UNIFYING BEHAVIOR, ENVIRONMENT AND TECHNOLOGY FOR OPTIMAL SITE MANAGEMENT PREVENTLICE: 901685

Final report – 07 June 2023

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1 Summary

1.1 Project organization – FHF901685

Project group

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1.2 Main findings

- All data and findings from this project have been summarized and compiled into a freely available web-based application which can be used by farmers to select and plan an effective lice prevention strategy tailored to the conditions at their site of interest. Recommendations are available for all 1023 salmon farming localities active in Norway. https://havforskningsinstituttet.shinyapps.io/preventlice/

- Environmentally responsive, dynamic louse prevention consistently reduces louse infestations across a range of sites and conditions without negatively impacting fish health or welfare.

- Snorkel cages, though highly effective at reducing louse infestations in ideal conditions, are sensitive to temperature and salinity variability and less effective when there is a halocline. Further, growth is slightly but consistently reduced in snorkel cages and amoebic gill disease severity is elevated, when present.

- Exposure to large waves significantly reduces the preventive efficacy of cages using both the dynamic and snorkel prevention strategies.

- 88% of sites are exposed to maximum louse infestation pressure in the upper 1m of the water column. Depth of maximum predicted infestation pressure does not exceed 10m at any sites.

- Deeper distribution of infective louse copepodids occurs more often in the south, where deeper more intense haloclines are common, than in the north.

1.3 Summary

The most common and widely used lice prevention strategies commercially available are barriers (snorkels and skirts) and behaviour modification using submerged lights and feeding. These tools have performed well in some trials, but none function optimally in all conditions. We examined the interactions between lice preventive tools and local environmental conditions by combining existing knowledge via meta-analysis with targeted data collection to fill identified knowledge gaps. In total 60 sampling visits were performed at commercial farms distributed along the Norwegian coast from 58 °N to 68 °N (Figure 9) throughout all seasons. All sites were equipped with either skirt or snorkel barriers.

We found that snorkel cages reduce louse infestations by 80% or more in ideal conditions, when salinity is uniform throughout the water column and the depth with temperatures nearest 14 °C are shallow, but that preventive efficacy is significantly reduced when conditions deviate from ideal (Figures 3 & 11). Further, even in ideal conditions, snorkel cages reduce growth compared to controls (Figure 4) and lead to increased amoebic gill disease severity when disease is present (Figures 5 & 14b). In contrast, dynamically deployed skirt barriers in combination with behavior modification consistently reduce louse infestations by more than half compared to standard production cages, regardless of temperature and salinity variability (Figure 3), without negatively impacting growth (Figure 4), gill condition (Figures 5 & 14a-c) or welfare (Figures 4 & 14d). Preventive efficacy of both dynamic skirt and snorkel strategies is reduced at sites with exposure to large waves (Figure 12), but efficacy is not practically impacted by maximum surface current speeds of up to 0.8 m s^{-1} (Figure 13).

These findings, in conjunction with modelled data of the salinity, temperature, current speed, wave exposure and louse infestation pressure for all 1023 active salmon farming localities in Norway were combined to create a publicly accessible decision support tool. The planning tool is a web application whereby users can directly access key environmental information and concrete recommendations to optimize lice prevention and fish welfare. The primary function of the application is to identify an effective louse prevention strategy for every salmon farm in Norway based on site-specific environmental variability and provide users with an approximation of how to optimally deploy prevention based on local conditions. The app also presents the key data underlying the recommendations, allowing users to better understand local hydrodynamic conditions and the reasons for a given recommendation. This deeper understanding will improve the capacity of farmers to respond to real-world conditions and fine-tune their use of lice prevention strategies. Additionally, the presentation of a several years long, historical hydrodynamic database from NorFjords160

dramatically improves the accessibility of an important resource, with implications beyond louse prevention.

2 Introduction

2.1 Background

Study of the biology and behavior of Atlantic salmon (*Salmo salar*) and salmon lice (*Lepeophtheirus salmonis*) allowed for the development of several lice preventative farming tools. The most widely used and commercially available tools are based on two strategies: (i) modified cage designs which aim to reduce encounter rates by ‘shielding’ salmon from inflowing surface water using a barrier, and (ii) manipulation of salmon behaviour by luring them to cage areas where louse densities are lowest. While most of the prevention strategies tested thus far have significantly reduced louse infestations in some trials, they have also had negligible impact in others (Barrett et al. 2020).

Barrier technologies

One of the earliest lice prevention tools developed was the ‘skirt’ – a barrier which completely encircles the uppermost portion of a cage. Though widely used, little data exists on the efficacy of skirts in commercial salmon aquaculture. As a lice prevention strategy, skirt effectiveness varies (Barrett et al. 2020). In one summer trial when surface waters were warmest and likely the cage area preferred by the fish, cages equipped with 10m deep skirt barriers had 80% fewer lice than control cages after 12 weeks, with no effect on fish welfare or growth (Stien et al. 2018). However, in a larger multi-year trial spanning 5 commercial sites, the average reduction in louse infestation was only 30% in cages equipped with either 6m or 10m skirts relative to control cages (Grøntvedt et al. 2018).

Snorkel cages are an evolution of the skirt which combines the protective barrier concept with submergence. A submerged net roof connected to the base of a central barrier tube (snorkel) is fitted within a standard cage, thus ensuring that salmon either remain below the depths with presumed highest lice densities or are protected by a barrier when they venture to the surface. Of the lice prevention tools tested commercially, snorkel cages are the most effective on average, reducing lice infestations by a median of 76% across nine trials (Barrett et al. 2020). Critically though, snorkel cages also have the most variable efficacy, with results ranging from an 8% increase to a 95% reduction in louse infestations (Barrett et al. 2020). In addition to variable protective efficiency, snorkel cages also come with operational challenges. Supplemental aeration or water exchange within the snorkel volume is continuously required to maintain acceptable water quality, and in periods when freshwater input is high a surface brackish layer must be maintained within the snorkel to prevent deformation and subsequent ‘closing’ of the snorkel. Failure to address these issues results in reduced snorkel efficacy due to the depth of protection being reduced and negative impacts on salmon welfare.

Behavior modification

Salmon behavior modification is an operationally simple and minimally invasive lice prevention strategy. Artificial lights, which salmon find attractive (Juell et al. 2003, Juell and Fosseidengen 2004, Wright et al. 2015), are already used to suppress sexual maturation on most farms. Observations of salmon behaviour at night in response to artificial lighting found that when lights were surface mounted on commercial cages the fish crowded in the upper 3m at up to 20 times the calculated fish density. Conversely, when lights were submerged the fish were more dispersed and swam deeper on average (Juell et al. 2003). Thus, with regards to louse management, artificial light attraction presents both a challenge and an opportunity. If not deployed thoughtfully with consideration for environmental conditions, artificial lights can attract salmon into the cage areas where infective stages of lice are most abundant (Hevrøy et al. 2003). On the other hand, if used in an environmentally informed manner, submerged artificial lights are a minimally invasive tool to attract salmon away from the surface and into the areas of the cage with the most favorable conditions (Bui et al. 2019).

Unfortunately, the attractive effect of lights when competing with other behavioural drivers in sea cages is variable. Salmon can respond rapidly to lighting changes, even following lights as they are moved through the cage, but whether they choose to or not depends on other environmental and biotic factors (Juell and Fosseidengen 2004, Wright et al. 2015). When (Oppedal et al. 2007) positioned submerged lights in sea cages at 1, 5 or 10m for 2 weeks during winter, spring and summer, salmon displayed distinctly different responses dependent on vertical temperature profiles. When lights were positioned at the depth of warmest temperatures, the fish remained at that depth throughout the diel cycle; however, if the depth with moderately warmer temperatures differed from that of the lights, the fish remained in the warmest waters during the day and moved to those with illumination at night. When there was a strong vertical temperature gradient, the depth with the warmest temperature was preferred regardless of light position or time of day. Thus, while light is an important driver of salmon behaviour, it can be over-ridden by other factors (Oppedal et al. 2011, Føre et al. 2013)

Few studies have investigated the impacts of artificial lighting in isolation on louse infestation. In the trials which have, the results are consistent: fish which swim shallower experience more louse attachment. If the lights are placed above the cage, fish in the lit cages experience the same or greater louse attachment than natural light cages (Hevrøy et al. 2003); if the lights are submerged deep, fish in the lit cages have the same or less louse attachment (Frenzl et al. 2014). In the only full-scale commercial study which used submerged lights alone as a lice prevention tool, fish in cages exposed to lights at 10m depth had 40 – 50% fewer lice than those in cages with lights at 1.5m in 2 out of 3 monthly sampling events (Frenzl et al. 2014).

Another determinant of salmon behaviour is hunger. Many fish species migrate downwards during daylight hours, and in the absence of human intervention, salmon in sea cages often will as well (Juell et al. 1994, Fernö et al. 1995, Oppedal et al. 2011). Standard farm practice, however, is to scatter feed across the cage surface throughout the day, luring the fish upwards. As a result, the vertical distribution of salmon in cages can be explained by trade-offs between hunger, day-time surface avoidance and temperature (Huse and Holm 1993, Fernö et al. 1995). Salmon crowd the surface during feeding, and only gradually return to their pre-feeding preferred depth as satiation is reached (Huse and Holm 1993). In a study which tracked environmental conditions and vertical fish distribution in cages at four commercial farming sites with different hydrodynamic conditions, Johansson et al. (2007) found that higher fish densities were consistently predicted in the surface during feeding periods. While the attraction of salmon to the surface to feed can be problematic with regards to louse infestation, like anti-maturation lights, it is also an opportunity ripe for exploitation. The amount of time salmon spend in the depths with highest lice densities can be dramatically reduced simply by adjusting feed distribution – a shift which decouples both the anticipatory and active feeding behaviors from the cage areas where lice are most abundant.

No trials have investigated the efficacy of submerged feeding in isolation, but a few studies have tested it in combination with other prevention strategies. Frenzl et al. (2014) compared 3 treatments, (a) surface feeding + lights, (b) surface feeding + submerged lights and (c) submerged feeding + lights, throughout the final three months of production at a commercial site. In this trial, louse prevalence was significantly lower in both submerged treatment groups (b & c) than the surface fed controls (Frenzl et al. 2014). In another trial which compared cages with continuously submerged lights and feeding to standard cages with surface feeding and no lights, salmon swam deeper in the submerged treatment cages than controls in some conditions, but not in others, resulting in no significant difference in lice numbers (Nilsson et al. 2017). Similarly, in a trial which compared standard commercial cages with cages equipped with, (i) submerged lights and feeding and (ii) skirts + submerged lights and feeding, the average swimming depth of both treatments with submerged lights and feeding was significantly deeper than that of fish in standard cages. However, during the summer when preferred temperatures were in the surface, fish in all treatments schooled in the surface regardless of light and feeding position (Bui et al. 2020). As a result, though new lice infestations generally trended lower in the submerged light and feeding group, overall the difference was not significant. In the cages which were also equipped with skirts, which shielded the salmon during periods when behavior modification was ineffectual, lice infestations were significantly lower than in cages without prevention measures (Bui et al. 2020).

Thus, while these behavioural modification strategies alone will not significantly reduce lice infestations in all conditions, working with the innate preferences and behaviour of salmon can reduce louse infestation pressure in some conditions, and are a potentially powerful tool if used in combination with a barrier. Optimal implementation of any behavioural modification strategy, however, requires knowledge of the site-specific environmental conditions, particularly vertical temperature and salinity gradients.

Re-imagining prevention

Although none of the lice prevention tools currently commercially available perform optimally in all conditions, they each perform well in some conditions. Thus, the key to developing a successful lice prevention strategy is identifying the strengths and weaknesses of each tool and deploying them accordingly.

Both barrier technologies and behaviour modification strategies were formulated based on the idea that infective lice copepodids are phototactic and migrate upwards toward light, concentrating near the surface (Flamarique et al. 2000). Recent evidence, however, shows that copepodid behavior is more complicated than previously thought. In mesocosm experiments, though unresponsive to thermal gradients, copepodids displayed clear salinity preferences which over-shadowed the influence of light (Crosbie et al. 2019, 2020). In homogenous salinity of 34ppt, copepodids distributed evenly throughout most of the column, with slightly higher densities in the surface; in the presence of even a weak halocline of 30ppt, copepodid distribution shifted so that more than 70% of individuals were either at or below the halocline (Crosbie et al. 2019). When in the presence of any salinity gradient, even just a 2ppt difference, highest copepodid densities were consistently within the halocline (Crosbie et al. 2019).

These findings suggest that re-imagining how lice prevention tools are deployed can improve efficacy. Rather than minimizing contact between salmon and the surface waters, a more effective strategy would be site-specific, chosen based on local environmental conditions. In locations with a frequent halocline, the strategy should be dynamic, adjusted in response to the real-time environmental conditions to shield salmon from the surface waters when salinity is homogenous, and maximize avoidance of the halocline when a brackish layer is present. When Bui et al. (2020) tested the continuous use of 6m lice skirts and submerged light and feeding (deployed separately and in combination) at a commercial site with a frequent halocline, a link was observed between louse infestation and distance from the halocline; treatments which swam closer to the halocline experienced higher rates of new louse attachment than those which swam below.

Thus far, all published studies have used static lice prevention strategies, but one recent trial has tested a dynamic, environmentally responsive lice prevention strategy at commercial scale with promising preliminary results. The dynamic strategy utilized skirts, aeration, and adjustable depth lights and feeding deployed according to the regime outlined in Figure 1. The strategy is based on the following principles: (a) shield the surface when salinity is homogenous throughout the water column, (b) feed the fish at the depth of their preferred temperature to optimize growth, (c) remove skirts and attract fish to the surface when there is a brackish layer, (d) use aeration to maintain water quality when skirts are in use, and (e) turn off aeration when there is a halocline to maintain the brackish layer and minimize mixing. Throughout a full production cycle, new lice infestations were reduced by more than half relative to control cages, resulting in 25% fewer delousing events (Oldham et al. 2022).

Dynamic lice prevention

	Homogenous temperature	Preferred temperature surface	Preferred temperature deep
Homogenous salinity	Deep feeding, deep lights, skirt and aeration	Surface feeding, deep lights, skirt and aeration	Deep feeding, deep lights, skirt and aeration
Halocline (26ppt @ 3m)	Surface feeding, surface lights	Surface feeding, surface lights	Deep feeding, surface lights

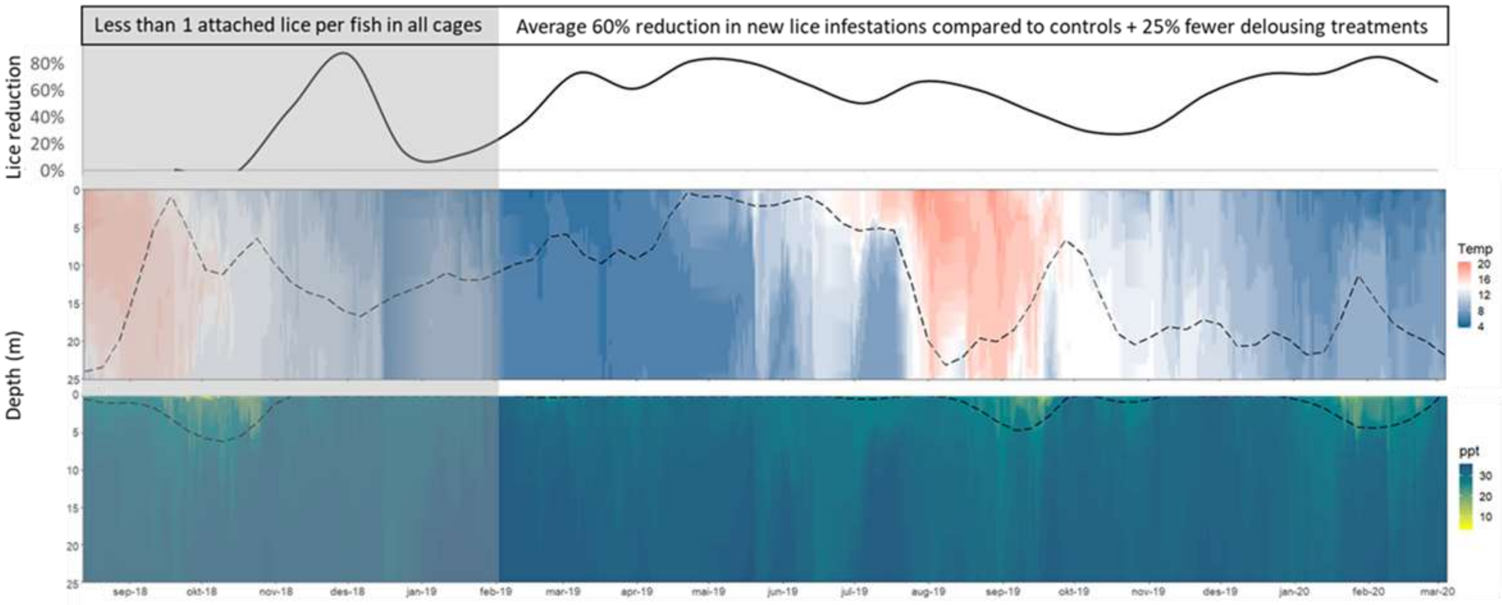

Figure 1: Dynamic lice prevention strategy using a skirt barrier with adjustable depth lights and feeding, adjusted according to real-time environmental conditions. (a) % reduction of attached lice in dynamic cages relative to controls, (b) vertical profile of temperature through time overlayed with a dashed line to show the preferred temperature of salmon, and (c) vertical profile of salinity through time overlayed with a dashed line to show the depth of a brackish layer of 26ppt.

2.2 Objectives

This application addressed the FHF call to develop new knowledge about effective methods for the prevention and control of lice. Specifically, sub-goal 1: *Acquire knowledge and prepare concrete recommendations on interactions between environmental conditions at sites and selection of prevention and control strategies through a production cycle.*

Objective 1: Review the state of knowledge and evaluate efficacy of the most commonly used lice prevention strategies in relation to environmental conditions (WP1). Perform a meta-analysis of all published data from trials using snorkel cages, skirt barriers, submerged lights and submerged feeding to estimate the effect size of lice prevention strategies in different environments.

Objective 2: Evaluate the lice prevention efficiency and production performance implications of snorkels, skirts and adjustable depth lights and feeding dynamically deployed in varied environments throughout Norway (WP2). Throughout the full production cycle at 24 commercial sites fitted with lice prevention measures divided between southern, mid and northern Norway we will continuously monitor local environmental conditions in real-time while also tracking lice infestation and production performance.

Objective 3: Create a publicly accessible database of environmental conditions and louse infestation pressure throughout the year for every aquaculture site in Norway (WP3). Using several years of historical data from high-resolution hydrodynamic and louse dispersion modelling, the temporal and vertical variations in current speed and direction, temperature, salinity and louse infestation pressure will be summarized for every approved aquaculture site in Norway.

Objective 4: Develop a web-based tool to provide concrete, site-specific recommendations for selection of optimal prevention strategies based on local environmental conditions (WP4). Recommendations will be based on synthesis of the knowledge acquired in WPs 1-2, and local environmental conditions as determined in WP3.

3 WP1 – Meta-analysis: lice prevention in relation to environmental conditions

3.1 Impact goals

The most common lice prevention strategies in commercial use are barriers (snorkels and skirts) and behaviour modification using submerged lights and feeding, but none of these tools function optimally in all conditions. Although several commercial-scale controlled studies have examined the efficacy of these tools in a broad sense, few have considered the interaction between local environmental conditions and preventive efficacy. The aim of this WP is to re-examine the wealth of data previously collected with focus on efficacy in relation to local conditions.

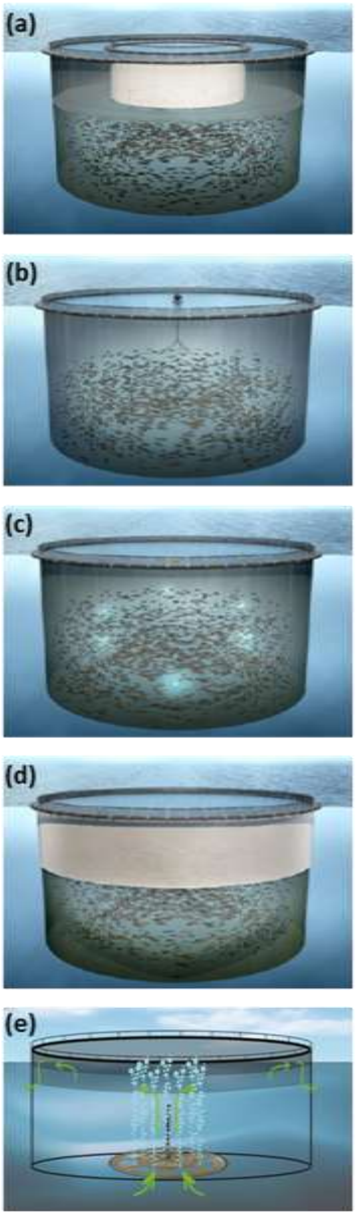

Figure 2. Schematic of each of the lice prevention tools to be evaluated: a) snorkel cage, b) adjustable depth feeding, c) adjustable depth lights, d) skirt barrier, and e) aeration device.

3.2 Methods

To evaluate the efficacy of louse barrier and behavior modification preventive methods we conducted a meta-analysis of published studies in the scientific and grey literature. Relevant studies were identified by searching ISI Web of Science and Google Scholar in September 2022 using the following search strings: *(skirt OR snorkel) AND (salmo*)* and *(light* OR feed* OR behav*) AND (salmo*) AND (lice OR louse OR salmonis OR caligus)*. We also found additional studies referenced within the articles returned by the search. The articles were then filtered for inclusion in the meta-analysis based on three criteria: a) measure of relative louse infestation densities for both test and control groups, b) inclusion of temperature and salinity data and c) commercial scale trial. In total we identified three relevant studies on behavior modification using lights and/or feeding, five studies on snorkel barriers, one study on skirt barriers alone and two studies on the integrated use of skirt barriers in combination with behavior modification which were suitable.

Effect size, here calculated as the response ratio (RR) of µT/µC, where µT is the test group response and µC is the control group response, was determined for each sampling point in each trial. To enable comparison across studies effect size was standardized using the natural log of the response ratio: LnRR = ln(µT/µC). Three response variables were included in the analyses, fish weight (*LnRR_growth*), amoebic gill disease (AGD) score (*LnRR_gill*) and mean number of attached lice per fish (*LnRR_lice*). To ensure that no bias was introduced because of differential use of cleanerfishes or delousing only attached louse counts were included. Each preventive strategy was then categorized as one of three *treatment* groups (categorical 3 levels: behavior, skirt+ or snorkel). Two additional explanatory variables were derived from the salinity and temperature data. Because copepodids, the infective stage of salmon lice, actively avoid brackish water (Crosbie et al. 2019), a brackish layer was defined as salinities of 26 ppt or less at 3 m water depth. These data were used to create the categorical variable *halocline* (categorical 2 levels: present or absent). Additionally, because temperature is the key determinate of salmon swimming depth in marine cages, the depth at which the temperature was closest to 14 °C (*depth nearest 14 °C*, continuous) was determined (Oppedal et al. 2011). Standard procedures for data exploration were followed to identify any outlying observations and test for collinearity between variables (Zuur et al., 2010).

To examine the influence of temperature and salinity on preventive tool efficacy, each response variable (*LnRR_growth, LnRR_gill* and *LnRR_lice*) was modelled as a function of *treatment, halocline* and *depth14C* using gaussian generalized linear mixed models (GLMM). Additional interaction terms included were *treatment x halocline* and *treatment x depth14C* to allow for different relationships between the environment and each preventive treatment group. To incorporate the dependency among measurements from the same trial, *trial* was used as a random intercept. The glmmTMB package (Brooks et al. 2017) in R version 3.6.1 (R Core Team 2018) was used to fit all models. To test for a significant effect of preventive strategy on response variables we conducted one way t-tests on the RR data, where mean RR under the null hypothesis of no preventive strategy effect = 0.

3.3 Results

The nine studies included in the meta-analysis provided 254 comparisons between test cages equipped with louse prevention tools and control cages (Table 1). In total there were 27 comparisons where behavior modification alone was tested (termed: behavior), 175 where snorkel cages were tested (termed: snorkel) and 39 where skirt barriers were used in combination with behavior modification (termed: skirt+).

3.3.1 Salmon lice

Snorkel barriers reduced new louse infestations but varied widely in their effectiveness (Figure 3). In 99 of 175 comparisons (57%) the cages equipped with snorkel barriers had fewer than half as many lice as control cages, and conversely, in 36 comparisons (21%) had similar or more lice. The protective effect of snorkel barriers was strongly influenced by both salinity and temperature, with median reductions in louse infestation of 49% when a halocline was present (t_{30} = -3.7, P = 0.001) compared to 59% when there was no halocline (t_{145} = -10.3, P < 0.0001). Similarly, snorkel barriers were predicted to reduce louse infestations by 76 – 81% when the temperature nearest 14 °C is in the surface, versus 43 – 53% when optimum temperatures are at 25m (Figure 3).

Behavior modification alone did not significantly reduce louse infestations in any of the measured conditions but appears to perform best when the temperature nearest 14 °C is in the surface (Figure 3). In only 4 of 27 comparisons (15%) the cages utilizing behavior modification had fewer than half as many lice as control cages, and conversely, in 11 comparisons (41%) had similar or more lice. Although behavior modification provided a median reduction of 42% when a halocline was present (t_8 = -1.9, P = 0.09), and only 16% in the absence of a halocline (t_{19} = 0.52, P = 0.61), the limited amount of data available were insufficient draw any conclusions (Table 2).

Table 1. Median and mean response ratios (test/control group) for fish weight, AGD gill score and attached lice count for each prevention strategy both with, and without, the presence of a halocline. t-stat and P refer to one sample t-test comparing response ratio data to the null expectiong of RR = 0. Values in bold are significant at α = 0.05.

Treatment	Halocline	N	EFFECT SIZE (T/C)												References
			Weight				AGD score				Lice				
			median	*X̄ ± SD*	*t-stat*	*P*	*median*	*X̄ ± SD*	*t-stat*	*P*	*median*	*X̄ ± SD*	*t-stat*	*P*	
Snorkel cage															Geitung et al. (2019), Bui et al. (2020), Geitung et al. (2021), Wright et al. (2017), Oldham, T. (unpublished)
	present	*30*	0.89	0.89 ± 0.19	-2.27	**0.033**	1.66	2.20 ± 1.93	2.41	**0.025**	0.51	0.68 ± 0.68	-3.71	**0.001**	
	absent	*145*	0.88	0.90 ± 0.23	-7.36	**<0.0001**	1.10	7.52 ± 47.8	2.78	**0.006**	0.41	0.75 ± 1.93	-10.32	**<0.0001**	
Skirt+															Oldham et al. (2022), Bui et al. (2019), Stien et al. (2018)
	present	*12*	1.01	1.01 ± 0.16	-0.53	0.615	1.00	0.93 ± 0.17	-1.00	0.423	0.37	0.53 ± 0.44	-4.17	**0.004**	
	absent	*27*	0.99	1.01 ± 0.19	-0.24	0.815	1.00	1.01 ± 0.38	0.36	0.727	0.44	0.48 ± 0.28	-6.15	**<0.0001**	
Behavior modification	*present*	*8*	0.94	1.05 ± 0.28	0.19	0.851	0.97	0.95 ± 0.07	-1.33	0.315	0.58	0.76 ± 0.55	-1.95	0.092	Nilsson et al. (2017), Bui et al. (2019)
	absent	*19*	0.95	0.99 ± 0.16	0.53	0.607	0.93	0.95 ± 0.28	-0.52	0.619	0.84	1.09 ± 0.60	0.52	0.613	

Skirt barriers used in combination with behavior modification tools consistently reduced new louse infestations both with a halocline present (median reduction = 63%, t_{12} = -4.17, P = 0.004), and without (median reduction = 56%, t_{27} = -6.15, P < 0.0001). In 25 of 39 comparisons (64%) the skirt+ cages had fewer than half as many lice as control cages, and conversely, in only 5 comparisons (13%) had similar or more lice. Temperature did not alter the preventive efficacy of the skirt+ strategy (Figure 3).

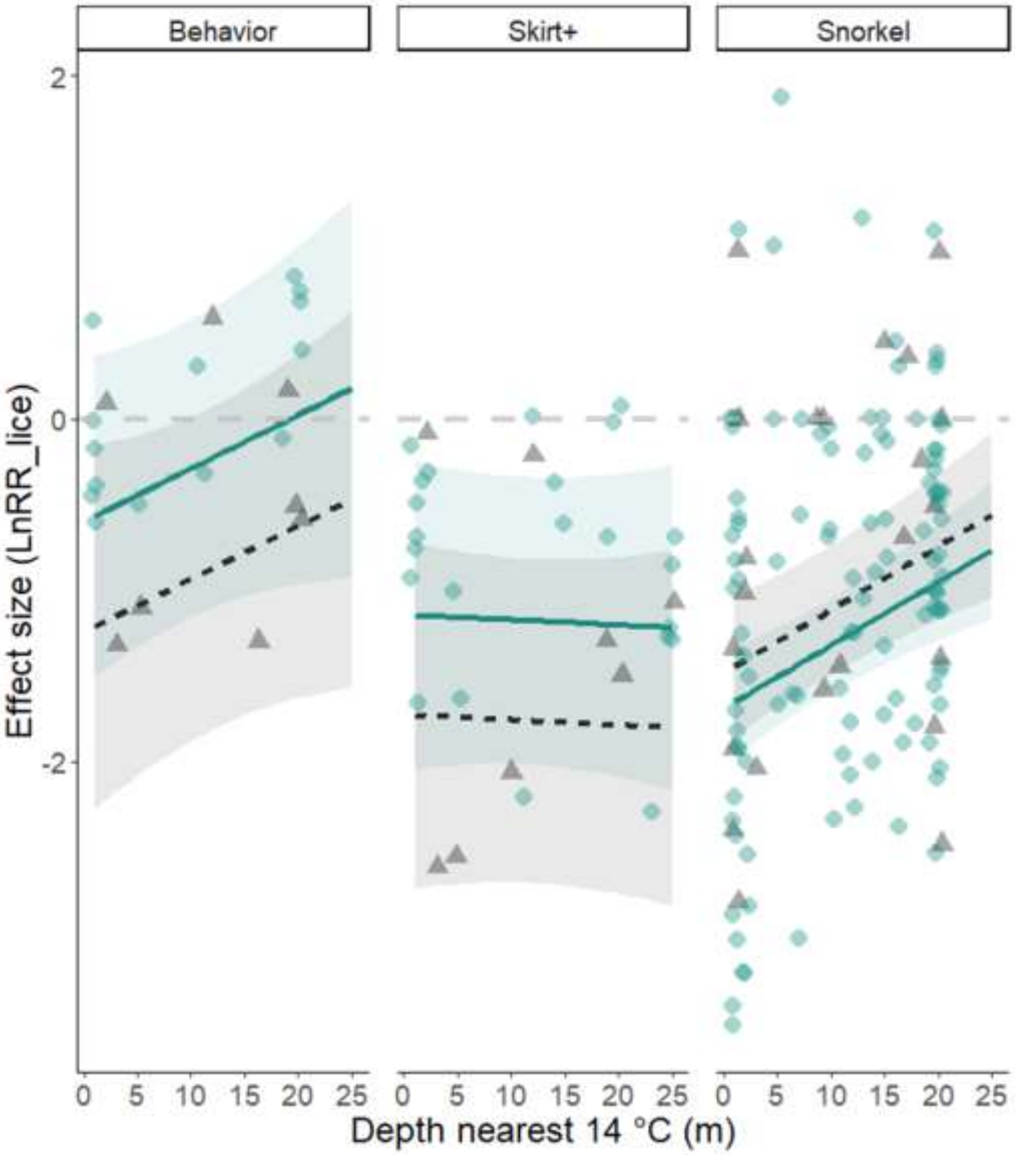

Figure 3. *Influence of temperature and salinity on lice preventive efficacy. Effect size (natural log of the response ratio: LnRR) of louse infestations as influenced by halocline (presence/absence), the depth of temperatures nearest 14 °C and preventive strategy. Solid lines and shaded areas display a fitted GLMM with 95% confidence intervals, while dot points represent each individual comparison. Green indicates no halocline, while grey indicates a halocline was present. LnRR = 0 corresponds to no difference between control and test groups, while negative values indicate fewer lice in test cages.*

Table 2. *Estimate, standard error (SE), z-value and P-values of the explanatory variables in the models of (a) louse infestation, (b) fish weight and (c) gill condition.*

	Estimate	SE	z value	P value
(a) New louse infestation				
Intercept	-0.239	0.411	-0.580	0.562
Treatment-Skirt+	-0.544	0.453	-1.201	0.230
Treatment-Snorkel	-1.088	0.495	-2.196	0.028
Halocline-present	-0.645	0.381	-1.692	0.091
Depth 14°C	0.031	0.023	1.381	0.167
Treatment-Skirt+ : Halo-present	0.061	0.522	0.117	0.906
Treatment-Snorkel : Halo-present	0.851	0.430	1.979	0.048
Treatment-Skirt+ : Depth 14°C	-0.034	0.028	-1.224	0.221
Treatment-Snorkel : Depth 14°C	0.006	0.024	0.236	0.813
(b) Fish weight				
Intercept	0.056	0.096	0.581	0.562
Treatment-Skirt+	-0.137	0.121	-1.133	0.257
Treatment-Snorkel	-0.158	0.111	-1.428	0.153
Halocline-present	-0.003	0.104	-0.030	0.976
Depth 14°C	-0.003	0.006	-0.446	0.656
Treatment-Skirt+ : Halo-present	-0.016	0.141	-0.111	0.911
Treatment-Snorkel : Halo-present	0.025	0.117	0.216	0.829
Treatment-Skirt+ : Depth 14°C	0.006	0.008	0.838	0.402
Treatment-Snorkel : Depth 14°C	0.000	0.007	0.031	0.975
(c) Gill condition				
Intercept	-0.063	0.484	-0.131	0.896
Treatment-Skirt+	0.096	0.634	0.151	0.880
Treatment-Snorkel	0.269	0.524	0.512	0.609
Halocline-present	0.006	0.630	0.009	0.993
Depth 14°C	0.000	0.034	0.001	0.999
Treatment-Skirt+ : Halo-present	-0.204	0.759	-0.257	0.797
Treatment-Snorkel : Halo-present	-0.077	0.656	-0.117	0.907
Treatment-Skirt+ : Depth 14°C	-0.001	0.038	-0.017	0.986
Treatment-Snorkel : Depth 14°C	0.014	0.035	0.405	0.686

3.3.2 Fish weight

Overall, fish in snorkel cages were smaller than fish in control cages (median reduction = 11%, n = 175; Table 1). Neither behavior modification alone (median reduction = 0%, n = 27) nor the skirt+ strategy (median reduction 5.5%, n = 39) affected fish weight (Figure 4). Neither the presence of a halocline nor the depth nearest 14 °C, nor their interaction with any of the preventive strategies tested, significantly impacted fish weight (Table 2).

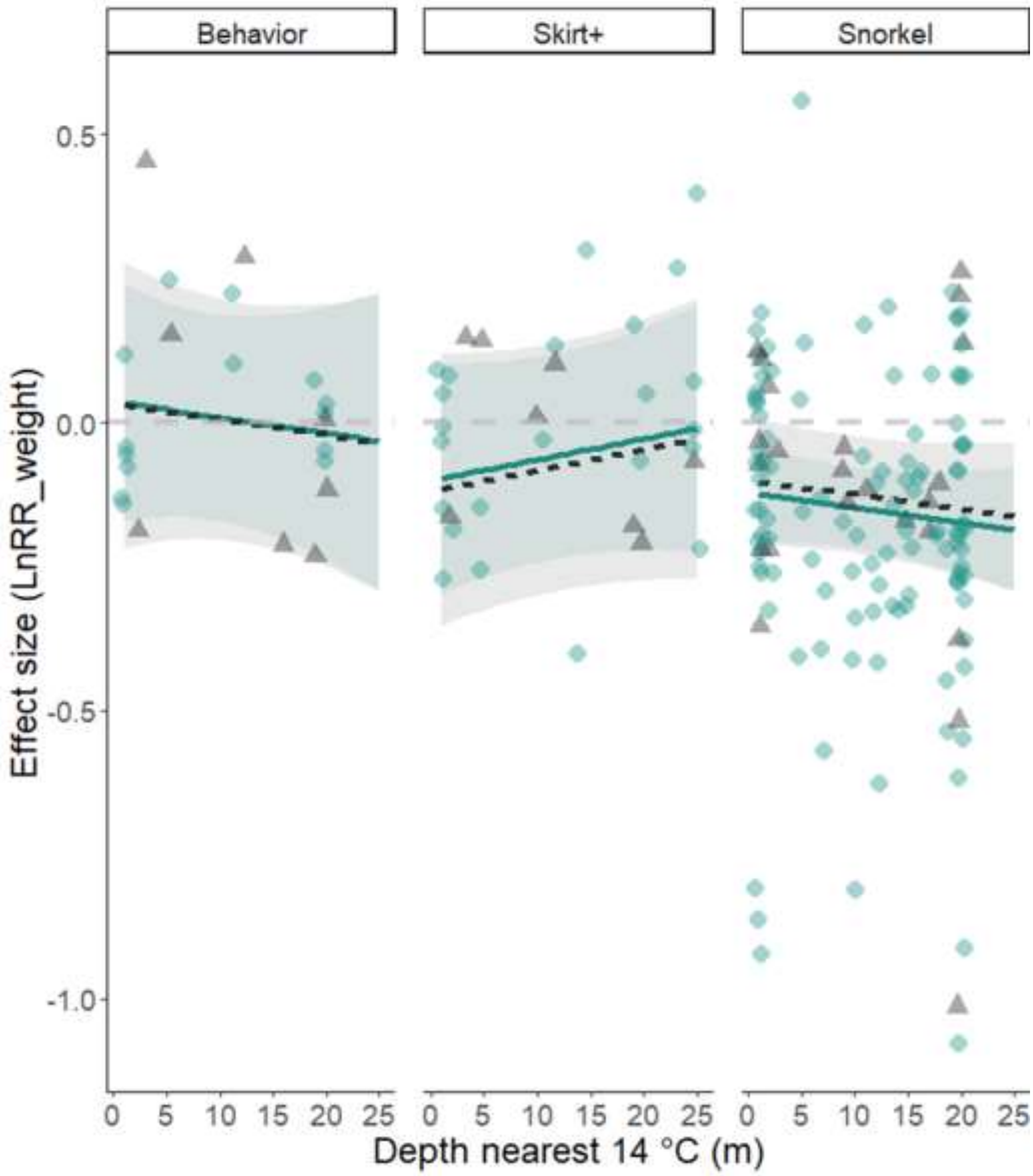

Figure 4. *Influence of temperature and salinity on fish weight when using preventive tools. Effect size (natural log of the response ratio: LnRR) of fish weight as influenced by halocline (presence/absence), the depth of temperatures nearest 14 °C and preventive strategy. Solid lines and shaded areas display a fitted GLMM with 95% confidence intervals, while dot points represent each individual comparison. Green indicates no halocline, while grey indicates a halocline was present. LnRR = 0 corresponds to no difference between control and test groups while negative values indicate smaller fish in test cages.*

3.3.3 Gill condition

Fish in snorkel cages had higher AGD scores than fish in control cages (median increase = 38%, n = 175; Figure 5). Compared to control cages, gill scores were worst in snorkel cages in the presence of a halocline (median increase = 66%, t_{30} = 2.4, P = 0.025) than without (median increase 10%, t_{145} = 2.8, P = 0.006). Neither behavior modification alone (median increase = 5%, n = 27), nor skirts in combination with behavior modification (median increase = 0%, n = 39), affected AGD score in any of the measured conditions (Table 2).

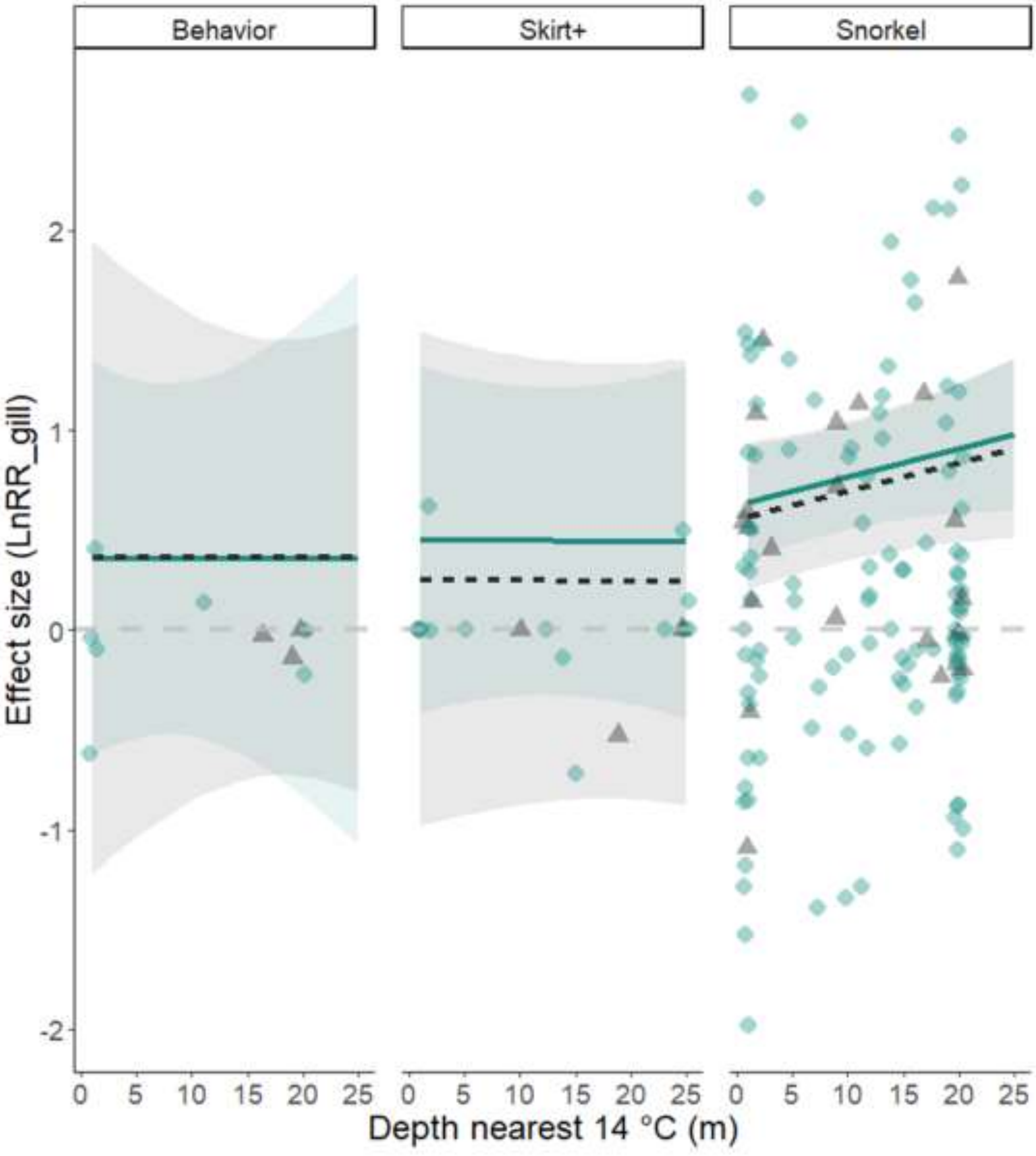

Figure 5. *Influence of temperature and salinity on gill condition when using preventive tools. Effect size (natural log of the response ratio: LnRR) of amoebic gill disease (AGD) score as influenced by halocline (presence/absence), the depth of temperatures nearest 14 °C and preventive strategy. Solid lines and shaded areas display a fitted GLMM with 95% confidence intervals, while dot points represent each individual comparison. Green indicates no halocline, while grey indicates a halocline was present. LnRR = 0 corresponds to no difference between control and test groups, while positive values indicate higher AGD scores (worse gill condition) in test cages.*

4 WP2 – Evaluation of the efficacy of preventive tools in varied environments

4.1 Impact goals

Snorkels, skirts and adjustable depth lights and feeding are all powerful lice prevention tools in some conditions, yet ineffectual in others (Barrett et al. 2020). Determining the reason for such varying results from the available data is difficult, as there are numerous confounding differences between trials. We will evaluate the lice prevention efficiency and production performance implications of these tools at commercial scale in varying conditions at sites distributed along the Norwegian coast. Sampling trips will be timed to evaluate the performance of the prevention strategies in one of four distinct environmental condition windows:

(a) Homogenous salinity, salmon preferred temperature within the barrier
(b) Homogenous salinity, salmon preferred temperature at or below the barrier
(c) Surface brackish layer of at least 26.5ppt at 5m, salmon preferred temperature above the halocline
(d) Surface brackish layer of at least 26.5ppt at 5m, salmon preferred temperature below the halocline

By aggregating data from many sites the influence of confounding effects can be minimized, thus allowing for the identification of broad trends which can not be identified with trials at individual localities.

Figure 6. Map showing study site locations for WP2. Snorkel cages (black), skirt+ prevention strategy (green).

4.2 Methods

4.2.1 Site selection

To minimize the influence of potential confounding factors a selection of sites distributed along the Norwegian coast equipped with either skirt or snorkel barriers were identified for follow-up. The aim was to sample as many different sites in varied seasons and environmental conditions as feasible so as to maximize the amount of variation captured.

The prevention strategies captured include cages equipped with static plankton mesh barriers used continuouosly (10m - figure 2d), cages using a dynamic, environmentally responsive strategy equipped with plankton mesh barrier (8m), aeration, and adjustable depth lights and feeding (Figure 2b-e, Table 3), or snorkel cages with 16m deep plankton mesh barriers used continuously (Figure 2a). The planned implementation of the dynamic strategy was a modified version of the strategy used by Oldham et al. (2022) (Figure 1). In principle the objective is to utilize local, real-time environmental data to optimally deploy each tool for the prevailing conditions (Table 3). When salinity is homogeneous and infective lice larvae are expected in highest density at the surface, attract fish away from the surface with lights below the skirt barrier. To protect fish which venture to the surface anyway, minimize the influx of copepodids by shielding the uppermost 8m of the cage with a lice barrier. To maintain optimal water quality within the barrier volume an aeration device is positioned at ~10m whenever the barrier is in place. Conversely, when there is a brackish layer of ≤ 26 ppt at 5m lice barriers are removed, aeration turned off, and lights moved to the surface to attract fish into the brackish layer above the halocline. Feeding position is chosen based on depth of preferred temperatures (14-16 °C): (i) in the surface when optimal temperatures are shallow, (ii) below the barrier when optimal temperatures are deep, or (iii) at the position of the lights if temperatures are uniform throughout the cage volume. All sites were equipped with, at minimum, continuously recording real-time temperature and salinity sensors at 5m depth.

Table 3: *Description of the planned dynamic lice prevention strategy in response to real-time salinity and temperature measurements.*

Dynamic lice prevention			
	Homogenous temperature	**Preferred temperature surface**	**Preferred temperature deep**
Homogenous salinity	Deep feeding, deep lights, skirt and aeration	Surface feeding, deep lights, skirt and aeration	Deep feeding, deep lights, skirt and aeration
Brackish layer (≤ 26 ppt @ 5m)	Surface feeding, surface lights	Surface feeding, surface lights	Deep feeding, surface lights

4.2.2 Sampling protocol

At each sampling at least 20 fish from 2 - 3 cages using the same strategy were evaluated for welfare, gill condition and louse infestation. If multiple strategies were in use within a site, then 2-3 cages of each strategy were sampled. Barrier status, cleanerfish status, aeration status, feed position, and light position were noted for each cage. Fish were collected using the typical method used on the farm, which could be either a seine net deployed across the cage, a crane-operated ring-net, or a 'jump-net' whereby a small containment net is placed within the cage and left for 1-3 hours to allow fish to passively jump into the containment net. Fish were then lightly anaesthetized, individually evaluated and returned to the cage.

All lice on each individual fish and in the anaesthetizing vessel were counted and identified at the following levels: (*Lepeophtheirus salmonis*) copepodid, chalimus 1, chalimus 2, pre-adult 1, pre-adult 2 male, pre-adult 2 female, adult male, adult female, adult female with eggs, and *Caligus* sp. attached or mobile. Fish were measured and welfare was evaluated using 14 morphological indicators outlined in the LAKSVEL scoring system, scored as 0 = ideal, 1 = light, 2 = moderate and 3 = extreme (Nilsson et al. 2022). The indicators scored were: emaciation, skin hemorrhaging, wounds, scale loss, fin condition, cataracts, eye hemorrhaging, eye protrusion, opercula condition, gill condition, mouth condition, backbone deformity, lower jaw deformity, and upper jaw deformity. Gill health was further evaluated by visually scoring each arch on the left side of the fish using the standard 0 to 5 scale for amoebic gill disease (AGD) (Taylor et al. 2016), and for the first 5 fish sampled in each cage using swabs to sample the surface of each gill arch on the right side of the fish for qPCR analysis.

4.2.3 qPCR analyses

Gill swabs were immediately inserted into 1 mL vials containing lysis buffer and stored frozen until PCR analysis (Patogen AS, Norway). All gill swabs were tested for *P. perurans* and some additionally for *Branchiomonas cysticola*, *Paranucleospora theridians,* and salmon gill pox virus when gill condition scores were elevated but AGD scores were low. Analyzed samples returned a cycle threshold (Ct) value indicating pathogen presence, where lower Ct values indicate greater pathogen load.

4.2.4 Environmental data

A multi-sensor CTD (SD204, SAIV AS) was used to collect vertical profiles of temperature, salinity and dissolved oxygen from the surface to cage bottom at each sampling. For 18 of the sites included in the study, data on wave exposure (50 year return) and maximum expected current speed were provided by the producers. Additionally, wave height data from the MyWaveWAM800m Norwegian Coastal wave forecasting system (Norwegian Meteorological Institute) were extracted for comparison.

4.2.5 Data analyses

Louse stages were grouped as either new infestations (attached stages: copepodid, chalimus 1 and 2) or existing infestations which could have been affected by delousing treatments or cleanerfish presence (mobile stages: pre-adult 1, pre-adult 2 and adults). For evaluation of preventive efficacy, all analyses were performed using new infestation data.

Predicted louse infestation pressure was estimated by: (1) using the measured temperature at 5m on the day of sampling to determine louse development rate (Hamre et al. 2019), (2) calculating the attachment time window prior to sampling that the observed new infestations could have occurred, and then (3) calculating the sum of the average daily infestation pressure for the attachment time window according to the salmon lice dispersion model (Myksvoll et al. 2018).

The lice preventive effect size was calculated as the Standardized Mean Difference (SMD) between predicted louse infestation pressure and observed new infestations. SMD was calculated as $\mu O - \mu P/SD$, where μO is the mean observed new infestation, μP is the mean predicted infestation pressure, and SD is standard deviation. This measure was chosen to account for the difference in scale between the observed and predicted values. Absolute SMD values of 0.2-0.5 are considered small, values of 0.5-0.8 are medium, and values > 0.8 are large. Negative values indicate fewer lice than expected based on predicted infestation pressure. Although these data cannot be used for performance comparison with previously conducted controlled experiments, they allow for relative comparison of effect size between treatments and conditions included in this study.

For both observed new infestations and SMD standard procedures for data exploration were followed to identify outlying observations and test for collinearity between potential explanatory variables (Zuur et al. 2010). Generalized linear mixed models (GLMM) were used to examine the influence of environmental conditions on lice prevention efficacy according to an information theoretic approach (Burnham and Anderson 2002). A list of all covariates considered is provided in Table 4. To determine which covariates influenced SMD a selection of candidate models were prepared a-priori based on specific hypotheses. Models were then compared using Akaike information criterion (AIC). Site was included as a random intercept in all models to account for potential spatial dependency between locations. The model formulations which best explained the SMD data were also applied to the observed new infestation data to compare and contrast results. Observed new infestations were modelled using a Gamma distribution with a log link function, while SMD was modelled using a Gaussian distribution with an identity link function. The ‘glmmTMB’ package was used to estimate the parameters of the GLMMs (Brooks et al. 2017). Spearman's rank correlation was calculated to examine the correlation between observed louse infestations and predicted infestation pressure.

To examine the relationship between overall gill condition and pathogen abundance a Total gill score was calculated by adding the mean AGD score (0-5) to the gill condition score (0-3). The coefficient of determination (R^2) was calculated for Total gill score and the Ct-value of each pathogen (*P. perurans, B. cysticola, P. theridians*, pox virus). All analyses were performed in R version 3.6.1 (Team 2018).

Table 4: *List of potential explanatory variables included in the GLMM's*

Covariate	Abbreviation	Continuous/categorical
Brackish layer (≤ 26 ppt @ 5m)	Halo26	Categorical (present or absent)
Brackish layer (≤ 28 ppt @ 5m)	Halo28	Categorical (present or absent)
Brackish layer (≤ 30 ppt @ 5m)	Halo30	Categorical (present or absent)
Temperature difference 1 - 10m	TempDif	Continuous
Temperature @ 5m	Temp5	Continuous
Wave exposure: 50 yr return	Wave50	Continuous
Wave exposure: max predicted wave height	WaveMax	Categorical (Low, Medium, High)
Current: max predicted speed	Current	Continuous
Treatment	Treatment	Categorical (Dynamic or Snorkel)
Feeding	Feed	Categorical (Surface or Deep)
Lights	Lights	Categorical (Surface or Deep)
Infestation pressure	PredLice	Continuous
Latitude	Lat	Continuous

4.3 Results

4.3.1 Site summary

Between January 2021 – September 2022 a total of 21 different commercial salmon production sites were sampled. Sites were distributed along the Norwegian coast from 58° N to 68° N (Figure 6). Altogether 60 unique combinations of site, environment and treatment conditions were examined, including 17 samplings of cages using snorkels, 3 samplings of cages using static skirts, and 40 samplings of cages utilizing a dynamic lice preventing strategy (Table 5).

Attached louse counts varied considerably throughout the study, ranging from 0 to a maximum of 4.2 attached lice fish^{-1} in cages using the dynamic strategy and 5.6 in snorkel cages. Overall new infestations did not differ between treatments, averaging 0.59 ± 1.03 attached lice fish^{-1} in dynamic cages and 0.83 ± 1.42 attached lice fish^{-1} in snorkel cages. SMD did not differ with treatment either (Figure 7).

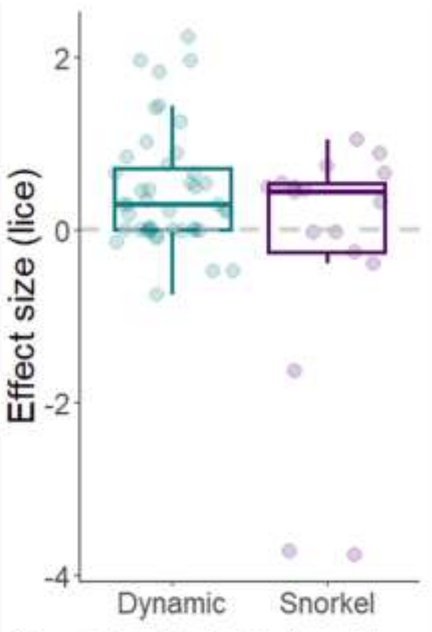

Figure 7: Boxplot showing the median and interquartile range of the standardized mean difference (effect size) between observed louse attachment and predicted infestation pressure for cages utilizing the dynamic (blue) and snorkel (purple) protection strategies.

Table 5: Summary of sampling locations and environmental characteristics including the number of sampling visits, whether or not there was a brackish layer at the time of sampling (≤28 ppt @ 5m), and the maximum predicted current speed at the site according to company provided data.

Site	Treatment	# visits	Brackish layer (≤28 ppt @ 5m)	No brackish layer	Maximum predicted current speed (m s^{-1})	Wave exposure (50 year return - m)	Wave exposure (hydrodynamic model prediction)
Almurden	Snorkel	2	0	2	0.72	1.5	High
Bekksneset	Dynamic	4	0	4	0.5	2.3	Medium
Bjørlykkestranda	Dynamic	2	0	2	0.58	2.0	Low
Fornes	Skirt	1	0	1	NA	NA	Low
Fosså	Snorkel	14	2	12	0.63	1.4	Low
Hallvardøy	Skirt	1	0	1	NA	NA	Medium
Haverøy	Dynamic	2	0	2	0.59	1.7	High
Høystein	Dynamic	2	2	0	0.8	1.7	Low
Kalvhodet	Skirt	1	0	1	NA	NA	High
Lian	Dynamic	2	1	1	0.62	2.5	Medium
Oksebåsen	Dynamic	1	0	1	0.61	2.1	Medium
Oksen	Dynamic	3	0	3	0.5	1.7	High
Olderbakken	Dynamic	2	0	2	0.72	2.1	Medium
Salvågvika	Dynamic	2	0	2	0.84	1.3	Low
Sandskjæret	Snorkel	1	0	1	0.6	3.3	Medium
Skorpeosen	Dynamic	2	0	2	0.5	2.6	High
Storstrompan	Dynamic	2	1	1	0.5	2.2	Medium
Trommo	Dynamic	2	2	0	0.72	2.3	Low
Tveit	Dynamic	4	3	1	0.5	2.0	Medium
Voldnes	Dynamic	1	0	1	0.75	2.0	Low
Åkre	Dynamic	2	2	0	0.5	2.7	Low

4.3.2 Predicted versus observed louse infestation

To evaluate the overall efficacy of each lice prevention strategy we examined the correlation between predicted infestation pressure according to the lice dispersal model and observed louse infestations. The less correlated observed infestations are with predicted, the more effective the prevention strategy. In these data new lice infestations in cages using the dynamic strategy were moderately correlated with predicted infestation pressure (S = 7237, p = 0.002, rho = 0.45), while new lice infestations in snorkels cages were not correlated with predicted infestation pressure (S = 584, p = 0.27, rho = 0.28) (Figure 8).

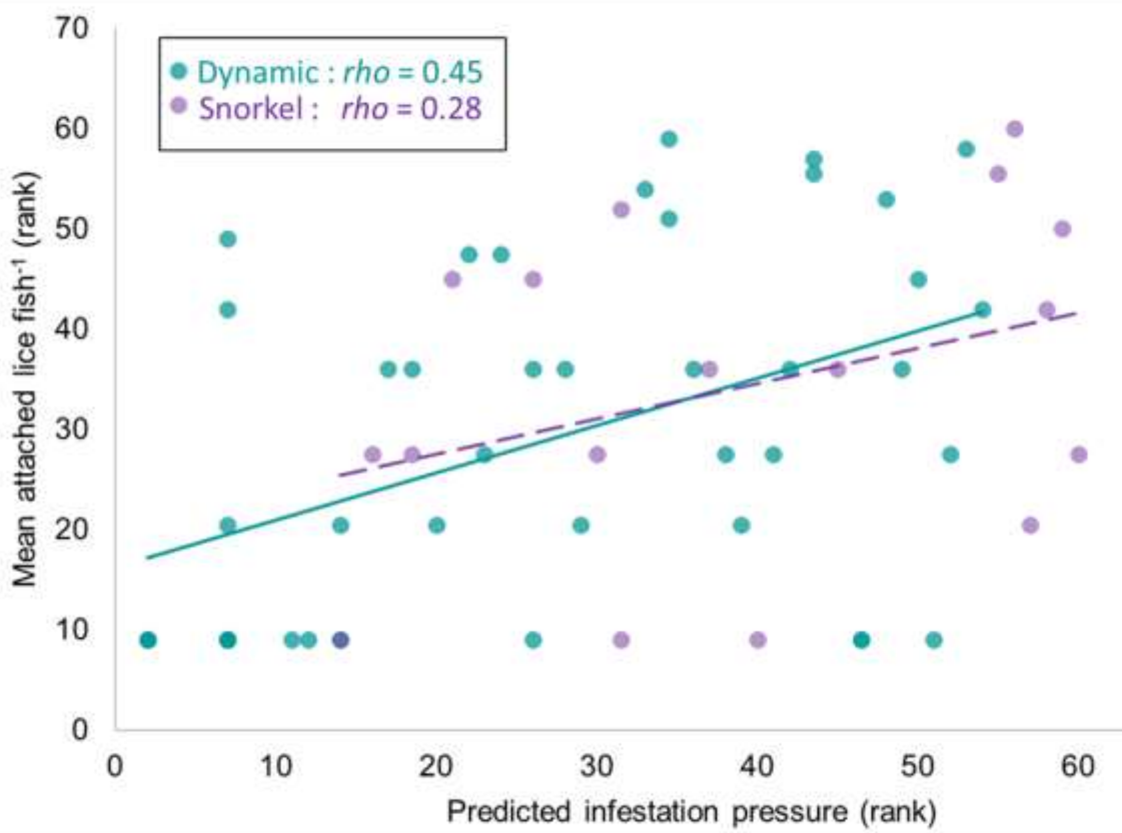

***Figure 8**: Relationship between the ranks of predicted infestation pressure and mean number of attached lice fish^{-1} observed at each sampling, as determined by Spearman's rank correlation.*

4.3.3 Preventive efficacy in relation to environmental conditions

The models tested, their rationale, AIC, and differences in AIC values (ΔAIC) for lice preventive effect size (SMD) are presented in Table 6. Lower AIC values indicate better model fit. Several of the potential explanatory variables considered were influential determinants of preventive effect size including the presence of a moderate halocline (Halo28), wave exposure, current speed, and predicted louse infestation pressure. Two models, M8 and M16 encompassed all of the most influential variables and were selected for further study (Table 7).

In contrast, other variables that were not influential were latitude, temperature at 5m, temperature difference between 1-10m, feeding depth and light position. Examination of the data showed that although predicted infestation pressure was greater in southern Norway, preventive efficacy was not correlated with geographic position (Table 6). Indeed, the sites with both the highest and lowest preventive efficacy were in southern Norway (Figure 9).

Table 6. *Akaike Information Criterion (AIC), degrees of freedom (df) and the difference in AIC between all of the candidate models of new louse infestation.*

Model	Expression	df	AIC	Δ AIC	Description
M0	null	3	175	29	none of the covariates impact preventive efficacy
M1	Lat	4	176	30	efficacy varies with geographic location
M2	Halo26	4	176	30	presence of a strong brackish layer alters preventive efficacy
M3	Halo28*Treatment	6	172	26	moderate brackish layers affect treatment efficacy, impact differs with treatment
M4	Halo30*Treatment	6	174	28	even weak brackish layers affect treatment efficacy, impact differs with treatment
M5	Wave50	4	171	25	wave exposure (50 year return) reduces preventive efficacy
M6	WaveMax	5	169	23	wave exposure (MET model) reduces preventive efficacy
M7	Current	4	171	25	current speeds alter preventive efficacy
M8	**WaveMax + Current**	**6**	**165**	**19**	**water movement reduces preventive efficacy**
M9	Temp5	4	176	30	differences in lice behavior and development affect preventive efficacy
M10	TempDif	4	173	27	salmon behavior in reponse to temperature alters preventive efficacy
M11	PredLice	4	146	0	louse infestation pressure
M12	PredLice*Treatment	6	149	3	dynamic and snorkel strategies respond differently to variations in infestation pressure
M13	TempDif*Halo28	6	177	31	the interactive effects of temperature and salinity determine preventive efficacy
M14	TempDif*Feeding*Lights	10	176	30	salmon behavior as driven by temperature and feed + light depth alters preventive efficacy
M15	TempDif:Feeding + TempDif:Lights + TempDif + Feeding + Lights	8	175	29	positioning of lights and feeding in relation to the preferred depth of salmon affects efficacy
M16	**Halo28*Treatment + PredLice**	**7**	**149**	**3**	**the interaction between louse behavior as driven by salinity and treatment combined with infestation pressure determines efficacy**

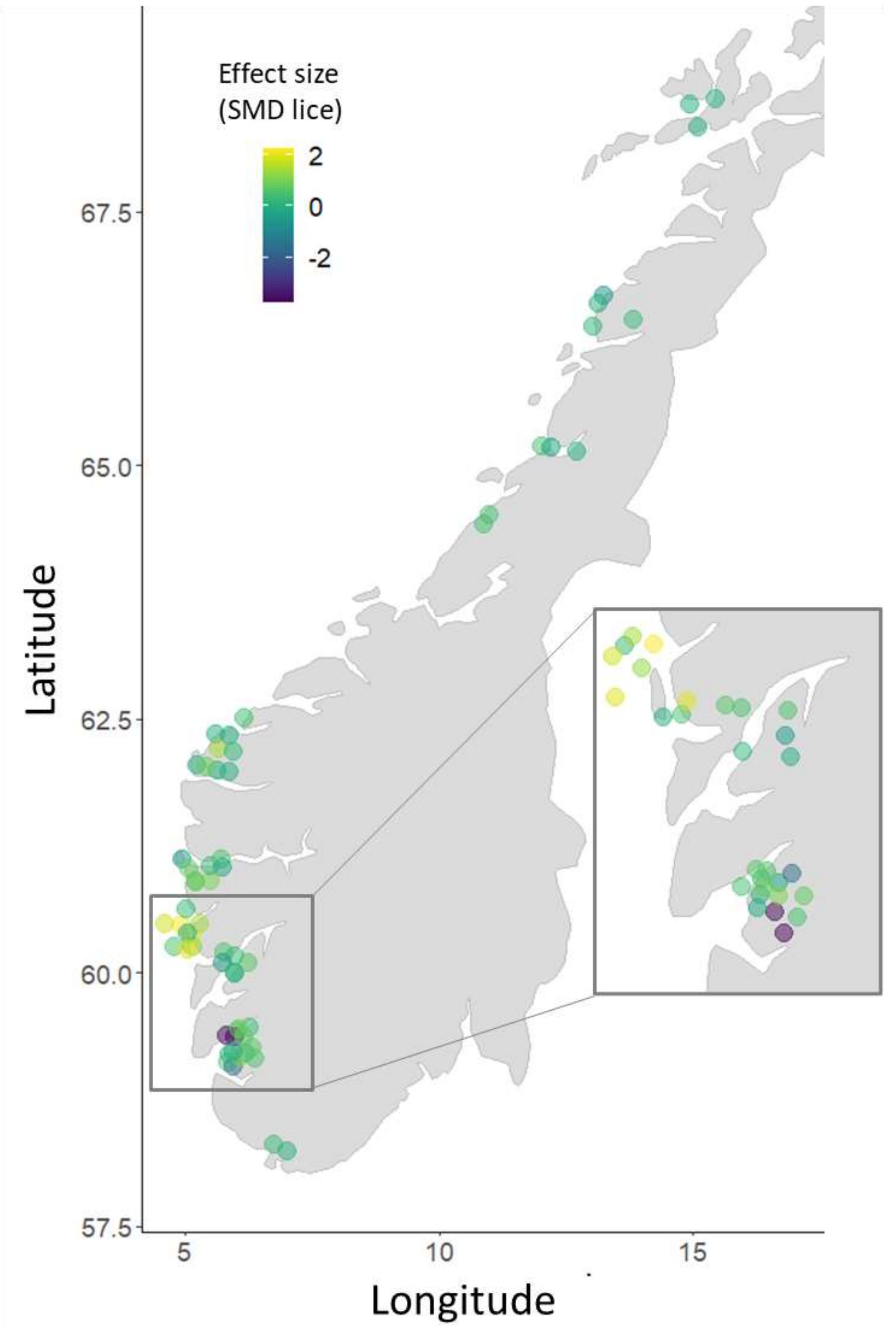

Figure 9: Influence of geographic location on lice preventive efficacy. Points indicate the approximate location of each sampling, colored according to the standardized mean difference between observed louse attachment and predicted infestation pressure (effect size). Purple (-) indicates high efficacy while yellow indicates poor (+) efficacy.

Table 7: *Estimate, standard error (SE), z-value and P-values of the explanatory variables in the selected models for preventive effect size (SMD) and observed new louse infestations.*

	Estimate	SE	z value	*P* value
Effect size (SMD)				
(a) water movement				
Intercept	-0.333	1.002	-0.332	0.739
Waves - Medium	0.275	0.315	0.874	0.382
Waves - High	1.168	0.344	3.397	<0.001
Current	0.512	1.560	0.328	0.743
(b) salinity, treatment & infestation pressure				
Intercept	0.680	0.132	5.148	<0.001
Halo28 - present	-0.492	0.281	-1.750	0.080
Treatment - snorkel	-0.216	0.273	-0.791	0.429
Infestation pressure	-1.741	*0.315*	*-5.524*	<0.001
Halo28 - present: Treatment - snorkel	0.982	0.626	1.569	0.117
Observed infestations (attached lice fish $^{-1}$)				
(c) water movement				
Intercept	3.863	2.112	1.829	0.067
Waves - Medium	-1.246	0.661	-1.884	0.059
Waves - High	0.528	0.687	0.769	0.442
Current	-7.118	3.244	-2.194	0.028
(d) salinity, treatment & infestation pressure				
Intercept	-0.483	0.357	-1.353	0.176
Halo28 - present	-1.481	0.281	-2.049	0.040
Treatment - snorkel	-0.379	0.665	-0.570	0.569
Infestation pressure	1.340	1.286	*1.042*	0.297
Halo28 - present: Treatment - snorkel	1.834	1.665	1.101	0.271

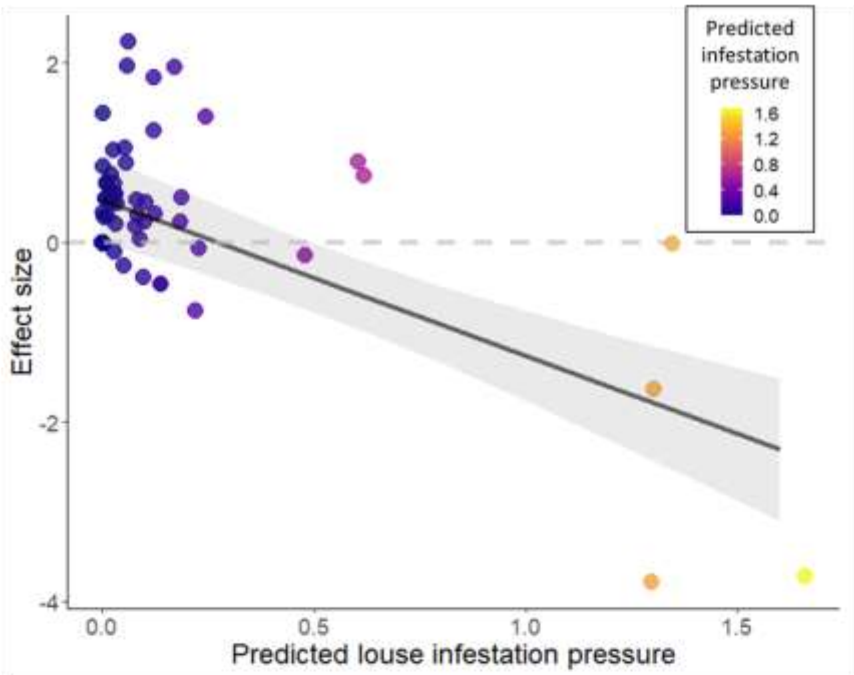

Figure 10: Influence of predicted louse infestation pressure on lice preventive efficacy. Points indicate the values of each individual sampling, while the line and shaded area display the fitted GLMM with 95% confidence intervals.

The single most important determinant of preventive effect size was predicted infestation pressure, with effect size increasing with higher infestation pressure (Figure 10).

Since salinity is an important driver of louse copepodid behavior and stratification can cause deformation of barriers, three different salinity variables were compared. Salinity thresholds were chosen based on the results of Crosbie et al. (2019) and were defined as the following: presence of a strong brackish layer (≤ 26 ppt at 5m), moderate brackish layer (≤ 28 ppt at 5m), and weak brackish layer (≤ 30 ppt at 5m) as well as their potential interaction with preventive strategy used (Table 6). Of the salinity variables tested, the presence of a moderate brackish layer was the only influential determinant of preventive efficacy. The same pattern is evident in both observed louse attachment and preventive effect size. In the absence of a brackish layer, snorkel cages and the dynamic strategy performed similarly. However, when a brackish layer was present, efficacy of the dynamic strategy improved, whereas preventive efficacy of snorkel cages declined (Figure 11).

Two alternate variables were also considered for wave exposure. Both skirt and snorkel barriers are designed to minimize the influx of infective louse copepodids into sea cages. Wave exposure, via several avenues including washing surface waters over the top of barriers, creating mixing which could carry lice into barriers from below, and damage of barriers, can reduce barrier efficacy. The first variable considered was the 50 year return value of the significant wave height as provided by the farm operator. The alternate variable tested was a categorical classification of sites as low, medium or high wave exposure based on the 95th percentile maximum significant wave height as predicted by the MyWaveWAM800m Norwegian Coastal wave forecasting system. Both wave exposure variables influence preventive effect size, with the categorical classification correlating slightly better with the observed data than 50 year return (Table 6). Again, wave exposure influenced the observed attached louse counts and preventive effect size similarly. Both the dynamic and snorkel cages provided the best protection at low wave exposure sites, and significantly worse protection at sites with high wave exposure (Figure 12).

Finally, although maximum predicted current speeds were technically an influential determinant of preventive efficacy, practically there were no differences among the sites sampled in this this project which ranged from maximum current speeds of 0.45 – 0.84 m s^{-1} (Figure 13).

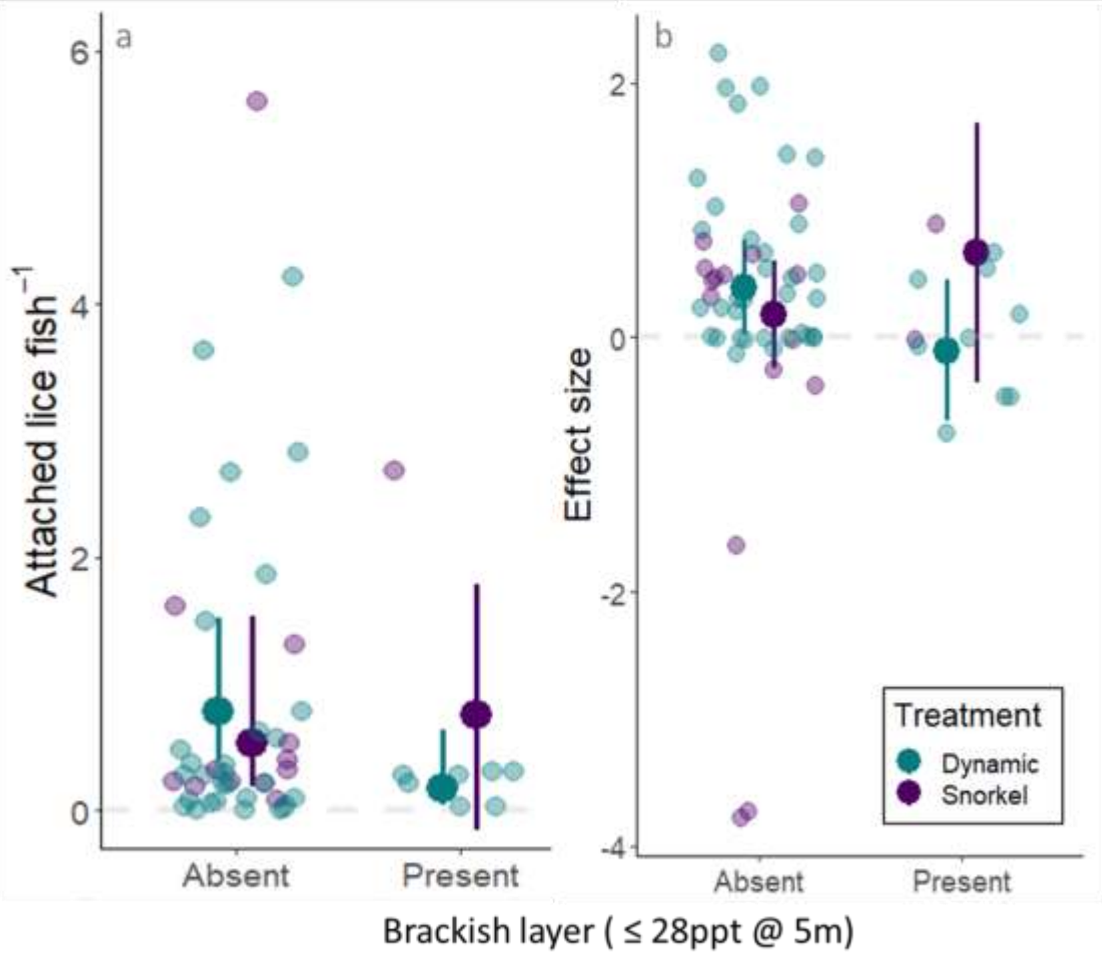

Figure 11: Influence of salinity on lice preventive efficacy. Plot (a) shows the average number of attached lice fish^{-1} (copepodid + chalimus 1 + chalimus 2), while plot (b) shows the standardized mean difference between observed louse attachment and predicted infestation pressure (effect size). Faded points indicate the values of each individual sampling, while solid points and error bars display the fitted GLMMs with 95% confidence intervals. Cages using the dynamic strategy are presented in blue while snorkel cages are purple.

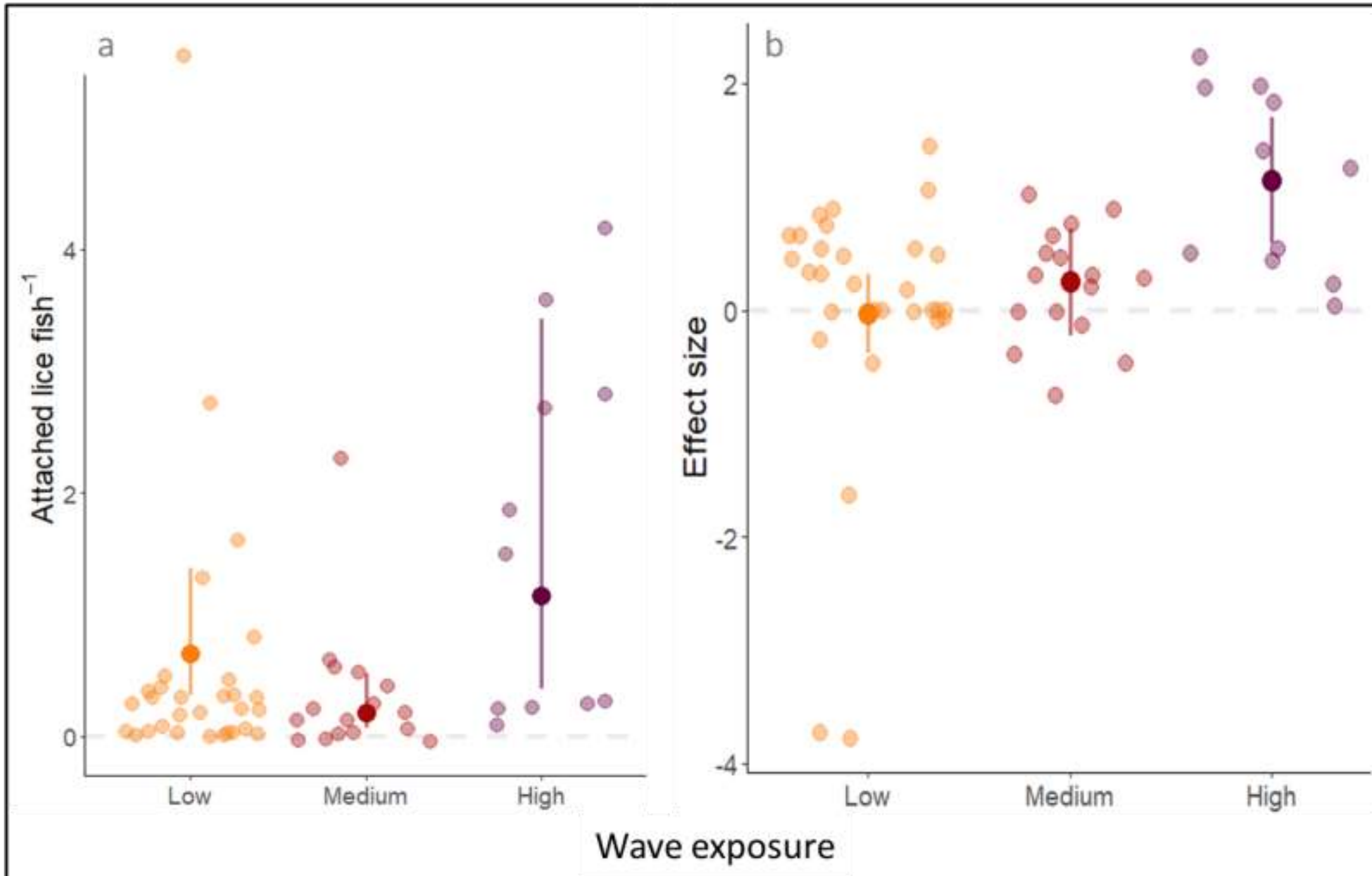

Figure 12: Influence of wave exposure on lice preventive efficacy. Plot (a) shows the average number of attached lice fish^{-1} (copepodid + chalimus 1 + chalimus 2), while plot (b) shows the standardized mean difference between observed louse attachment and predicted infestation pressure (effect size). Faded points indicate the values of each individual sampling, while solid points and error bars display the fitted GLMM with 95% confidence intervals.

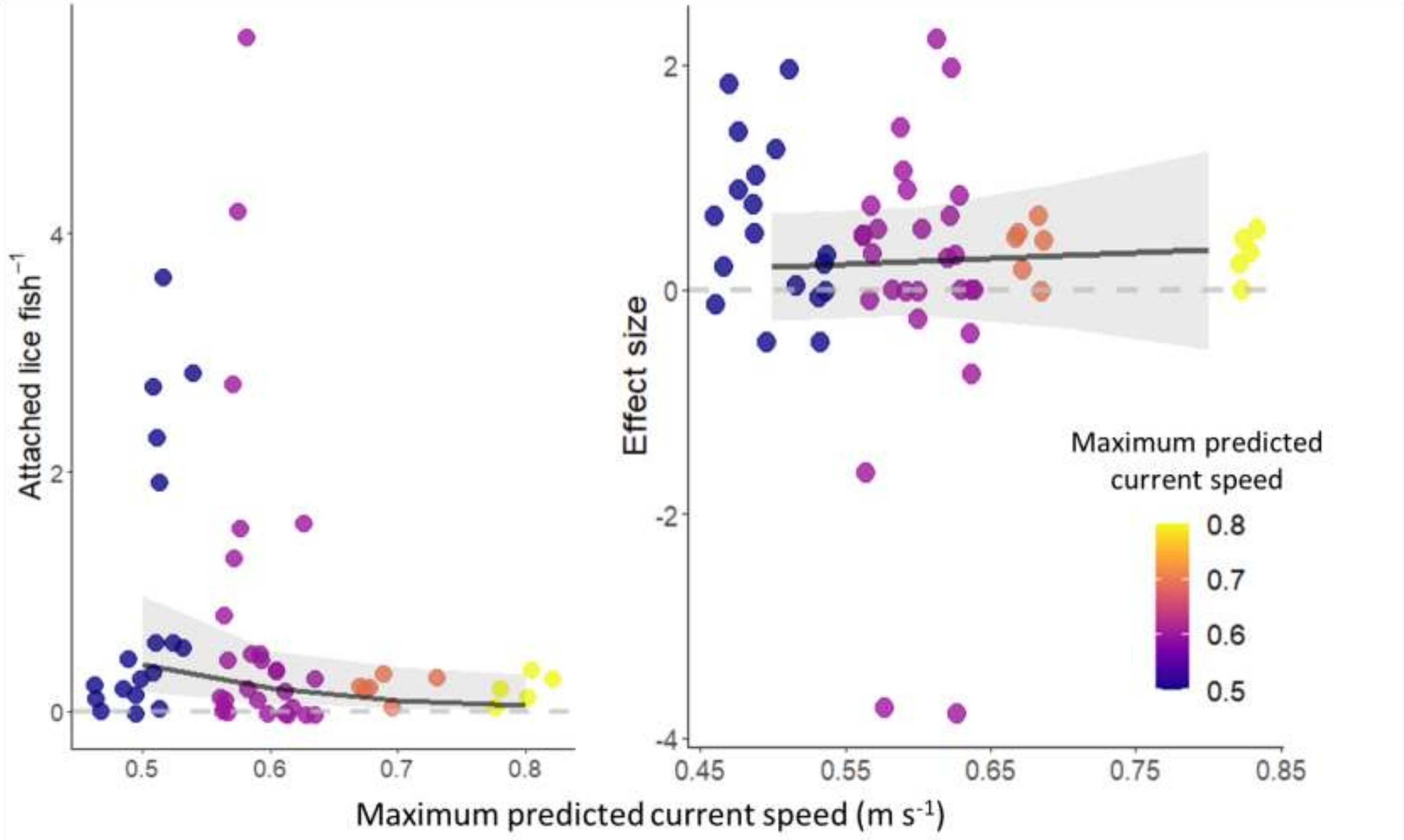

Figure 13: Influence of current speed on lice preventive efficacy. Plot (a) shows the average number of attached lice fish^{-1} (copepodid + chalimus 1 + chalimus 2), while plot (b) shows the standardized mean difference between observed louse attachment and predicted infestation pressure (effect size). Faded points indicate the values of each individual sampling, while solid lines and shaded areas display the fitted GLMMs with 95% confidence intervals.

4.3.4 Health and welfare

As there were no control cages present at the sites followed in this project, we cannot relate health and welfare in cages using the dynamic or snorkel strategies to standard production. However, comparison of the dynamic strategy to snorkel cages showed no differences in mean AGD score, gill condition or welfare between preventive strategies (Figure 14a, c, d). However, when AGD was present gill scores were higher in snorkel cages than dynamic (Figure 14b). These findings align with those of Oldham et al. (2020) which found that AGD progressed faster in salmon exposed to diel-cycling moderately hypoxic conditions. Although the oxygen conditions within the snorkel cages in this study are unknown, previous work has shown that maintaining optimal dissolved oxygen conditions within snorkel cages is challenging.

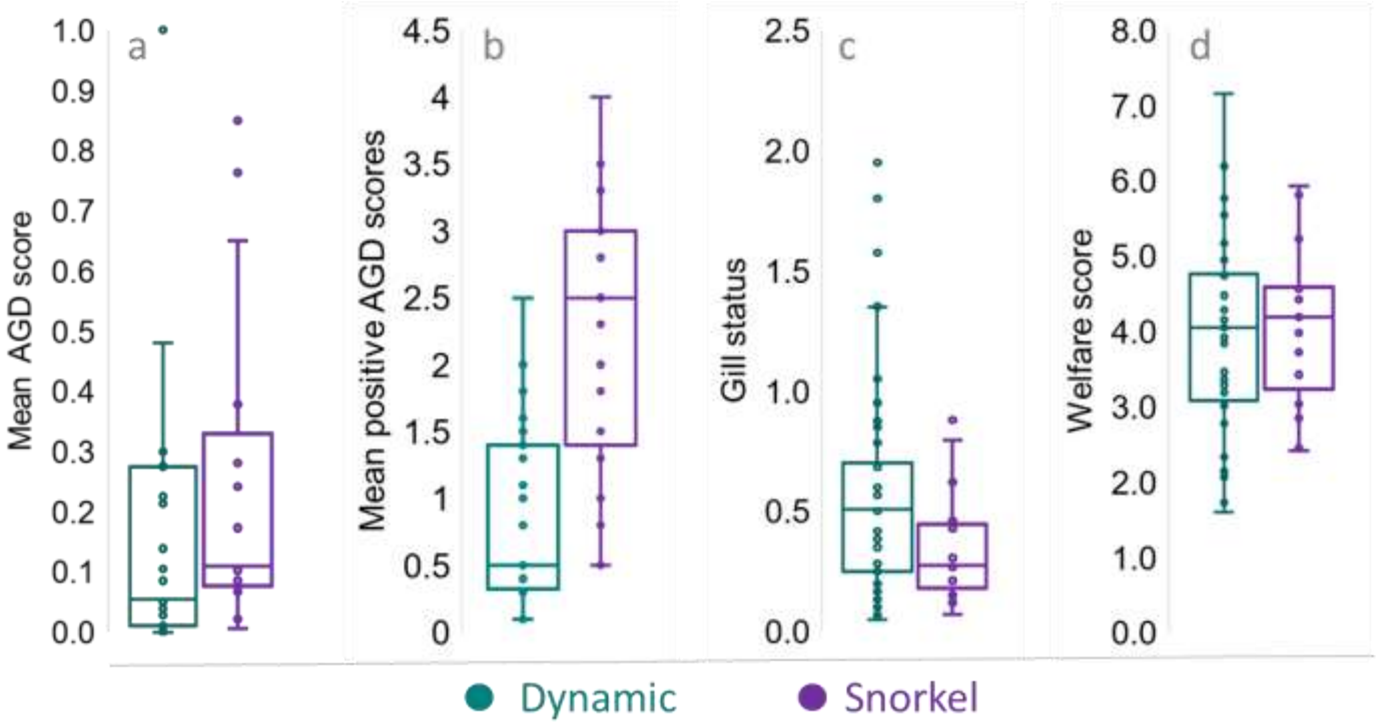

***Figure 14**: Boxplots showing the median and interquartile ranges of, (a) mean AGD gill score (0-5), (b) mean of all non-zero AGD scores, (c) mean non-AGD gill status score (0-3), and (d) average total welfare score (0-39) for cages utilizing the dynamic (blue) and snorkel (purple) louse prevention strategies.*

Further, to examine the relationship between gill condition and putative pathogens the correlation between total gill score and Ct-value was examined. Data were segregated to include only individuals where Ct-values were available for all four pathogens. There were strong correlations between total gill score and the pathogen loads of *P. perurans* and *B. cysticola* (Figure 15). Little to no correlation was found between the pathogen loads of *P. theridians* or salmon pox virus and total gill score.

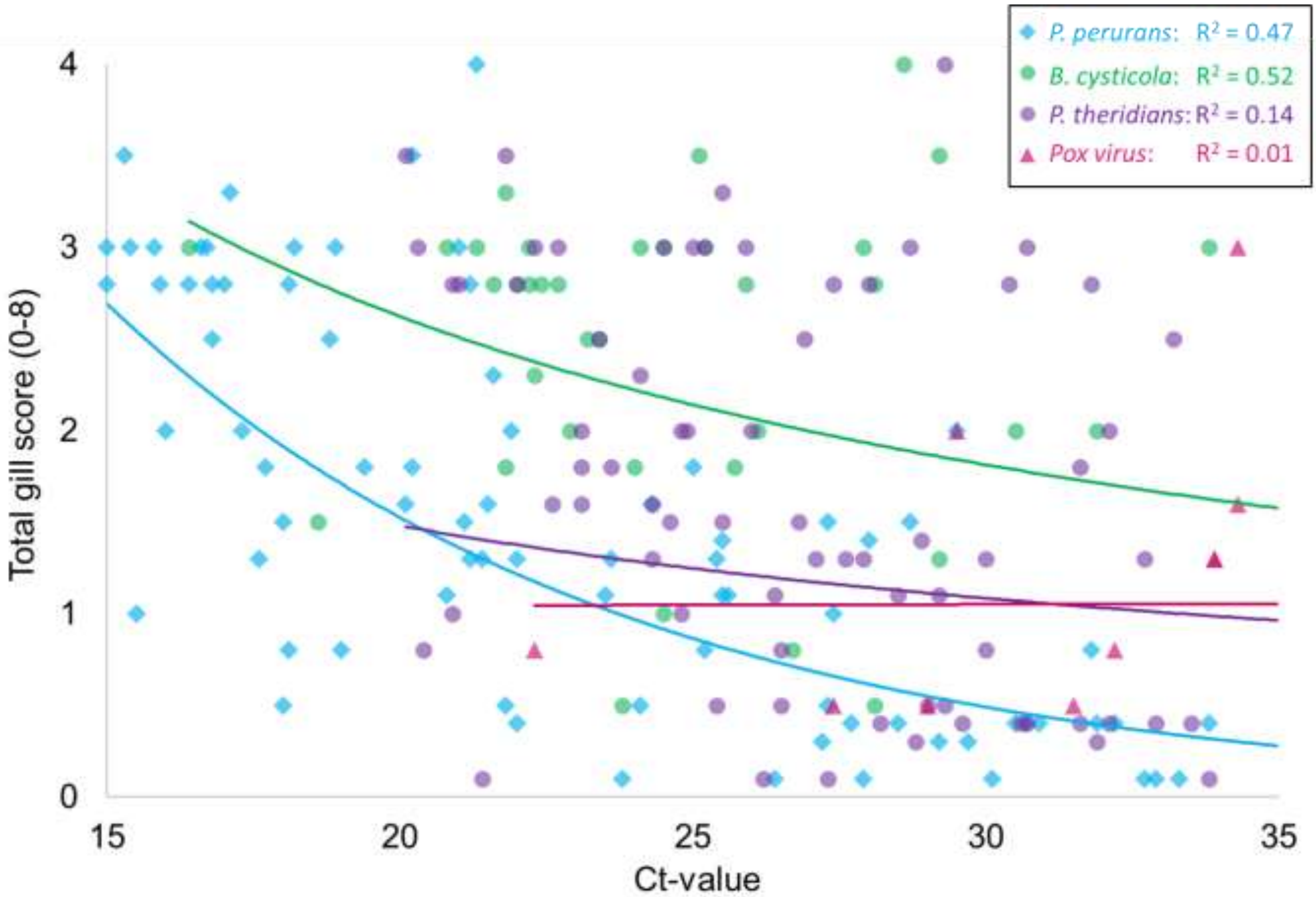

***Figure 15**: Relationship between gill condition and qPCR Ct-values for the gill pathogens Paramoeba perurans (blue), Branchiomonas cysticola (green), Paranucleospora theridians (purple) and salmon gill pox virus (pink). Data are values for individual fish and fitted regression lines. The coefficient of determination is shown as R^2.*

5 WP3 – Create a publicly accessible database of environmental conditions

5.1 Impact goals

Selecting the appropriate louse prevention tools for local environmental conditions will improve efficacy, but this is only possible if farm managers know the conditions at their location and how they vary throughout the year. The aim of WP3 is to establish a publicly accessible database of historical environmental conditions for every approved aquaculture site in Norway and use that information to categorize each site according to suitability for snorkel cages and dynamic use of skirts and adjustable depth lights and feeding.

5.2 Methods

Hydrodynamic conditions such as currents, salinity and temperature define the physical environment and are critical determinants of behaviour and development for salmon and salmon lice. In co-operation with the Norwegian Meteorological Institute (MET), IMR has established two hydrodynamic models for the Norwegian coast (NorKyst800) and fjords (NorFjords160) which provide hourly values of horizontal currents at 35 depths, salinity and temperature (see Asplin et al., 2020 for details about the model system and validation of model data). NorKyst800 operates on an 800m grid and has provided high quality data on currents, temperature, and salinity for the entire Norwegian coast from 1995 to present. NorFjords160 operates on a higher resolution 160m grid, covers the entire Norwegian coast using 13 model areas and resolves more details of the coastline, bottom depths and currents. Data from NorFjords160 is generated from spring 2017 to present based on input from NorKyst800 along the open boundaries (see e.g., Dalsøren et al. 2020 for a thorough evaluation of NorFjords160 in PO3 (Hardangerfjorden). Results from these models have repeatedly proven robust in validated studies against available observations in a variety of locations and conditions (e.g. Myksvoll et al. 2018, Asplin et al. 2020, and Albretsen et al. 2022). As such, results from these models are commonly used in advice and risk assessments from IMR.

Beyond hydrographic data, the state-of-the-art salmon lice dispersion model was used to extract vertical profile estimates of the louse infestation pressure (Myksvoll et al. 2018). Finally, and as a supplement for relevant physical description, we extracted significant wave height estimates from the operational wave model run operationally at MET (MyWaveWAM). The wave model applied is set up with 800m resolution and covers the entire Norwegian coast using five model areas (Behrens et al., 2013).

5.3 Results

5.3.1 Data extraction

Historical data from NorFjords160 (2017-2022) has been used to provide a comprehensive database of the vertical and temporal variation in salinity, temperature and currents at every approved aquaculture site in Norway (detailed description in section 6.2.1). In addition, wave heights from MET's operational WAM800-models have been extracted. Finally, predicted louse infestation pressure data (copepodids m^{-3}) were extracted from the lice dispersion model.

5.3.2 Environmental data validation

Results from the environmental database were compared to industry provided temperature and salinity measurements at 5m as well as to vertical profiles collected during sampling visits. The correlations between observed temperatures and comparable model results were strong, although in contrast to previous work the highest observed temperatures were not present in model results (Figure 16). These findings require further investigation.

Observations from the western part of Øygarden (Oksen (31697), Skorpeosen (11640) and Haverøy (11740) all revealed periods with upwelling of cold water abruptly replacing the relatively warm surface water. This was realistically reproduced by the model as seen in Figure 17, exemplified from Haverøy.

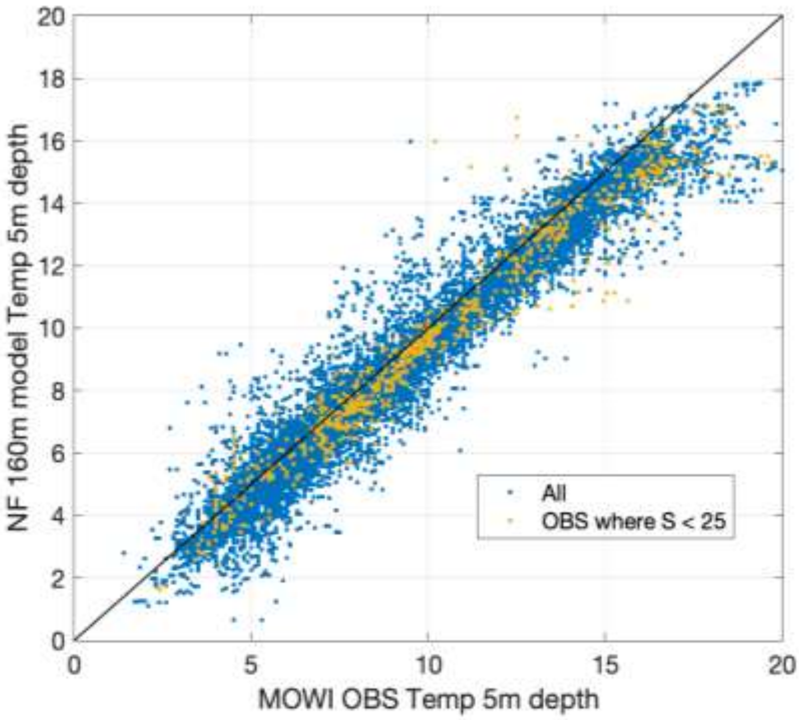

Figure 16: *Observations of temperature at 5m depth versus model results.*

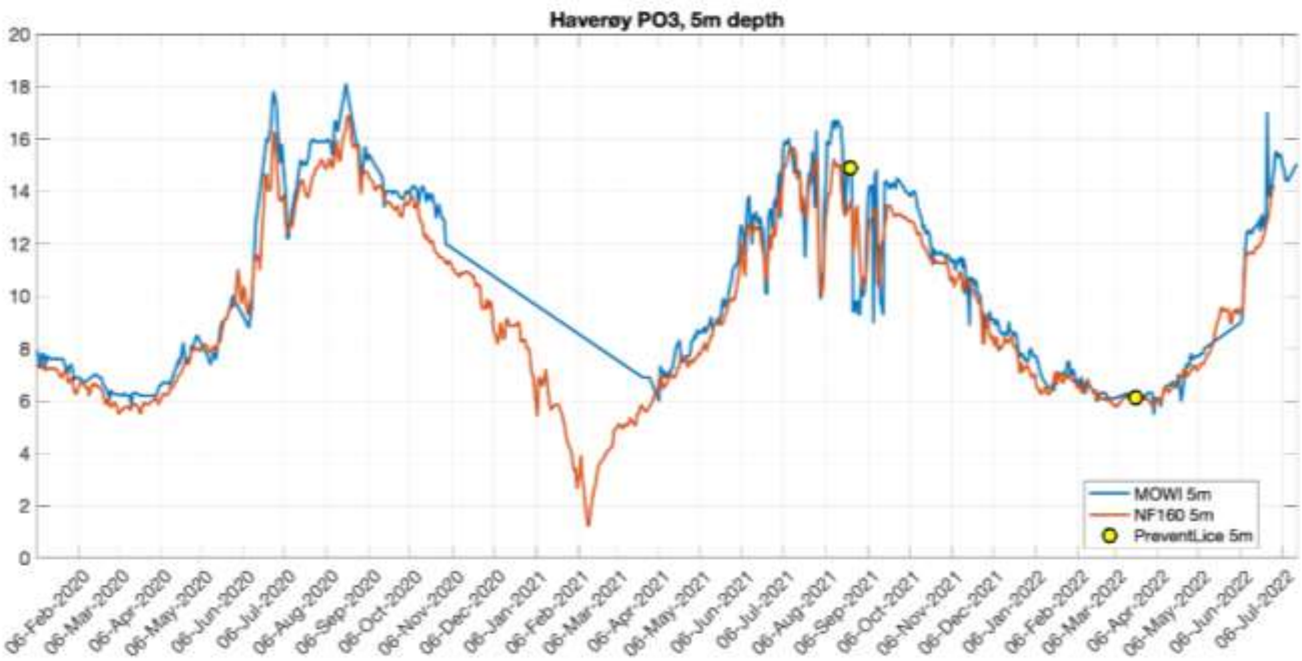

Figure 17: *Temperature at 5m depth at Haverøy on the western side of Sotra. Observations (blue) and model results from NorFjords 160 (red). Yellow dots indicate the times when there was a project sampling measurement at this location.*

Observations of salinity are notoriously difficult as biofouling rapidly results in an increased low-bias. An example of this can be seen in Figure 18 where the salinity at Haverøy was observed to drop from 32-33 in June to 25 in October and then abruptly back to 32-33, probably coinciding with a cleaning of the conductivity-sensor.

Figure 18: *Salinity at 5m depth at Haverøy on the western side of Sotra. Observations (blue) and model results from NorFjords 160 (red). Yellow dots indicate the times when there was a project sampling measurement at this location.*

5.3.3 Stratification determination

As a supplement to the online tool, we here demonstrate how the hydrographic properties (salinity, temperature and density) extracted can be applied to classify whether the adjacent waters are primarily homogeneous, stratified or a combination and how this characteristic varies during seasons. Although fluctuations in density are mainly driven by changes in salinity, temperature also modifies density, particularly in warming (lower density) and cooling (higher density) events.

Focusing on four sites with different hydrographic conditions, 10806 (Rakkenes in PO11), 11640 (Skorpeosen in PO3), 11809 (Krabbestig in PO4) and 11856 (Salvågvika in PO1). Figure 19 shows density variability at the 1m and 20m depths from 2017 - present. While the density at 20m is mainly influenced by coastal and offshore waters, the surface waters are more exposed to lighter (less saline) water masses during periods of increased river runoff. In addition, seasonal variability in summer heating and winter cooling will decrease or increase the surface density, respectively. Using the time series in Figure 19, the density difference between 1m and 20m was calculated (Figure 20) and a threshold of 0.5 $m^3 s^{-1}$ was applied to examine stratification. For site 10806 the density difference is below threshold except from April/May to September. In contrast, the density difference at site 11856 is almost always above threshold, indicating more stratified water masses. These data were used to visualize the degree of stratification of sites throughout the year (Figure 21). All example sites indicate stratified water masses during summer (June-August). Site 10806 is mainly homogeneous the rest of year, while site 11809 is almost always stratified and 11856 is permanently stratified. Site 11640 experiences a mixture of homogeneous and stratified conditions (Figure 21).

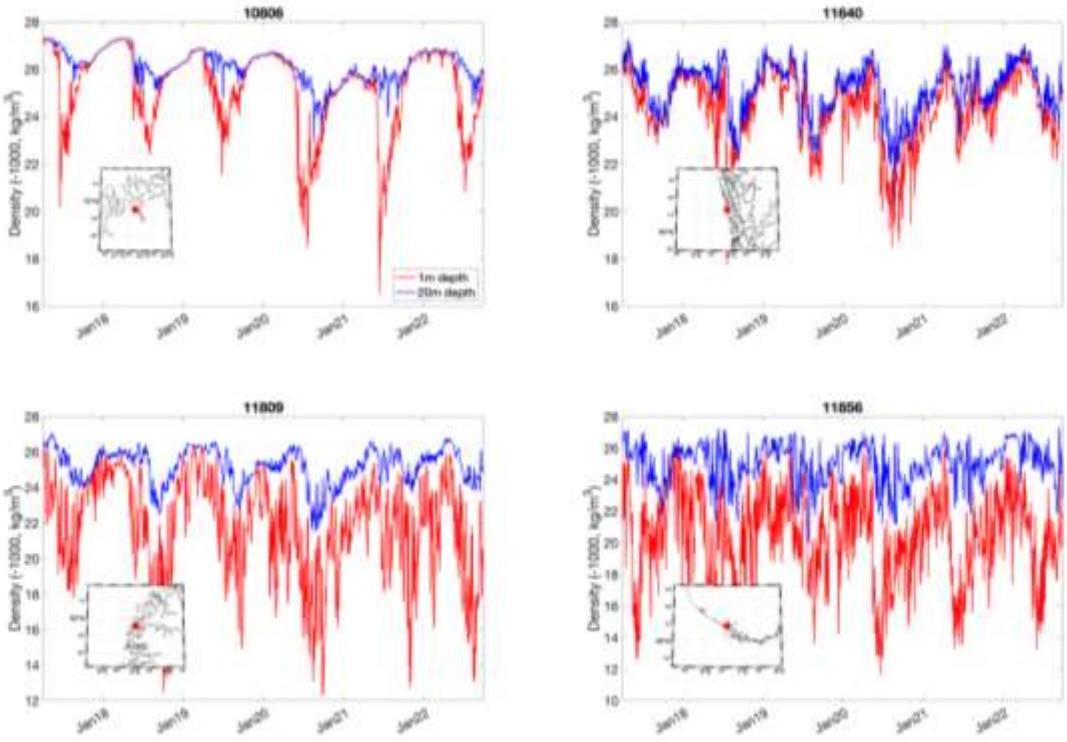

Figure 19: *Time series of density at 1m (red lines) and 20m (blue lines) from the NorFjords160 modelling system from April 2017 to September 2022 at four aquaculture sites identified in the header of each panel and plotted as a red dot in the separate map panel*

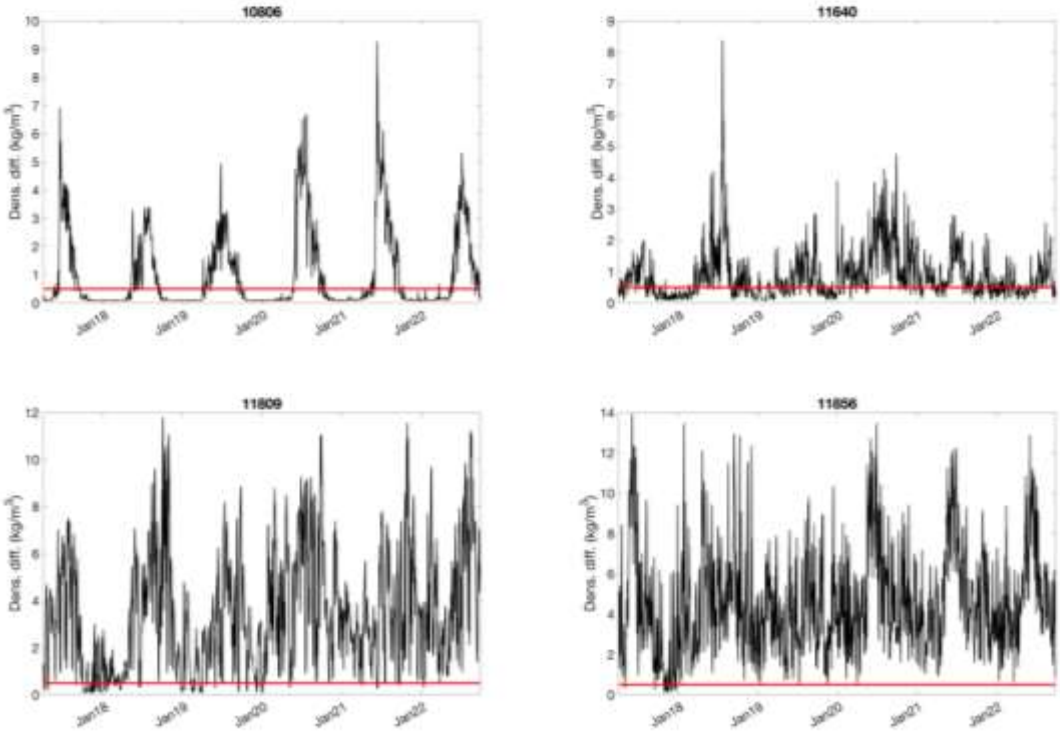

Figure 20: *Time series of density difference between 20 and 1m depth from the same aquaculture sites as shown in Figure 19. The red line denotes the chosen criteria which separates the condition between stratified (dens. diff > 0.5 kg m^{-3}) and homogeneous (dens. diff < 0.5 kg m^{-3}).*

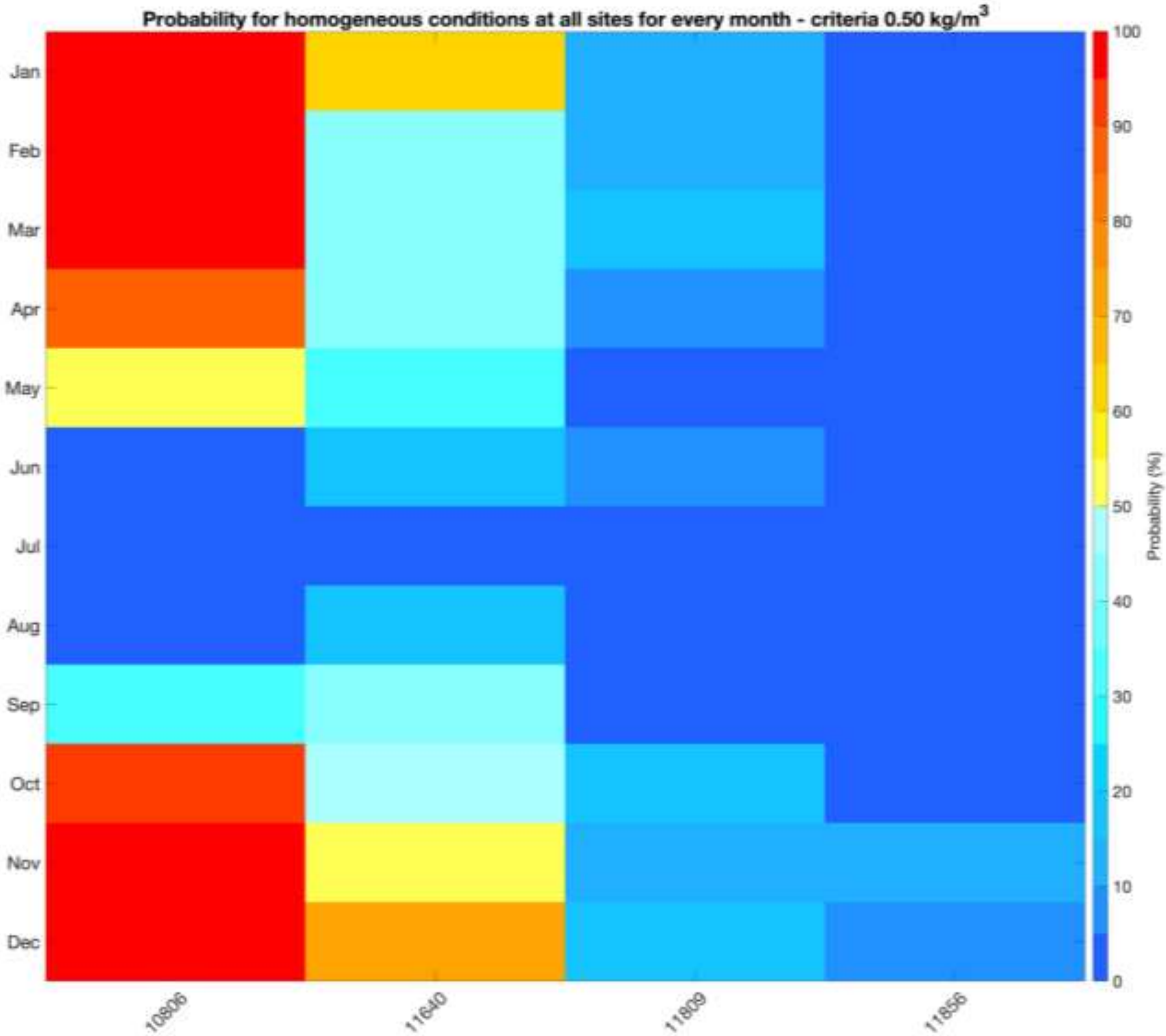

Figure 21: *Visualization of the probability of having homogeneous conditions for each calendar month at the same aquaculture sites as shown in Figure 19 and 20. The probability is based on daily time series of density differences between 20m and 1m depth and whether this difference is above (stratified) or below (homogeneous) 0.5 m^3 s^{-1}. Blue colors indicate likely stratified conditions.*

5.3.4 Copepodid distribution

The vertical distribution (0 – 20m) of salmon lice larvae infestation pressure is provided for all Norwegian aquaculture sites for the period January 2020 – November 2022. These data are implemented in the web-based louse prevention tool. The integrated (~3 years) salmon lice pressure at the geographical positions of the Norwegian aquaculture sites were computed. Estimating the depth of maximum lice pressure, it was found that 88% of sites are exposed to maximum lice pressure in the upper 1m of the water column, while at the remaining sites the maximum exposure was between 2 and 10m (no sites had maximum below 10m), as illustrated in Figure 22.

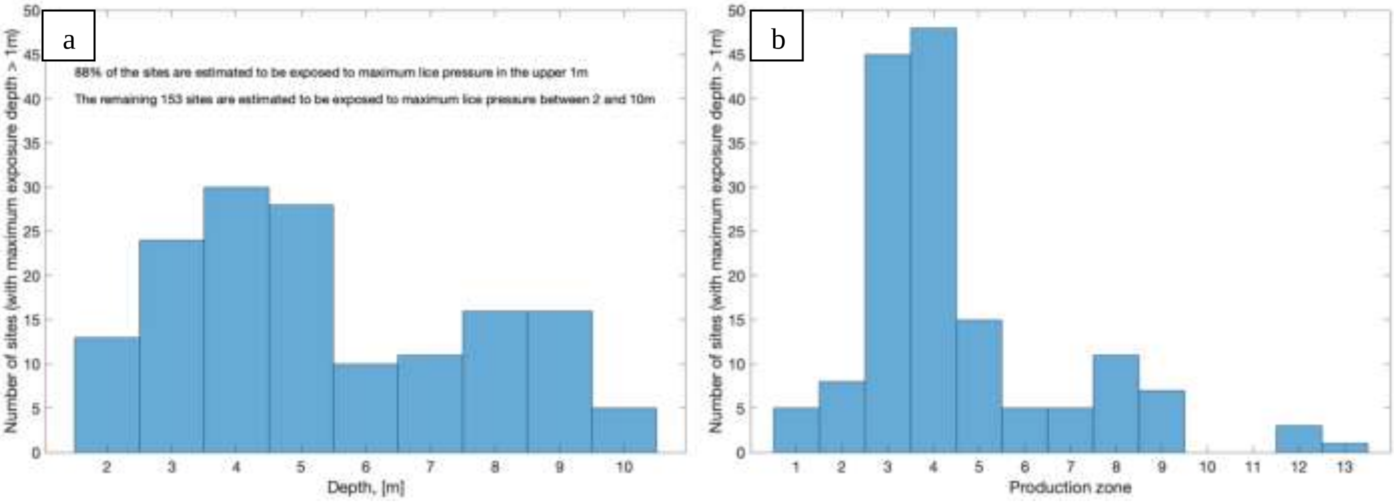

Figure 22: *Plot (a) shows the number of sites where the estimated maximum exposure to salmon lice was found to be deeper than 1m. Plot (b) is the same as (a), but here distributed between production zones.*

The distance between the sites and the open ocean, defined as > 10km from any land grid-cell in the NorKyst800m model (Johnsen et al 2021) are plotted against the dept of maximum exposure in Figure 23. Despite most sites having maximum exposure in the upper 1m of the water column, independent of the distance to the open ocean, there is a clear tendency toward increased depth with increased fjord-index.

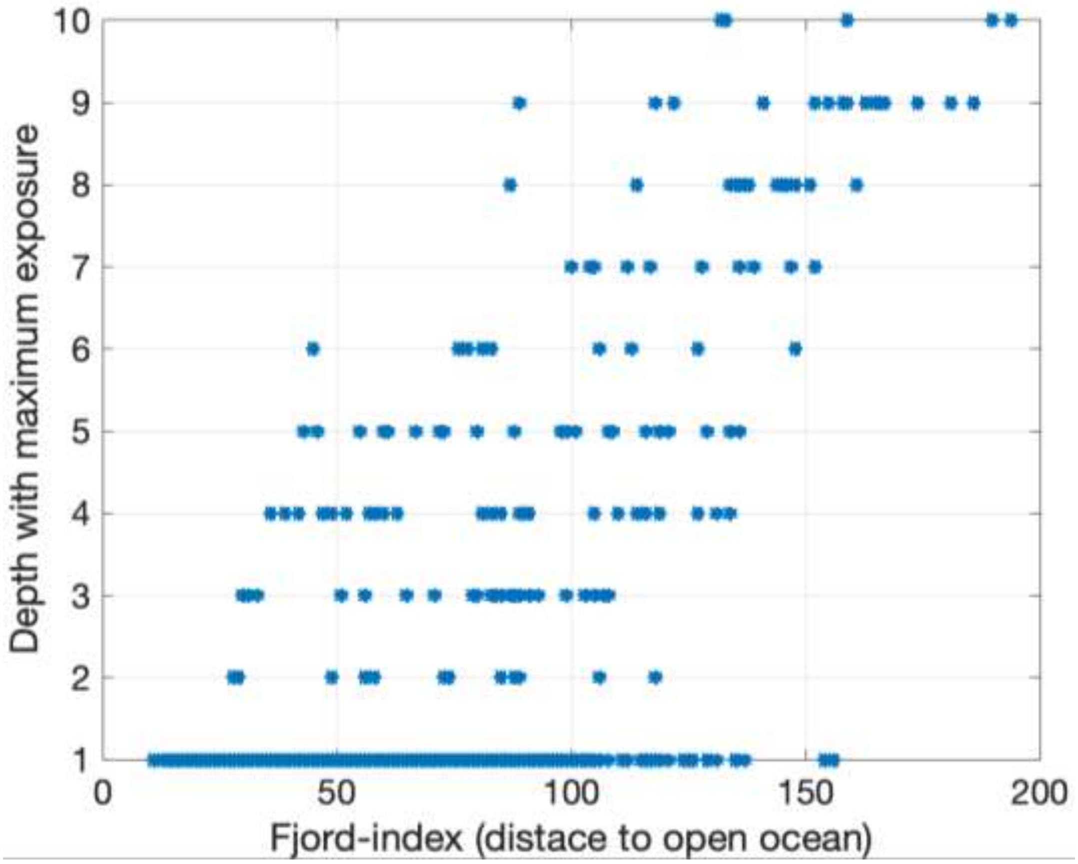

Figure 23: *Relationship between Fjord-index, computed as the distance from the aquaculture sites to the open ocean, and the depth of maximum exposure to salmon lice during the period 2020 – November 2022.*

The locations where the integrated louse infestation pressure was below 1m were identified and plotted on a map, example from PO3 in Figure 24. It was found that this mainly occurred in the inner part of southern fjords where we also found the most well-defined halocline. *As* hypothesized, deeper more intense haloclines, and following deeper distribution of the salmon lice larvae (which swim upwards against the light and downward if the salinity is low), occurred more frequently in southern fjord sites than northern.

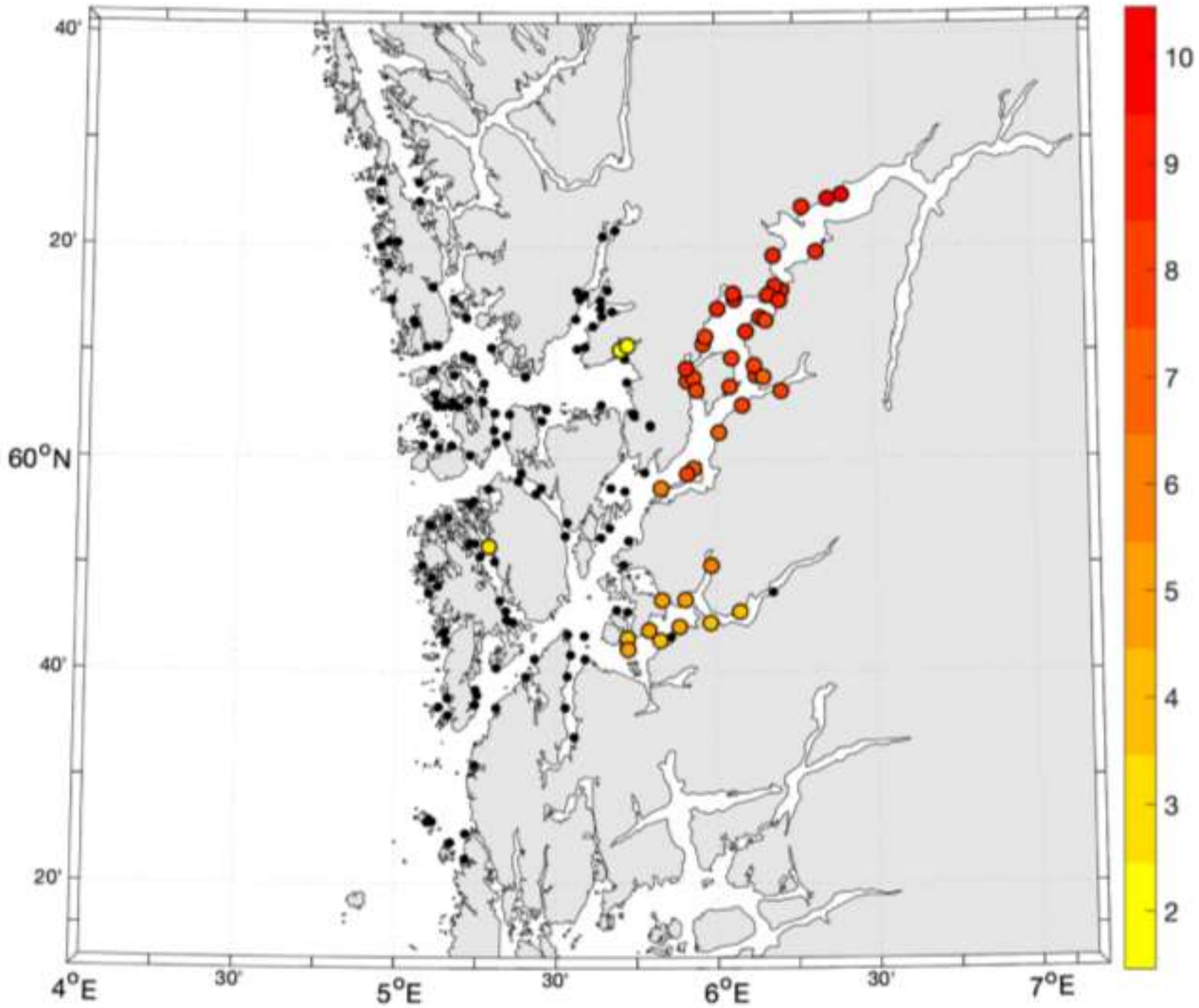

Figure 24: *The depth (m) of maximum exposure to infective salmon lice copepods during the period from January 2020 to November 2022. Colored circles identify sites where the depth is between 2m (yellow) and 10m (red). Locations where the maximum was found at 1m are marked with black dots.*

While the large scale (geographical size of ~PZ) salmon lice pressure will follow the seasonal cycle with minimum in spring when the water is relatively cold and the number of adult females on the farmed fish are kept below 0.2 LPF (Figure 25), the local salmon lice pressure will also be influenced by the production cycle (Biomass) and local dispersion of lice between farms in the same network (Huserbråten and Johnsen 2022). For details on specific sites, refer to the app.

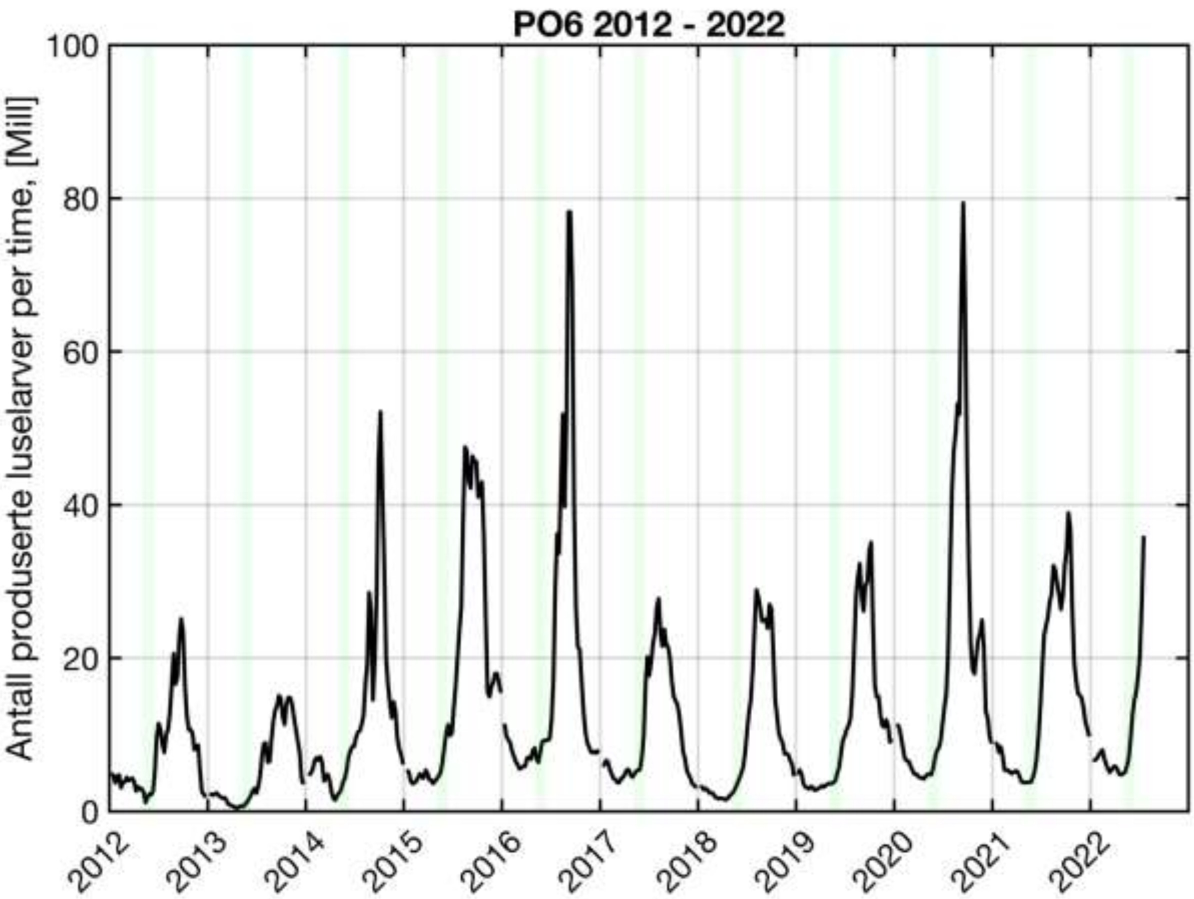

Figure 25: *Estimated release (reports from farms and equation from Stien et al. 2005) of salmon lice larvae from salmon farms in Production zone 6. This figure is updated and published yearly in the "Trafikklys rapport".*

6 WP4 – Develop a web-based louse prevention planning tool

6.1 Impact goals

This work package synthesizes the knowledge and data gathered in WPs 1-3 into a user-friendly and publicly accessible decision support tool, delivered in the form of a web application ('app' hereafter). Key information and recommendations to optimize lice prevention and fish welfare are provided directly to farm managers and other interested parties via this tool. The primary function of the app is to recommend an effective louse prevention strategy for every salmon farm in Norway and provide users with an approximation of how to optimally deploy prevention based on site-specific environmental variability. The app also presents the key data underlying the recommendation, allowing users to better understand local hydrodynamic conditions and the reasons for a given recommendation. This deeper understanding will improve the capacity of farmers to respond to real-world conditions and fine-tune their use of lice prevention strategies. Environmental predictions are generated by the NorFjords160 model. Additionally, the presentation of hydrodynamic data from NorFjords160 dramatically improves the accessibility of an important resource, with implications well beyond louse prevention.

6.2 Implementation and consultation

The app was developed using the R programming language (version 4.2.2: R Core Team 2022) with RStudio (version 2022.07.2). The construction of an interactive and reactive web app was facilitated by the 'shiny' package (Chang et al. 2022; https://shiny.rstudio.com/) and a range of other packages that provided tools for app layout, styling and deployment: 'shinydashboard' (Chang and Borges Ribeiro 2021), 'shinydashboardPlus' (Granjon 2021), 'shinycssloaders' (Sali and Attali 2020), 'bslib' (Sievert and Cheng 2022), and 'rsconnect' (Atkins et al. 2022).

Shiny apps have two main components: a user interface ('UI') function that defines the basic layout of the graphical user interface and accepts user inputs, and a 'server' function that fetches data, computes, and renders outputs (images, text) for display by the UI function. We opted for a Shiny-based approach as it directly integrates the powerful data manipulation, analysis and plotting tools available for R (both in base R and the tidyverse suite of packages: https://www.tidyverse.org/) with reactive binding of inputs and outputs and convenient widgets and templates. App deployment can also be done directly from R/RStudio using the rsconnect package, facilitating regular maintenance and updates, with the option to self-host a Shiny server or use secure and scalable third-party hosting services (e.g. https://www.shinyapps.io/).

6.2.1 Data sourcing

Hydrodynamic profiles were provided by the NorFjords160 model, an implementation of the Regional Ocean Modeling System (ROMS) covering Norwegian coastal waters (Albretsen et al. 2011, Asplin et al. 2020, Dalsøren et al. 2020). For each of 1023 active salmonid farms in Norway, we extracted nearly 6 years of hydrodynamic profiles from the nearest point on the 160 x 160 m model grid (April 2017 to September 2022, inclusive). For each farm, that hydrodynamic time-series was aggregated to provide daily values for temperature (average, °C), salinity (average, ppt), current speed (average, m/s), and peak current speed (95th percentile, m/s) at 1-m depth increments. A wave height dataset (daily significant wave height, m) was also included, using estimates obtained from the MyWaveWAM800m Norwegian coastal wave forecasting system (https://thredds.met.no/thredds/fou-hi/mywavewam800.html). Wave data were only available from June 2017 onwards. To provide an indication of baseline infestation pressure for each farm, we also extracted estimates of infective copepodid abundance (copepodids/m^3) from the salmon lice dispersal model (Myksvoll et al. 2018), also at daily resolution with 1-m depth intervals, from January 2020 to September 2022.

The data are stored as a single comma separated value (*.csv) file per farm, arranged as a 'rectangular' data frame with variables/parameters as columns and observations as rows, yielding 1 row per depth increment per day. Depending on the maximum depth of the profile at a given locality, there is a total of ~15000–100000 rows of data and a file size of ~1–6 MB per farm. Using a nested list format such as *.json would reduce file size but require conversion to rectangular format after reading the data into R, while storing data in R's native format, *.Rds, would likely speed up computation but inhibit cross-compatibility.

6.2.2 Data manipulation and key variables

Once the user selects a locality of interest, the server function reads in data from the corresponding .csv file and performs a variety of data manipulation tasks. All application code will be made available on GitHub upon the release of the app, but the key tasks are outlined below.

The first step was the calculation of variables with the full temporal and depth resolution, including:

- Season, based on timing of temperature changes rather than calendar seasons, such that winter = January-March, spring = April-June, summer = July-September, and autumn = October-December.
- Seawater density, from salinity and temperature using the 'marelac' package (Soetaert and Petzoldt 2020).

A range of variables are then integrated over the depth profile and stored in a new data frame with 1 row per day over the ~6 years covered by the model data (rather than 1 row per day per depth increment):

- Seawater density gradient over the top 20 m of the water column, or if the maximum depth is <20 m, the full depth profile.
- Presence/absence of stratification, defined as >0.5 kg/m^3 density gradient (see above).
- Presence/absence, strength and depth of halocline and thermocline, using functions modified from the 'castr' package by Jean-Olivier Irisson (https://github.com/jiho/castr).
- Average salinity above the halocline, if one is present.
- Average current speed in the top 1 m of the water column.
- Temperature, salinity and current speed averaged over the top 5 m of the water column.
- Temperature, salinity and current speed averaged over the 15-25 m depth band
- Temperature difference between the 0-5 m and 15-25 m depth bands.
- Presence/absence of a substantial brackish layer, defined as the presence of stratification and salinity <28 ppt over 0-5 m.

- Presence/absence of a substantial deep halocline, i.e. one that should influence the depth of a snorkel, defined as the presence of stratification with a halocline deeper than 12 m and <31 ppt salinity above the halocline.
- Snorkel depth required to avoid potentially high lice densities below the halocline, if present (snorkel depth = halocline depth + 3 m buffer + significant wave height).
- Depth of best temperature for feeding and growth. The average temperature over shallow (0-5 m) and deep (15-25 m) depth bands is compared. If both depth bands are between 14-16 °C, there is considered to be no important difference. If that condition is not met, then the depth band that is closest to 15 °C is preferred.
- Significant wave height (this is unchanged from the original dataset, as wave height is measured at the surface only).

With these variables having been created, the depth-integrated data frame is aggregated to weeks within years by averaging, summing or taking the maximum of daily values (as appropriate for the end use), and saved as a new data frame with a row for every week over April 2017 to September 2022. Generally, the last 1-2 days of the year are assigned to week 53. Rather than over-interpreting 1-2 days of data, rows corresponding to week 53 are removed from the weekly data frame.

Finally, the weekly data frame is aggregated to weeks by averaging, summing or maximizing across years as appropriate, and is saved as a new data frame with 52 rows corresponding to the weeks of an average year.

In summary, when the user selects a locality, the app server function loads an initial data frame and then creates 3 more data frames with differing degrees of aggregation as needed for the various plots and summary tables across the app:

- Original, daily resolution with depth profile
- Depth-integrated, daily resolution
- Depth-integrated, weekly resolution
- Depth-integrated, weekly resolution, averaged over years

6.2.3 Recommendations and decision thresholds

Overall recommendations are made for each season (winter, spring, summer, autumn) of the average year at the selected site. The snorkel-based strategy is preferred whenever possible, so if the conditions meet the requirements for safe and effective snorkel use, the snorkel will be recommended. The app currently takes 4 requirements into account:

- Requirement 1: Haloclines should be rare or shallow enough that a snorkel can extend beyond them.
- Requirement 2: Snorkels should not reduce feeding and growth by restricting access to optimal temperatures.
- Requirement 3: Snorkels should not be deformed for extended periods by currents or density gradients.
- Requirement 4: Waves should not be large enough to damage snorkels or carry lice into the snorkel volume.

These requirements are mapped to 4 logical tests within the app, applied to each season within an average year:

- Requirement 1: A deep halocline is present on fewer than 20% of days, and the recommended snorkel depth through the season does not exceed 16 m. Note, a deep halocline is one that is deeper than 12 m with less than 31 ppt salinity above the halocline.
- Requirement 2: Fewer than 20% of days have better temperatures for feeding and growth in the shallow depth band (0-5 m) compared to the deep band (15-25 m). Note, it is acceptable for the shallow depth band to have better temperatures than the deep band if both are between 14-16 °C.
- Requirement 3: The maximum 95th percentile daily surface current speed is less than 0.7 m/s, and the average density difference over 1-20 m is less than 3 kg/m^3 (regardless of the direction of the gradient).
- Requirement 4: The maximum significant wave height did not exceed 2 m within that season in any of the years for which we have model data.

Currently, the app only considers Requirements 1 and 2 when making an overall recommendation for each season, as we have lower confidence in the thresholds for Requirements 3 and 4. This is because the dimensions and construction of moorings, cages, and barriers will influence their vulnerability to deformation or damage. Additionally, we have relatively low confidence in the wave height data for sites in complex coastlines, as wave heights on an 800 x 800 m grid may not account for sheltering by small islands or other geographic features. Therefore, when the modelled conditions at a farm don't meet Requirements 3 or 4, snorkels may still be recommended so long as Requirements 1 and 2 are met, but with a comment to "Consult your engineer" regarding the failed requirement(s). Otherwise, a dynamic strategy will be recommended.

Given environmentally responsive nature of the dynamic strategy, it is intended to work (in some form) at all farm sites facing problems with salmon lice. As such, the app does not conduct any tests of the suitability of the strategy. Rather, it highlights conditions that might trigger a change in the setup of the skirt/aeration, feeding depth and lighting. Currently, 4 triggers are considered:

- Trigger 1: Take advantage of strong brackish layers when they occur.
- Trigger 2: Adjust feeding depths to follow the best temperatures.
- Trigger 3: Raise skirts when severe deformation is likely.
- Trigger 4: Consider removing skirts when large waves are likely.

Regarding Trigger 1, the app recommends that the removal of skirts be expected for weeks in which (based on all available model years) there is at least an 80% probability of a substantial brackish layer occurring (=stratification and <28 ppt in the top 5 m), and an average halocline depth >5 m. Such a strong brackish layer is expected to be worth using for lice avoidance, particularly if keeping the skirt down would cause fish to be in the high-risk zone just below a strong halocline.

For Trigger 2, the app identifies which weeks, in an average year, are likely to have better temperatures at the surface, at depth, or if depth is not important with respect to temperature. This is analogous to Requirement 2 for snorkels and leads to a recommendation to feed fish at the depth range with the best temperature, even if the skirts remains in place as per Trigger 1.

Triggers 3 and 4 are treated as for Requirements 3 and 4 for snorkels, in that expected high deformation risks or wave heights will prompt a note to consult an engineer.

6.2.4 Consultation with industry stakeholders

Research from the field of terrestrial precision livestock farming has demonstrated that data visualization tools, similar to the PreventLice app, can improve acceptance and adoption of modern data-driven farming techniques, but that training is necessary for efficient use (Van Hertem et al. 2017). In our case, it is not feasible to train hundreds or thousands of potential users, so instead, we conducted several workshops and informal feedback sessions with farm managers and other industry personnel to understand which features were confusing or unclear. We made changes in response, and then consulted with the same users to find out whether they felt the app had improved relative to the previous version. At the same time, we sought feedback from other (naïve) users to capture the first-time user experience of the revised app. This resulted in an app with more features than initially planned, as many users suggested additional variables or visualizations that they felt would improve the utility of the app. In general, feedback from users also led to the simplification of data presentation and more clear signposting indicating the relevance of variables and visualizations.

6.2.5 Hosting, maintenance and availability

The final version of the app is accessible at:
https://havforskningsinstituttet.shinyapps.io/preventlice/. All code will be made available on GitHub, and the underlying data will be available at Zenodo or a similar repository.

6.3 The user interface / user experience

The application provides a relatively simple graphical user interface with a dashboard layout that is similar to other products commonly used by the industry. Information is divided across 8 pages which can be navigated via a collapsible sidebar. The pages consist of a welcome page; two pages showing plots relevant to the snorkel and dynamic strategies, a summary page giving overall recommendations and summarizing overall conditions affecting the outcome, two pages displaying depth profiles for an average year and a (user-selected) single year, a page showing general information with a glossary, and a contact page where users can give feedback. Refer to Figures 26-31 and their captions for explanations of the content of each page.

Figure 26. *Screenshot of the "Welcome" page, featuring an infographic that explains the general concepts and key background information, especially the conditions that determine the suitability of snorkels or a dynamic strategy using skirts, aeration and lighting. Only the upper portion of the infographic is visible in this screenshot. The user can select a locality of interest while on this page, or else do so on any other page. Note: This infographic will be updated to better scale across a range of screen resolutions.*

Figure 27:. *Screenshot of the "Snorkel strategy" page. This page is divided across 4 tabs; each corresponding to one of the 4 requirements for safe and effective use of snorkels. For simplicity, we summarize the main variables using single-axis tile plots with a red-green color scale and weekly resolution. In this case, the user is viewing plots relevant to Requirement 1, which concerns halocline conditions and the required depth of a snorkel, if one was to be used. Throughout this page, green = "good for snorkels" and red = "bad for snorkels". The color scale also differs in luminance so should be visible to users with red-green colorblindness. Figure captions are also provided (mostly out-of-frame in this screenshot).*

Figure 28: *Screenshot of the "Dynamic strategy" page, which presents data corresponding to 4 trigger conditions. Each trigger leads to a specific intervention, for example, raising or lowering skirts and artificial lighting depth. In this case, the user is viewing plots relevant to Trigger 1, which concerns the presence of a substantial brackish layer. Throughout this page, the grey-purple color scale is agnostic with respect to the intervention, while the cyan-navy color scale indicates whether the farmer should have the skirts and/or lights raised or lowered. For example, in the displayed tab (Trigger 1), cyan indicates weeks where a substantial, deep brackish layer is likely to be present, and as such raising the skirt and lights to the surface to bring the fish into the brackish layer could improve preventive efficacy. Figure captions are also provided (mostly out-of-frame in this screenshot).*

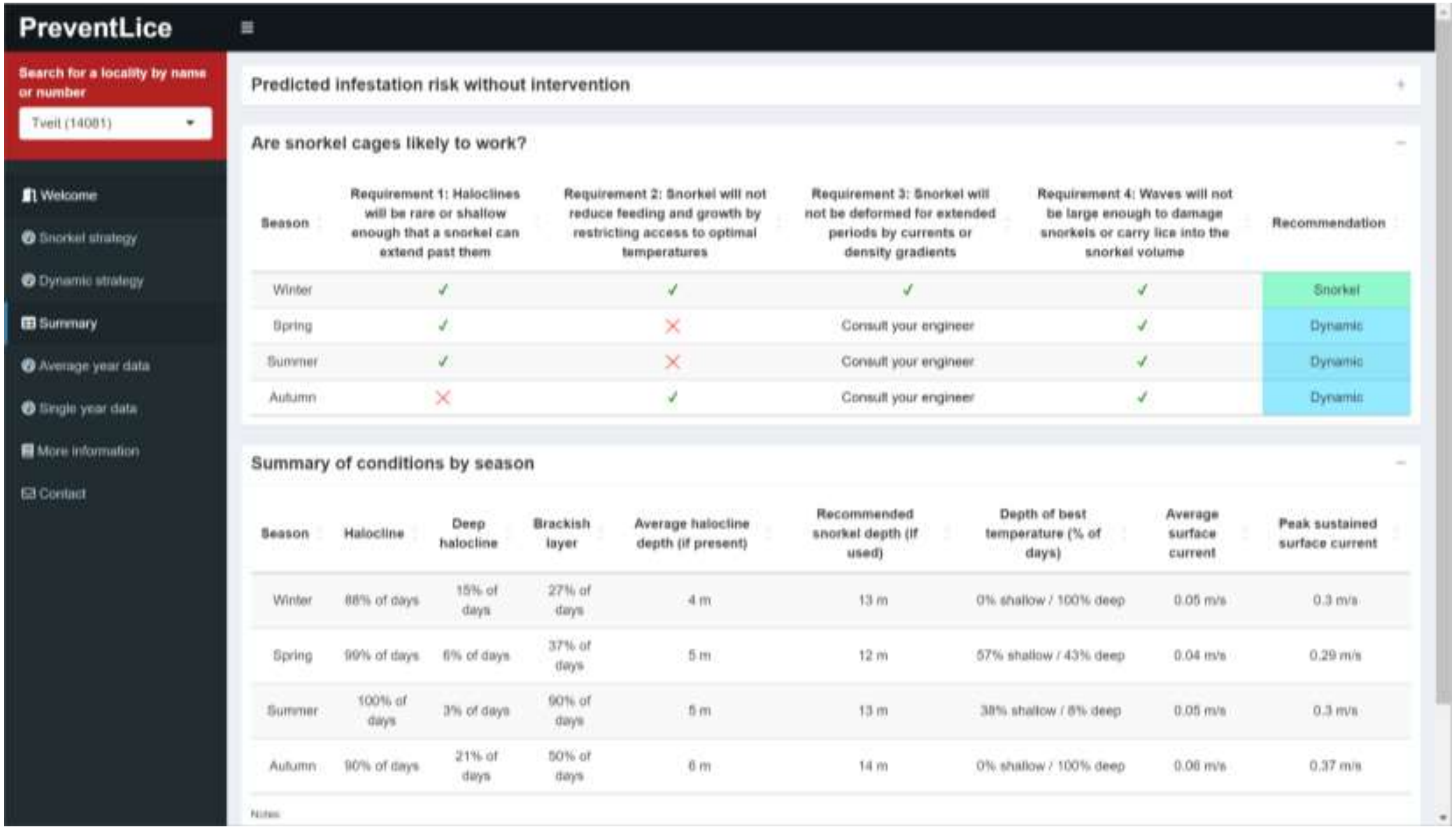

Figure 29: *Screenshot of the "Summary" page, where information relevant to snorkel and dynamic strategies is summarized, and the most suitable strategy is recommended for each of 4 seasons. Snorkels are recommended if Requirements 1 and 2 are met. If Requirements 3 or 4 are not met, users are encouraged to consult an engineer to advise whether snorkels can be safely used for not. If one or both of Requirements 1 and 2 are not met, a dynamic strategy will instead be recommended. A plot of predicted infestation risk is also provided to indicate baseline infestation risk through an average year (collapsed for this screenshot).*

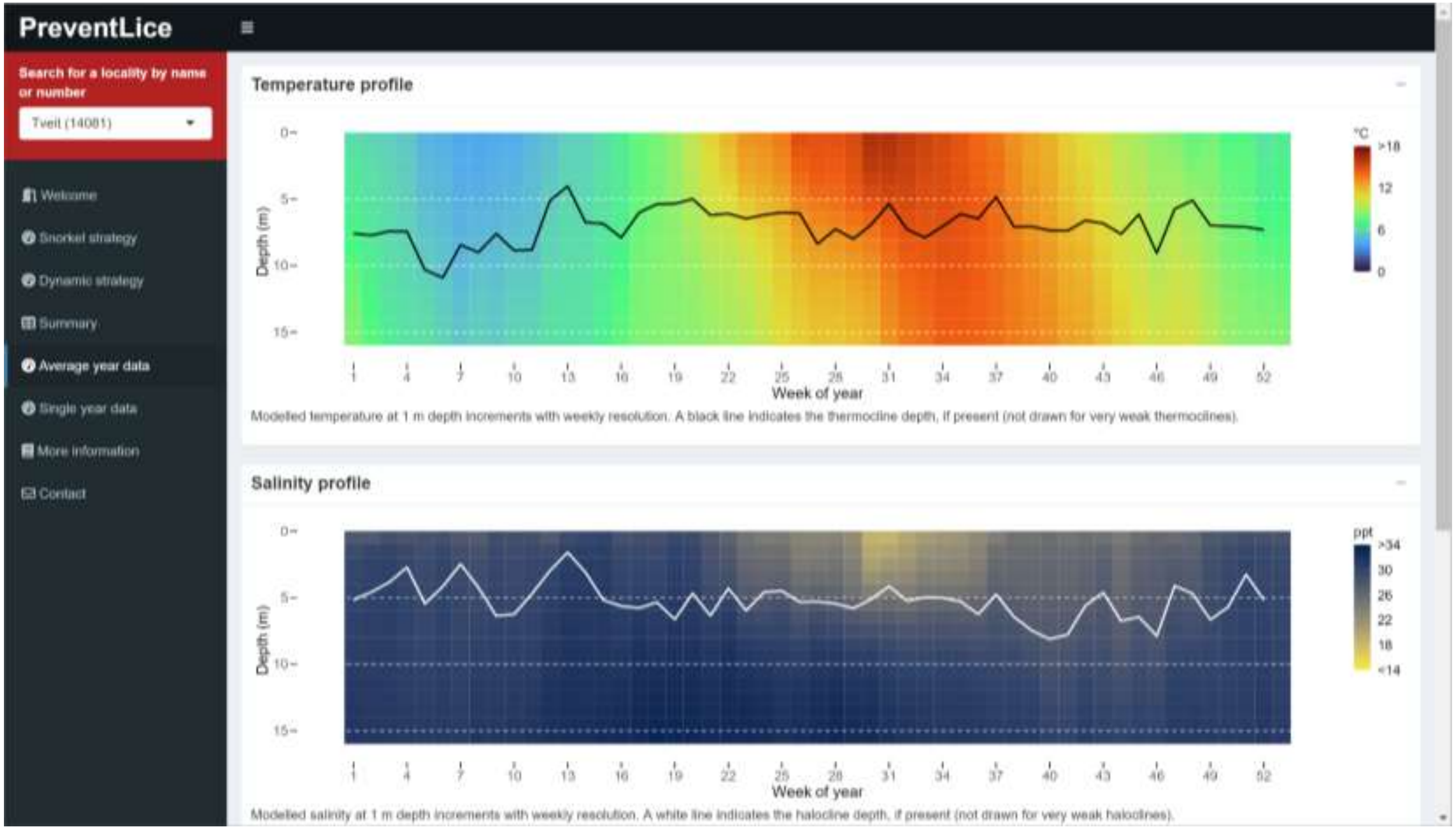

Figure 30: *Screenshot of the "Average year data" page, showing modelled temperature, salinity and current speeds by depth and time-of-year (weekly resolution). This allows the user to better understand the data underlying the tile plots shown on the "Snorkel strategy" and "Dynamic strategy" pages. The current speed plot and caption is out-of-frame.*

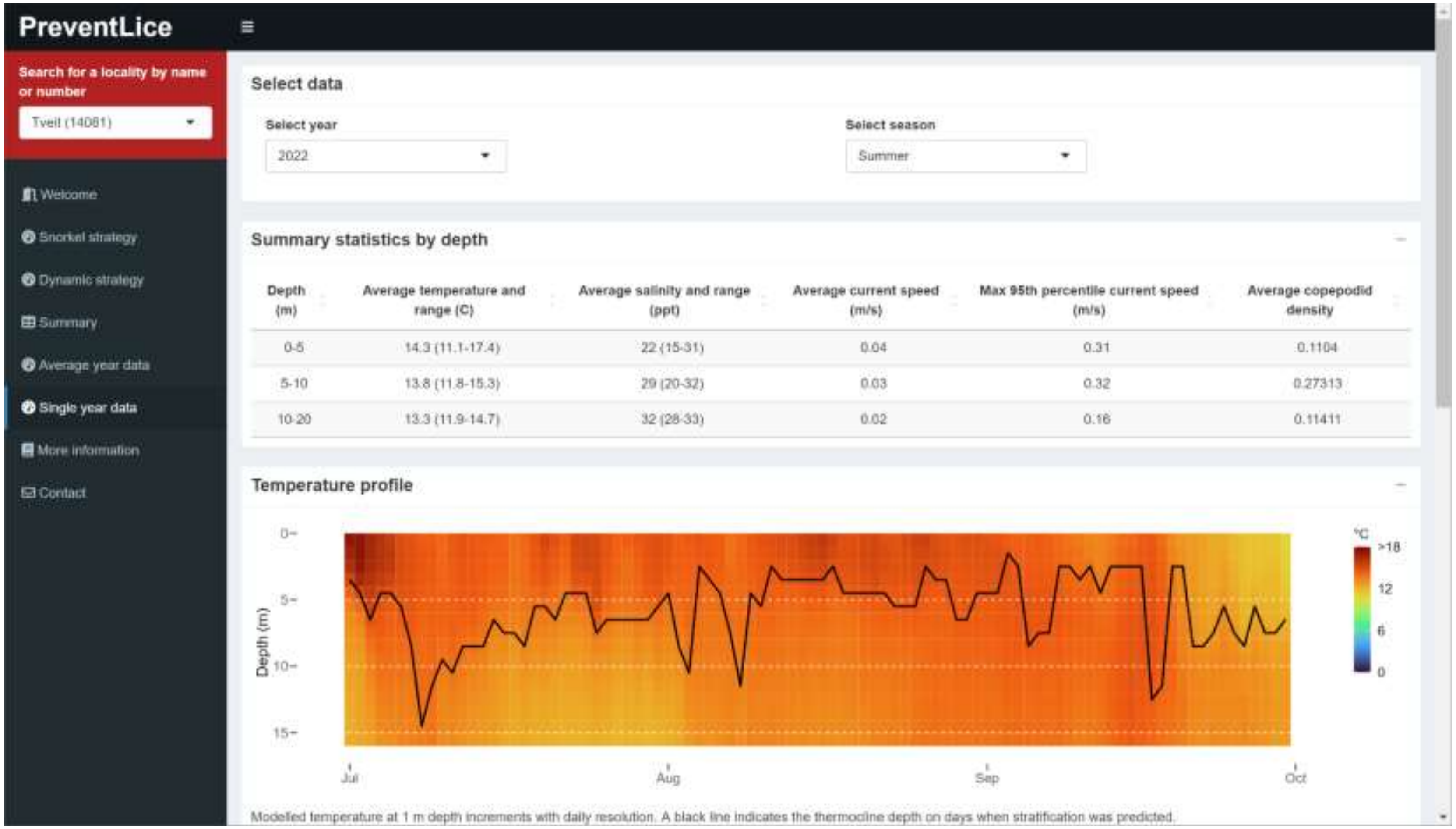

Figure 31: *Screenshot of the "Single year data" page. This shows the same variables as the "Average year data" page, but the data are filtered to a single season within a single year to better show interannual variability. These shorter time-series are shown with daily resolution. The salinity and current speed plots and captions are out-of-frame.*

7 Deliverables

D1.1: Peer-reviewed article evaluating the lice preventative efficacy of snorkels, skirts, and adjustable depth lights and feeding in relation to environmental conditions.

Oldham, T. Salinity and temperature alter the efficacy of salmon louse prevention. Aquaculture 2023 (accepted).

D2.1: Peer-reviewed publication presenting the interaction between snorkel cages and environmental conditions, with concrete guidelines for situations in which snorkel cages perform well and when they do not.

During the meta-analysis it became apparent that a large amount of data were available on snorkel cage efficacy from previous trials, so only 3 sites were included in the project sampling regime. While this provided interesting data, it is insufficient for publication on its own. Instead, D2.1 and 2.2 will be combined into a single manuscript according to the analyses presented herein.

D2.2: Peer-reviewed publication presenting the performance of a dynamic lice prevention strategy in different environmental conditions, with concrete guidelines for optimal deployment of skirts and adjustable depth lights and feeding.

Environmental determinants of lice preventive efficacy in salmon aquaculture. 2023. (in preparation)

D3.1: Compile a publicly accessible database of temporal variability of currents, temperature, salinity and salmon lice infestation pressure for all aquaculture sites in Norway.

*The NorFjords160, lice dispersal and MyWaveWAM800m models were used to extract data on the temporal and spatial variability of salinity, temperature, current speed, louse infestation pressure and wave exposure for all 1023 active salmon farming localitites along the Norwegian coast. These data are publicly accessible via the PreventLice Planning Tool (*https://havforskningsinstituttet.shinyapps.io/preventlice/*).*

D3.2: Peer-reviewed publication classifying every aquaculture site in Norway according to environmental variation (vertical salinity, temperature, and current gradients) with recommendations of which louse prevention tools are most effective in each group.

During planning of D4.5 it became apparent that this information makes more sense to include in that manuscript rather than as two separate articles. In this way we can show the variation between sites and highlight the need for the web-tool, as well as explain the function of the web-tool.

D4.1: Beta version of the web-tool shared with external researchers and industry personnel for feedback.

Completed March 2022.

D4.2: Hold workshop with key stakeholders to test a release-ready version of the web-tool.

Several workshops both with naïve and repeat users from a variety of backgrounds including site managers, fish health personnel, area managers, researchers and students were held throughout the development of the web-tool. In this way we were *able to continually to optimize and streamline both the usability and functionality of the tool iteratively as we received feedback.*

D4.3: Public release of the web-tool providing detailed environmental modelling data and site-specific lice prevention strategy recommendations for every currently active aquaculture site in Norway.

*The PreventLice Planning Tool (*https://havforskningsinstituttet.shinyapps.io/preventlice/*) is finished and functional. The tool was formally launched at the FHF lusekonferansen 2023, and subsequently announced on Kyst.no (https://www.kyst.no/havforskingsinstituttet/ny-app-gir-oppdretterne-lusehjelp/1521739).*

D4.4: Peer-reviewed article describing the need for and function of the web-tool.

PreventLice- a Shiny app to optimize parasite prevention in salmon aquaculture. 2023. (in preparation)

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