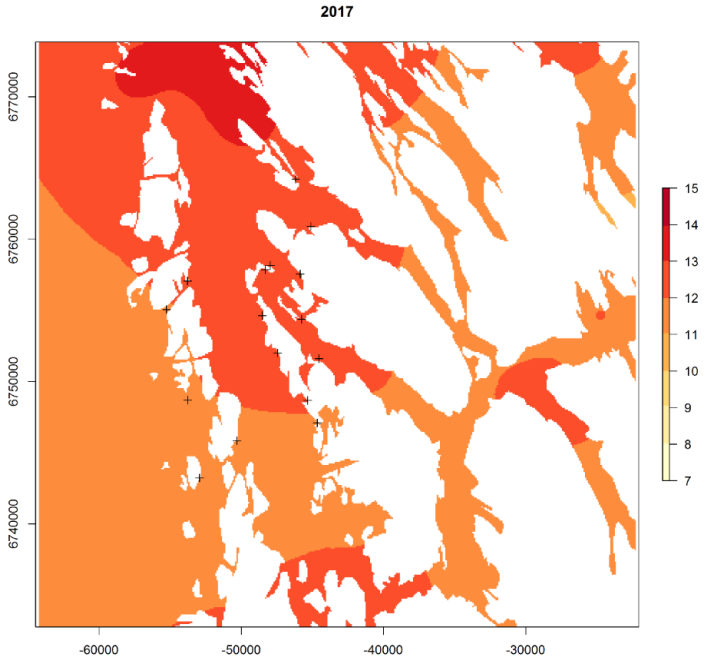

Figure 2 Output from the infestation pressure model from VI for the study period of 2017. The scale is log transformed infestation pressures (number of lice per fish per week) as described in Kristoffersen *et al.* (2014). The crosses indicate the locations this year. For the models from the study periods 2012 – 2016 see appendix: Figure 14 – 18.

2.3 Sentinel cages

The data from the sentinel cages was collected around the northern part of Askøy, in Norway (Figure 1). The cages are 65 cm in diameter, and 145 cm long (Figure 3). One cage was placed on each of the 16 locations, at one-meter depth. At location 9, 11 and 16 two cages were placed 3 meters apart in the surface, while 1 cage was place at 4 meters depth and another cage was placed at 7 meters (Figure 4). Fifteen smolts were placed in each cage at 26.05.2017, and collected on 14.06.2017, when they were euthanized and frozen for lice counting in the lab. The smolts where hatchery reared at Voss Klekkeri. The fish were delivered as eggs from the genebank "Haukvis kraft-smolt AS" in March 2016, and they hatched in April 2016. They genetically originate from Vosso. Out of the 15 smolts in each cage, five were vaccinated with emamectine benzoate (SLICE), and were excluded from the dataset. Five of them were also vaccinated with only the buffer from the emamectine vaccine. This was done to analyse the effect of SLICE on the salmon lice in the region in a separate study. At 06.06.17 and 14.06.17 salinity and temperature were measured at each 2017 cage location using a CTD logger (model SD208). In addition to the data collected during my masters, data from smolt cages collected by Uni Research dating back to 2012 was also used. From 2012 to 2015, there was only 10 fish in each cage, with no vaccinated fish. While in 2016 and 2017 there were 15 fish in each cage, with 5 vaccinated (Appendix: Table 8). The date when the smolts were placed in the cages has varied among years, from as early as 21.05 in 2015, to as late as 12.06 in 2012. The date at which the fish have been brought back up has varied as well. The earliest date at which the fish was brought back was 11.06 in 2015, and the latest date was 28.06 in 2012 (Table 1).

Table 1 Overview of the data collected from the smolt cages from 2012 to 2017. N is number of fish per year. Number of cages is number of cages per year. Total lice are the total number of lice per year. Average estimated lice infestation is the average log transformed lice infestation per year based on Kristoffersen *et al.* (2017). Days at sea is the number of days the cages were in the sea. Date of placement is the date at which the fish was placed in the cage. Date of retrieval is the date at which the fish was retrieved. Which location that has been used each year is described in appendix: Table 8.

Year	N	Number of Cages	Total lice	Avarage estimated lice infestation	Days at sea	Date of placement	Date of retrieval
2012	97	10	310	12.162	16	12.06	28.06
2013	177	18	0	8.243	21	29.05	19.06
2014	183	19	50	11.718	21	20.06	10.06
2015	116	14	65	11.737	21	21.05	11.06
2016	158	19	272	13.451	21	26.05	16.06
2017	243	25	48	12.34	19	26.05	14.06
Total	974	105	745	11.629	119		

Figure 3 One of the smolt cages used in this study.

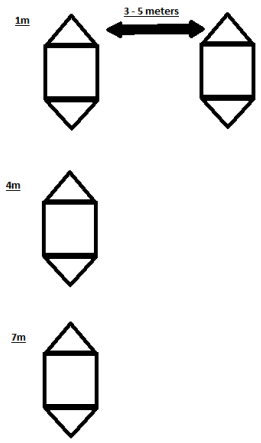

Figure 4 Illustration of how the cages where placed in a cluster, with the number on the side of the cage showing which depth the cage was placed.

2.4 The *smoltsimulator*

The *smoltsimulator* is a cylinder-shaped cage 2,5m long and 1,3m in diameter, with a flat front and back (Figure 5). To make it more stable in the water there is attached one pipe with floaters on one side, and a lead pipe on the opposite side of the cage. These pipes also make the cage more rigid, causing less movement during the tow. Since the tows where done in an area with high boat traffic, orange floaters were attached to the rope connecting the *smoltsimulator* to the boat. All six *smoltsimulator* tows where done in Hjeltefjorden, and Radfjorden northwest of Bergen (Figure 6), within the time period 30.05.2017 to 09.06.2017. Each tow started with 29 to 32 smolts, all of which had only been in freshwater prior to the *smoltsimulator* tow. Due to some mortality during the tow, the final sample of each tow varied from 13 to 31. The *smoltsimulator* was towed 40 meters behind the boat, at 1 (± 0.5) knots, for a duration of six to six and a half hours each, with the exception of one (nr. 6), which was cancelled at five hours due to high mortality. To monitor the mortality, two cameras (custom made bullet camera, as described in Vollset *et al.* (2016)) were placed inside the *smoltsimulator*, with monitors on the boat. A combined salinity and temperature

logger was placed in the back center of the *smoltsimulator* (Solinst LTC Levelogger Edge). A digital flowmeter (KC Denmark A/S) was also placed in the centre of the *smoltsimulator*. It was then estimated the volume sampled by the fish each tow. Based on the flowmeter which rotates 0.3 times per meter. The distance measured by the flowmeter was then multiplied by the reactive distance (the distance from where a louse will react to the fish) from Heuch, Doall and Yen (2007), then multiplied by the number of fish alive in the end of the tow.

Table 2 Overview of the data collected from the *smoltsimulator* tows. Stretch shows which of the routes showed in Figure 6 were used. Hours shows the duration of the tow. N is the number of surviving smolts at the end of the tow. Total lice show how many lice there was in total per tow. Avg. Sal and Avg. Temp shows the average salinity and temperature measured in each tow. Sampled volume is an estimation on how many litres the smolts sampled in each tow. Avg. Estimated lice per week is an estimation of how many lice each fish should have after a week at that location, based on the average estimates from the VI model. Avg. estimated lice infestation is the average log transformed lice infestation per tow based from the VI model. And date shows which date the tow occurred.

Tow	Stretch	N	Hours	Total lice	Avg. Sal (in ppt)	Avg. Temp (in C°)	Sampled Volume (in liters)	Avg. Estimated lice per week	Avg. estimate lice infestation	Date
Tow 1	1	27	6	6	23.296	10.793	1906640.12	0.10	12.28	30.05.17
Tow 2	2	24	6.5	4	19.645	11.827	1675975.84	0.12	12.59	01.06.17
Tow 3	3	28	6.5	0	19.199	11.480	2044288.63	0.13	12.72	02.06.17
Tow 4	1	12	6	1	20.757	11.471	771634.47	0.13	12.55	07.06.17
Tow 5	4	31	6.33	2	20.339	11.700	1958321.08	0.12	12.55	08.06.17
Tow 6	1	20	5.25	1	21.767	10.773	1111973	0.11	12.28	09.06.17

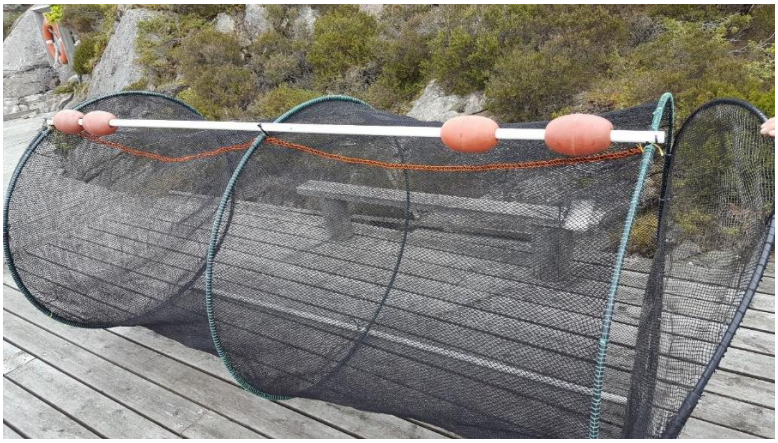

Figure 5 Picture of the *smoltsimulator*,

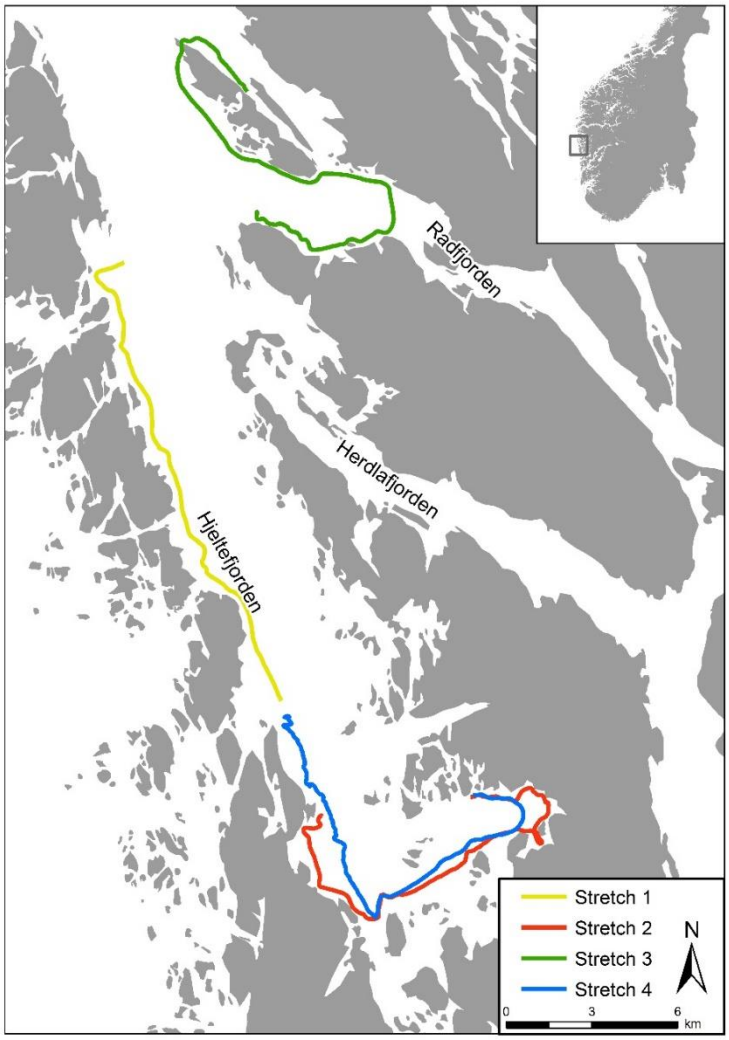

Figure 6 Each line shows one of the stretches the *smoltsimulator* was towed trough, with 3 repetitions on stretch 1.

2.5 Data Analysis

Figure 7, figure 8, and figure 10 and all the models were made in R (R Core Team 2017), while the tables and the rest of the figures have been made in Microsoft Excel 2016. The maps were made in ArcGIS (version 10.3). The Akaike Information Criterion was used for model selection (Bozdogan 1987).

2.5.1 Smolt cages compared to the VI model.

Due to the big variation of how long the cages had been in the sea, the lice values were standardised to average number of lice per cage, for one week. The estimations from the VI model were standardized to weekly infestation as well. In the best-fitted model average

number of lice were used as response, and the estimated number of lice were used as predictor in a Gaussian distributed generalized linear mixed model (GLMM). Year was set as a random intercept to correct for potential random variation between years. This was done using the glmer function from the lme4 package (Douglas Bates 2015) in R. No other predictors were used in this model.

2.5.2 Smoltsimulator and cages compared to VI model in 2017

A separate analysis was run for 2017 because of more variables during that year. The data from the clusters were grouped regardless of the depth, because of the small sample size. The additional variables were environmental variables (salinity and temperature), and method (*smoltsimulator* versus cages). These variables were placed in a Gaussian distributed generalized linear model, together with the predictions from the VI model. Due to the number of variables measured in 2017, the "dredge" function from the R package "MuMIn" (Kamil Barton 2018) was used to find the best fitted model (Table 4). The full model included all variables and an interaction between the VI model and method. No other interactions were considered due to the low number of datapoints.

3. Results

3.1 Smolt cages compared to VI model

Uni Research has been collecting data from the smolt cages from 2012, with the number of cages varying yearly between 10 and 25. Counting all the years, the total sample size of smolts from the cages is 974, with 745 lice. The number of lice per year was highly variable, ranging from 310 in 2012, to 272 in 2016, and 0 in 2013. (Table 1).

The best fitted model was a generalized mixed model with estimated lice as predictor and lice in sentinel cages as response, including year as random effect (Table 3). In general, the estimated number of lice (model from the Veterinary Institute) were lower than observed. The difference was increasing as the estimated infestation increased (Figure 8). In 2012 the observed average number of lice was about 1 lice per cage more than the estimated values. The average number of lice for all the other years was below 1 (Figure 7).

Table 3 Fixed effect parameters from the GLMM with estimated lice as predictor and lice from sentinel cages as response and year as random effect. Variance of random effects is 0.22, with 0.47 standard deviation.

Fixed effects			
	Estimate	**Std. Error**	**t value**
(Intercept)	0.1915	0.2218	0.864
estl	2.0722	1.2042	1.721

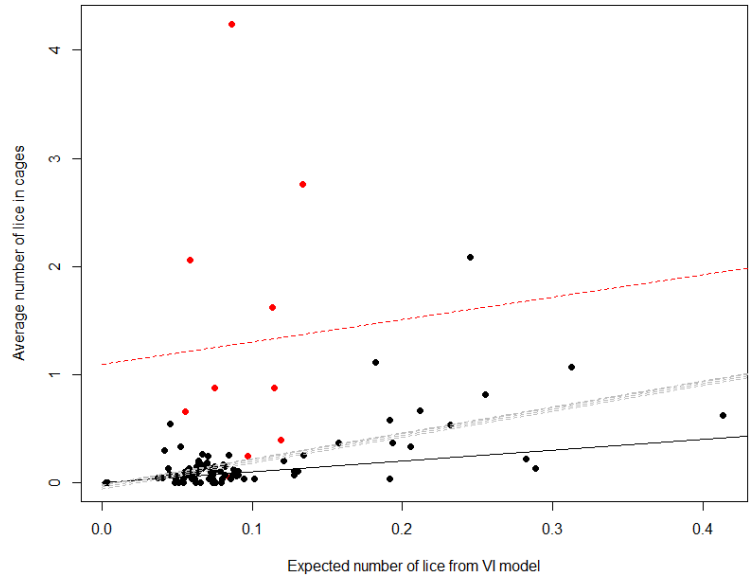

Figure 7 The expected number of lice, based on the VI model, compared to the observed average number of lice per cage. Each black point is one cage from the time period 2012 to 2017. Each red point is one cage from 2012. The black line shows the 1:1 ratio, which you would expect with a perfect correlation between estimated lice from the VI model and the observer number of lice. Each of dashed grey lines is one year, and the red line represents 2012.

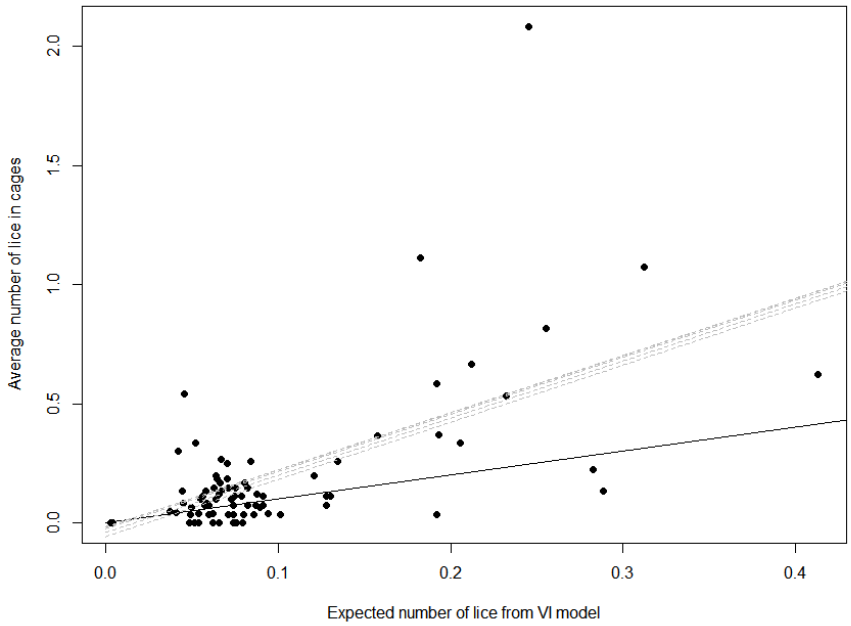

Figure 8 Plotted expected number of lice, based on the VI model, compared to the observed average number of lice per cage. Each black point is one cage from the time period 2013 to 2017. Points from 2012 has been removed to see the slopes at a finer scale.

3.2 *Smoltsimulator* and cages compared to VI model in 2017

Even though each *smoltsimulator* tow started with 29 to 32 smolts, some mortality made the final sample from each tow vary from 13 to 31. Thus, the total sample size from all *smoltsimulator* tows is 142, with an average of 23.6 per tow. Number of lice varied from 0 to 6, with an average of 2.33 lice per tow. The average temperature was uniform across all tows, varying from 10.8 to 11.8 °C. Average salinity varied among tows from 19.2 to 23.3 point per thousand (ppt, Table 2). In addition, there was a sudden drop in salinity in tow 3 where it dropped from 21.15 ppt to 13.89 ppt (Figure 9). The average estimated number of lice in 2017 was 0.08 lice per fish per week.

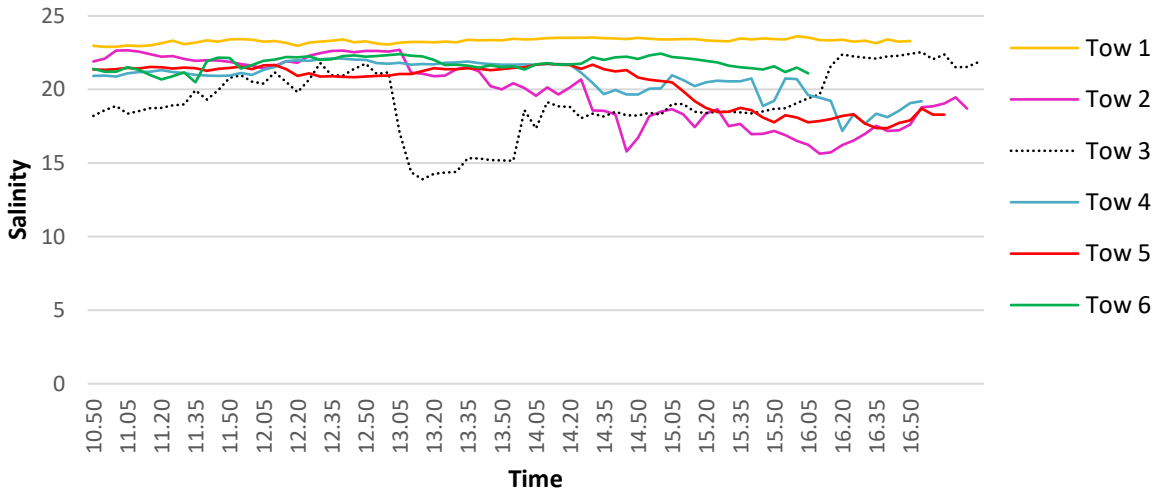

Figure 9 Salinity log from the *smoltsimulator* tows. The Y axis shows the salinity in ppt, and X axis shows the time of day. Each line shows a separate tow.

The output from dredge shows that the best fitted model includes the interaction between method and estimated lice as predictor and observed number of lice as response (Table 4). However, this interaction showed a significant negative correlation between the *smoltsimulator* and the estimations from the VI model (Table 5). This pattern is illogical, and I therefore presents the best-fitted model without the estimation from the VI model. This model only included method as predictor (Table 6).

Table 4 Output from the dredge function in R. This shows the 6 best fitted models from all combinations of parameters measured in 2017.

Model	(Int)	Estimated lice	Avg. Salinity	Avg. Temp	Method	Placement	Interaction est:met	df	logLik	AICc	delta	weight
42	0.1017	-0.27			+		+	5	-23.87	60.1	0	0.527
46	-1.251	-0.73		0.1105	+		+	6	-23.58	62.7	2.52	0.15
44	0.1517	-0.56	-0.00111		+		+	6	-23.87	63.2	3.1	0.112
58	0.09573	-0.22			+	+	+	6	-23.87	63.2	3.1	0.112
48	-4.658	6.15	0.02925	0.282	+		+	7	-23.16	65.2	5.05	0.042
62	-1.503	-0.21		0.1257	+	+	+	7	-23.53	65.9	5.8	0.029
60	0.1483	-0.51	-0.00121		+	+	+	7	-23.87	66.6	6.47	0.021
64	-5.568	7.98	0.03319	0.3323	+	+	+	8	-23.02	68.6	8.44	0.008
10	2.053	-27.28			+			4	-38.55	86.6	26.49	0
9	0.08221				+			3	-40.44	87.8	27.63	0

The fish from the sentinel cages would on average have 0.08 (± 0.18 std. error) lice after a week, while fish that had been in the *smoltsimulator* would on average have 2.62 (± 0.42 std. error, Table 6) lice after one week ($P < 0.01$, $R^2 = 0.56$, with 29 DF, Figure 10). The variables that was not selected for in this model was salinity, temperature, estimates from the VI model, and position of the cages (surface vs depth).

Table 5 Summary from the GLM using number of lice as response, and interaction between method and estimated lice as predictor.

Coefficients from the model including the interaction.					
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	**Significance**
(Intercept)	0.09	0.73	0.13	0.90	
estl	-0.27	9.96	-0.03	0.98	
metSmoltsimulator	21.17	2.69	7.86	0.00	***
Interaction Estimations : smoltsimulator	-156.44	23.97	-6.53	0.00	***

Table 6 Summary from the GLM with number of lice as response, and method as predictor.

Coefficients from the model only including the method.					
	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**	**Significance**
(Intercept)	0.08	0.18	0.39	0.70	
metSmoltsimulator	2.62	0.42	6.26	0.00	***

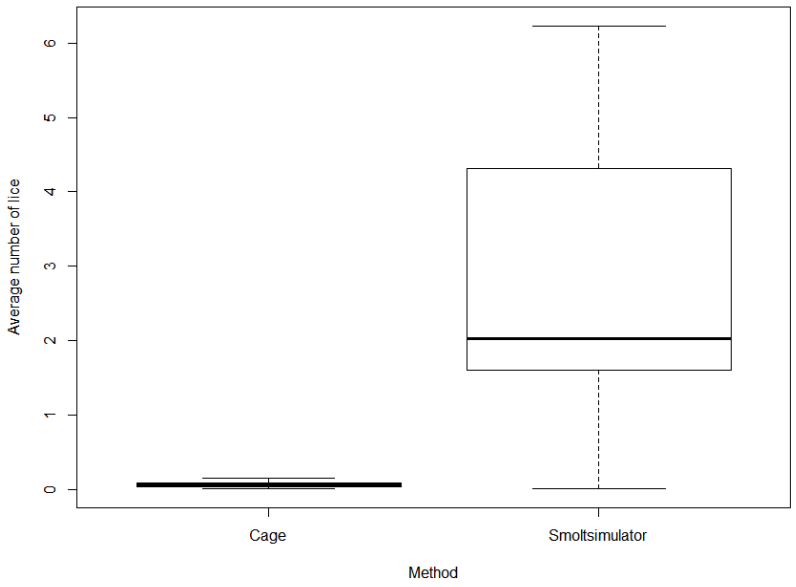

Figure 10 The difference in the average number of lice per week (Y axis) with the two methods (X axis), as well as the variation.

3.3 Clusters

At location 11 the number of lice varied from 1 to 5 lice per cage, whereas at the other clusters the number of lice only varied by 2 between each cage (Table 7). The salinity profiles from the clusters shows that there was a sudden increase in salinity with depth from 26ppt to 31ppt at location 9, and 16 (Figure 11, figure 13), but not at location 11 (Figure 12). This increase occurred at about 5 meters, meaning for location 9 and 16 the cage at 7 meters were placed at a higher salinity than the others. There was no general pattern that could explain the number of salmon lice at the different depths.

Table 7 Overview of the data collected from the clusters. Location shows at which location the cluster of cages was placed. Depth shows at which depth the cage was placed. Total is the total number of lice per cage, and Avg. lice is the average number of lice per cage. Avg. Sal and Avg. Temp is the average salinity and temperature from the measures at the two different dates.

Location	Depth (in meters)	Total	Avg. lice	Avg. Sal	Avg. Temp
11	4	1	0.07	31.05	12.05
11	7	3	0.2	31.18	11.82
11	Less than 4 meters	5	0.38	30.68	12.46
11	Less than 4 meters	1	0.07	30.68	12.46
16	4	1	0.077	29.16	11.75
16	7	2	0.13	30.95	11.02
16	Less than 4 meters	3	0.21	17.74	13.27
16	Less than 4 meters	3	0.2	17.74	13.27
9	4	0	0	28.44	11.95
9	7	1	0.07	30.82	11.02
9	Less than 4 meters	2	0.13	19.10	13.16
9	Less than 4 meters	0	0	19.10	13.16

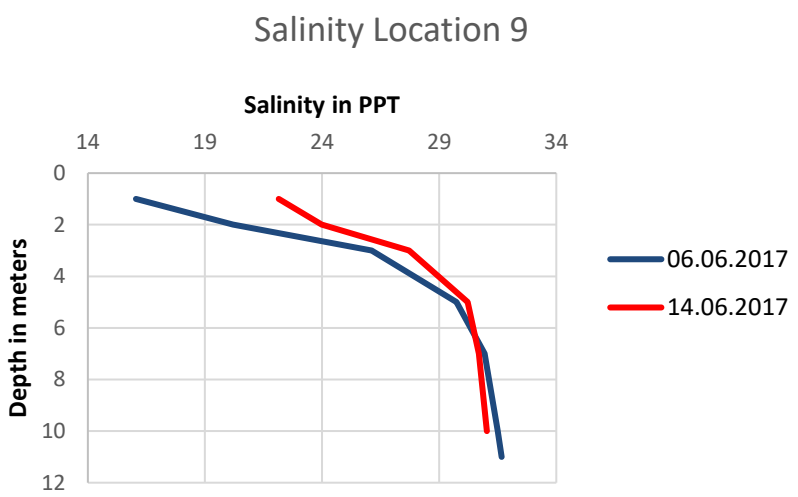

Figure 11 Salinity profile showing how the salinity changes as the depth increases at location 9. Each line shows the salinity measured at the different dates.

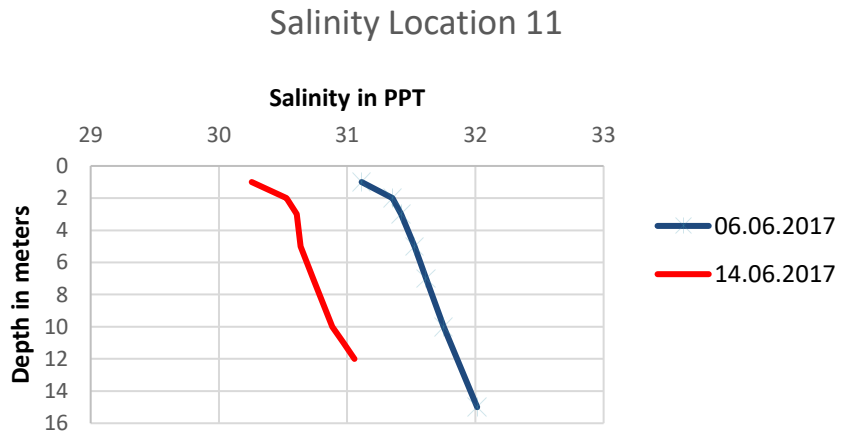

Figure 12 Salinity profile showing how the salinity changes as the depth increases at location 11. Each line shows the salinity measured at the different dates.

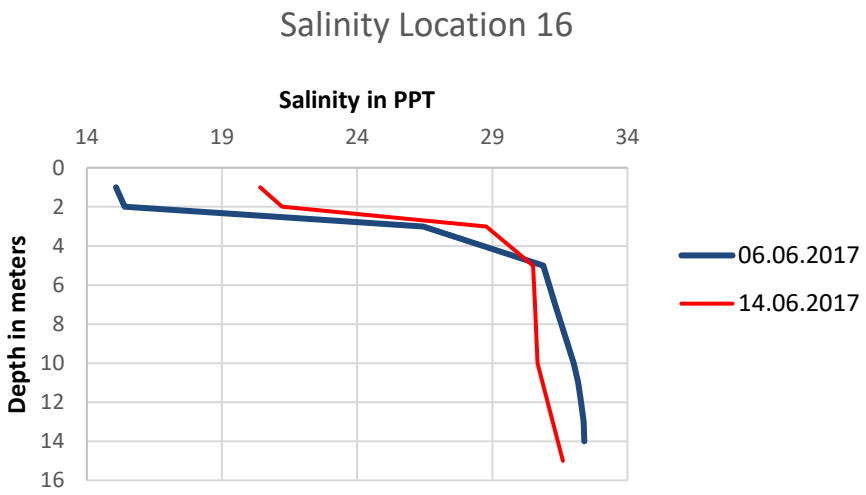

Figure 13 Salinity profile showing how the salinity changes as the depth increases at location 16. Each line shows the salinity measured at the different dates.

4. Discussion

This study has looked at how an infestation estimation model predicts salmon lice infestation on salmon smolts from sentinel cages placed northwest of Bergen, in the period 2012 to 2017. In 2017 other variables were also included, such as mobile versus sentinel cages, salinity, temperature, and depth. The VI model (Kristoffersen *et al.* 2017) shows that it can accurately predict the number of lice when the infestation is low but will underestimate when the lice density increases (Figure 7). Also, in 2012 the number of lice was much higher than what was estimated (around 1 lice per cage). However, when comparing lice counts from the cages in 2017, the *smoltsimulator*, and estimates from the VI model it becomes clear that the *smoltsimulator* gets a higher number of lice per time unit (2.62 per week) than either sentinel cages (0.08) or the VI model estimates (0.08). Among all the variables measured in 2017 the method explained most of the variation.

4.1 Smolt cages compared to the VI model.

The VI model predicted the number of lice well each year when the infestation was low but was underestimating as the estimated infestation increased. In 2012, the observed number of lice was about 1 more than the model estimated. During the other years, the average number of lice was lower than 1 (Figure 7). This could possibly be because the model missed a change in the temperature, which caused the lice to reproduce faster than estimated (Samsing *et al.* 2016). It could also be a change in the currents which is not accounted for in the model. Stronger currents passing the cages causes more water to be sampled, which increase the chance of a smolt encountering a louse.

The correlation between the VI model and the cages is consistent with other studies that have compared estimation models with observed number of lice in smolt cages (Sandvik *et al.* 2016). This shows that newer models can correctly estimate the densities of salmon lice copepods in an area. However, as discussed in Kristoffersen *et al.* (2017), the sentinel cages do not correctly mimic the behaviour of a wild salmonid. A wild salmonid will sample a greater volume of water compared to a sentinel cage because it is active. In addition, one of the main strategies a salmon louse uses to locate its host is to sense vibration in the water caused by a moving fish (Heuch & Karlsen 1997). This might limit the louses' ability to detect the fish in the cages, since they have limited movement within the cage. The reason for why

the model underestimates at higher densities could be that there is a parameter that is not accounted for in the model, for instance salinity or currents, that causes an unexpected increase in the number of salmon lice at certain locations.

4.2 *Smoltsimulator* and cages, compared to the VI model.

When comparing the number of lice counted on fish from the cages to fish from the *smoltsimulator* it was clear that the *smoltsimulator* attains higher numbers of lice than predicted. One explanation for this might be that the fish in the cages are stationary, and the only chances of a host – parasite encounter comes from the water that flows through the cage from natural currents. The *smoltsimulator* on the other hand is constantly moving through water, which increase the chance of a smolt encountering a louse. However, the cages were also placed in bays, eddies, and narrows, which often accumulates higher densities of salmon lice than the pelagic waters (Asplin *et al.* 2014).

As mentioned earlier, sentinel cages have been criticised because they do not mimic correctly the natural behaviour of a wild salmonid. This is the reason why Uni Research developed the *smoltsimulator*. Fish in the *smoltsimulator* will most likely be closer to the exposure to salmon lice as the wild salmonids, because of the greater volume sampled. The *smoltsimulator* also causes the fish to be more active, which provides more realistic vibrations around the fish, which is one of the main strategies a salmon louse detects its hosts (Heuch & Karlsen 1997). Both the VI model (Kristoffersen *et al.* 2017), and sentinel cages assume a temporal relationship between salmon lice density and infestation, which applies to the wild salmonids. However, these results suggest that the movement of the fish might have greater impact on salmon lice infestation than time, since the *smoltsimulator* get such high numbers of lice.

Of all the variables measured in 2017 the method was the most important factor. In the output from dredge (Table 4) method is included in the 10 best fitted models. The best fitted models also included an interaction between method and the estimated infestation. However, when fitting a model with an interaction between method and the VI model, a negative correlation between the *smoltsimulator* and the VI model appeared. The reason for the negative correlation was most likely tow 1 and number 3. Tow number 1 occurred in the area with the lowest estimate based on the VI model, while also acquiring the highest number of lice. Tow number 3 occurred in the area with the highest estimated number of lice, yet still had 0 lice (Table 2). It is hard to explain the high number of lice in tow number 1 and could possibly just

be an extreme occurrence, since no other anomalies were detected. However, a salinity drop about halfway through the tow may explain the results from tow number 3, where the salinity did not get above 20 ppt until the tow was almost over (Figure 9). This could have caused that any lice already attached to the fish to release itself from the fish when the salinity dropped. And the lice that attached itself later in the tow would maybe not have enough time to make a more permanent attachment (Bron *et al.* 1991). Bricknell *et al.* (2006) found that lice avoid water with salinity lower than 27 ppt, whereas the exact salinity when salmon lice alter their behaviour, and start experiencing biological difficulties, depends on the origin of the salmon lice population (Ljungfeldt *et al.* 2017). However, the area where the salinity drop occurred might be an area the lice will avoid, since the drop was so severe (dropped from 21.15 ppt to 13.89 ppt, Figure 9). It could also be that only the top layer had such low salinity, and the salmon lice was avoiding this by staying at a deeper depth (Heuch, Parsons & Boxaspen 1995), and thereby avoiding the *smoltsimulator*.

There was no separate analysis on the data from the cage clusters, because of the small sample size. The data collected from the clusters was set in the analysis for 2017 as a binary factor instead, based on whether the cage had been in the surface or not. However, looking at the variation from the data, there was a difference of 4 lice between the cages at a location 11 (Table 7). One of the surface cages had 5 lice, while the cage next to it, and the cage 4 meters below it only contained 1 lice. This could be because that cage was placed in a spot with a stronger current then the adjacent cages. Even though the study focused on sea trout, Tully *et al.* (1999) found that there could be big local variation in salmon lice infestation within the same bay. Looking at the salinity values from the CTD logger, there was a distinct change in the salinity at location 9 and 16 (Figure 11, Figure 13). This change happened at around 5 meters, meaning you would expect more lice in the cage at 7 meters. However, it was not observed any changes in the cage at 7 meters, possibly because the lice migrates to the surface during the day, and only stays at deeper depth during the night (Heuch, Parsons & Boxaspen 1995). It is not possible to make strong inferences on this, because of the small dataset. Nevertheless, it is important to note there can be a relatively high local variation and it would be important to test a bigger dataset in future studies.

Whether the cage had been in the surface or not, salinity and temperature were not selected for in the model, even though studies have shown that salinity and temperature affect the salmon lice (Johnson & Albright 1991; Brooks 2005; Arriagada *et al.* 2016). The reason these factors were not selected for could be that the variation caused by the method overshadowed

the variation caused by these three factors. Alternatively, the relatively low number of lice in the cages in 2017 could explain the lack of detection of any effect of salinity and temperature.

As the *smoltsimulator* is a relatively new method of measuring salmon lice infestations, some improvements are expected. Some were accounted for based on previous studies (Barlaup 2013), and others became apparent during the study. Possibly the most important thing to consider if replicated is the distance between the *smoltsimulator* and the boat. This distance must be long enough to ensure the turbulence caused by propeller to disappear before reaching the *smoltsimulator*. Turbulence caused by the cage itself could also be a source of error, by disturbing the salmon lice larvae's and lowering the infection. The vibration caused by the cage could also trick lice to think it is a fish (Heuch *et al.* 1997), making it jump towards it and thereby increasing the infestation. It is also important to consider the speed, which should be as close to the speed as a moving salmonid as possible. If possible, the lice should also be counted in the field, removing any chance of dissolving the lice as it freezes. Another improvement that appeared during the study is to add a mechanism that makes it easier to remove the fish from the cage (for instance a zipper). It is also important to consider the duration of the tow. By extending the duration of the tow the estimates will be more precise. This is because the number of lice is relatively few, causing one lice to have great impact on the results. Also, early in the settlement phase the lice use a reversible filament (Bron *et al.* 1991), which increases the chance of a lice dethatching itself.

5. Conclusion

All three methods described in this report are methods worth considering when estimating lice densities. It is important to consider the advantages and disadvantages of each method considering the objective of the study. Cages will most likely underestimate the lice densities, since the fish will be have limited movement throughout the study (Bjørn *et al.* 2011). However, if the objective is to estimate the number of lice at an exact location, or annual variations, this might be a method to consider. Because it is already a well-established method, making the results comparable to other studies, and the cages also appears to be detecting trends in salmon lice densities well (Bjørn *et al.* 2011). The *smoltsimulator* on the other hand, might overestimate the abundance of lice, because it assumes that the fish has been moving without stops throughout the tow. This could be accounted for by looking at the distance travelled, or volume sampled, instead of time at sea. This is probably the method best suited for studies related to salmon lice on migrating post-smolt. This is because from the management point of view, it is important to know the number of lice that a salmon smolt encounters on its migration to the sea. Finally, the VI model shows good predictions of the number of lice in the cages at low densities. Therefore, it is possible to get good estimates of the salmon lice infestation in big areas, since this model has been made for the entire Norwegian coast. However, the model only predicts the number of lice in the cages, which might also be an underestimate.

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7. Appendix

Table 8 Number of fish at each cage location during each year, and total number of fish per year, and per cage across all years.

Cage number	2012	2013	2014	2015	2016	2017	Total number of fish at each location
1	10	10		10	9	10	49
2	10	10	10	10	10		50
3	10	10	10	8	8		46
4	10	10	10	9	9	10	58
5	10	10	10	4	9	10	53
6	10	10	10	9	9	8	56
7	10	10	10	9	10	10	59
8	8	8	10	8	8	10	52
9	9	10	10	9	9		47
10	10	10	10	9	10	10	59
11		10	9				19
12		9	10		3	10	32
13		10	10		10	10	40
14		11	10	8	8	9	46
15		10	10	7	9		36
16		10	10	8	10		38
17		9	10	8	9	10	46
18		10	10		9	9	38
19			4				4
20			10				10
21					9		9
22						10	10
11:4m						9	9
11:7m						10	10
11:A						10	10
11:B						10	10
16:4m						9	9
16:7m						10	10
16:A						9	9
16:B						10	10
9:4m						10	10
9:7m						10	10
9:A						10	10
9:B						10	10
Total number of fish each year	97	177	183	116	158	243	974

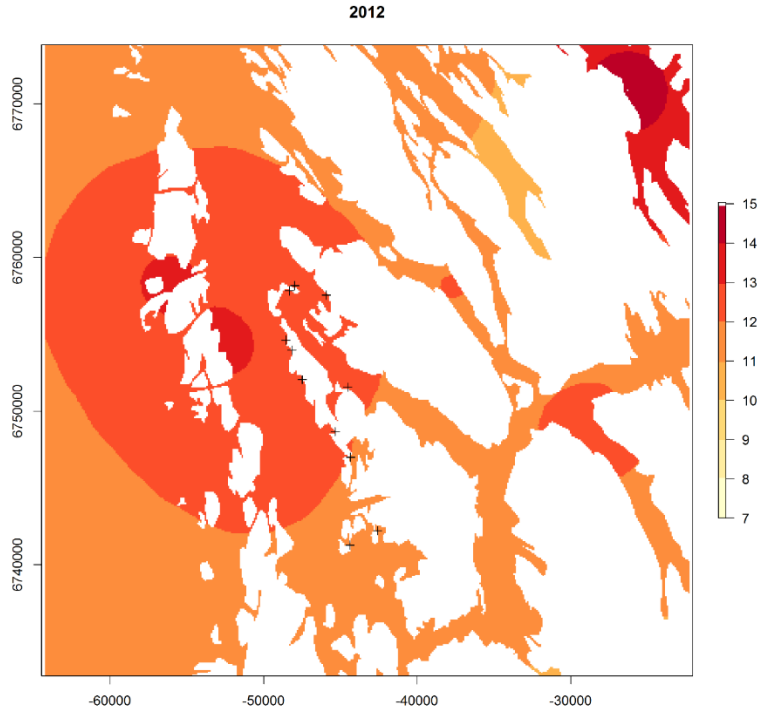

Figure 14 VI model predictions for 2012.

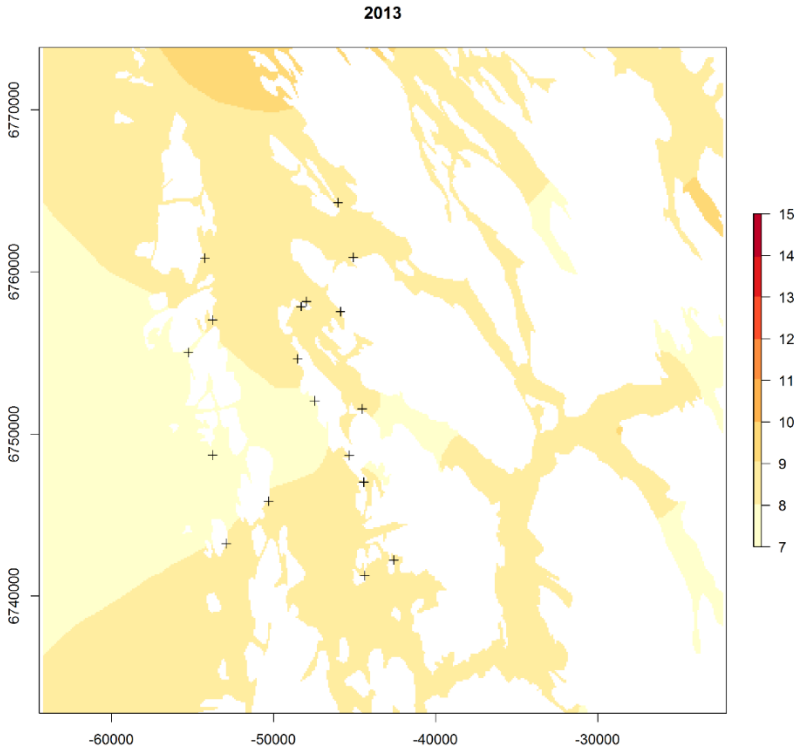

Figure 15 VI model predictions for 2013.

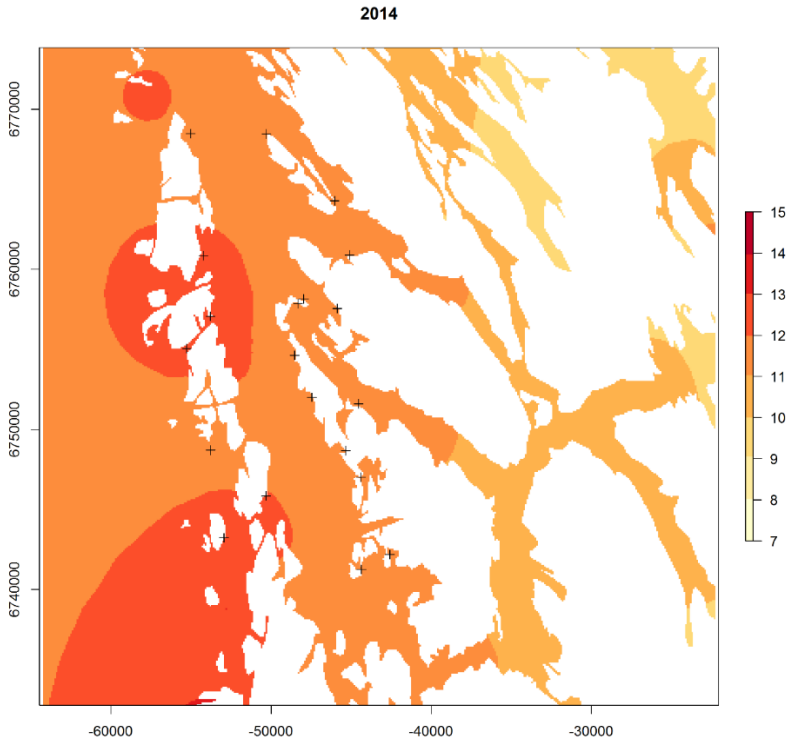

Figure 16 VI model predictions for 2014.

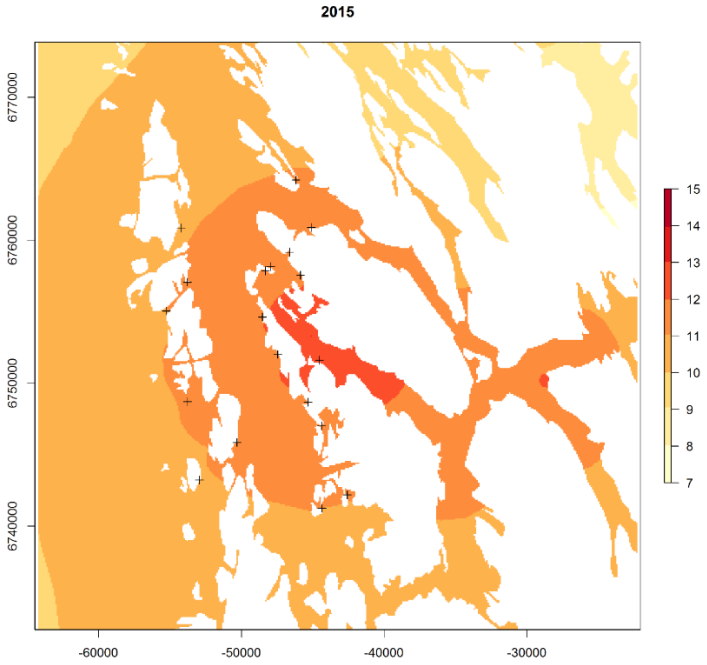

Figure 17 VI model predictions for 2015.

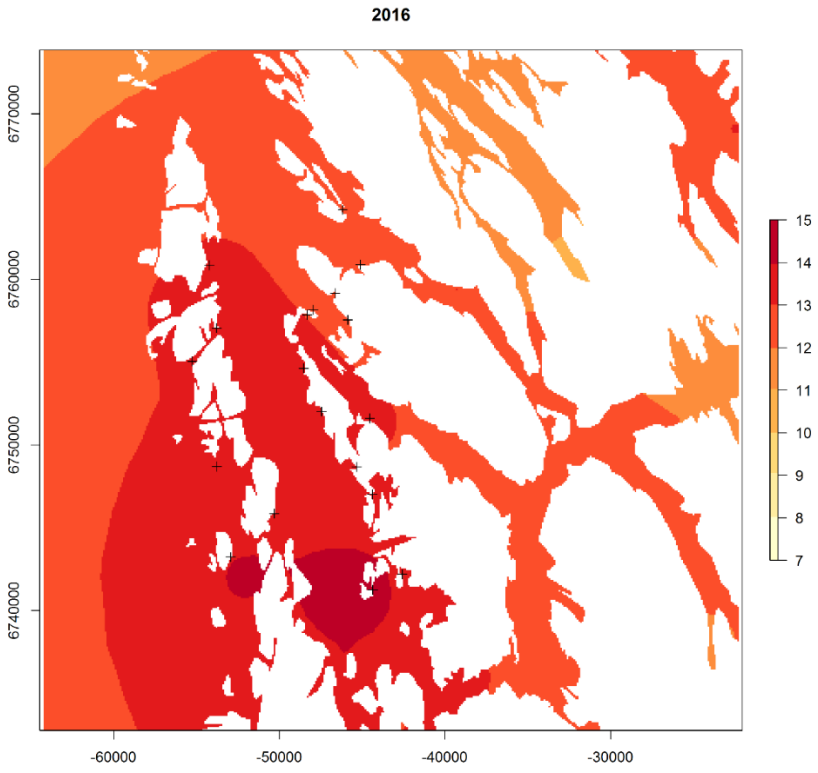

Figure 18 VI model predictions for 2016.