



Temperature-driven suitability shifts of sea lice species under climate change and the implications for salmon farming

Amy Leigh Mackintosh^{1,*}, Jorge Assis^{1,2}, Mark John Costello¹

¹Faculty of Biosciences and Aquaculture, Nord University, 8026, Bodø, Norway

²Centre for Marine Sciences, University of Algarve, 8005-139, Faro, Portugal

ABSTRACT: Salmonids are the most valuable marine aquaculture family, worth approximately US\$26.2 billion in 2022. However, the industry's economic value is threatened by sea lice infestations, which can cause production losses and require expensive treatments to control. Climate change is driving distribution shifts in many marine species, including a potential poleward movement for several parasites. Currently, only the distribution response of the Chilean sea louse *Caligus rogercresseyi* has been examined under climate change conditions, while other harmful sea lice species remain unassessed. Here, we use a maximum entropy model to project the current and future thermal suitability of *Lepeophtheirus salmonis*, *C. elongatus*, and *C. rogercresseyi* under 3 climate change scenarios: SSP1-1.9, SSP3-7.0, and SSP5-8.5. The species' thermal niches are similar, with preferred mean temperature ranges of 7.1 to 11.1°C for *L. salmonis*, 6.8 to 11.9°C for *C. elongatus*, and 11.0 to 12.8°C for *C. rogercresseyi*. Thermal suitability for all 3 species shifts and intensifies polewards under progressively warmer climate scenarios. As ocean warming also facilitates poleward range shifts of many salmonid species, the overlap in host and parasite distributions indicates that salmon aquaculture at higher latitudes could face increasing lice infestations and associated challenges.

KEY WORDS: Sea lice · Temperature · Climate change · Salmon · Aquaculture

1. INTRODUCTION

Salmonids, including salmon, trout and char species, are the most valuable family in marine aquaculture, with an estimated global value of US\$26.2 billion in 2022 (FAO 2024). Norway leads global production, followed by Chile, largely due to the farming of Atlantic salmon *Salmo salar* Linnaeus, 1758. However, one of the industry's most persistent challenges is infestations of sea lice (Costello 2009b, Abolofia et al. 2017). Climate change is considered to compound problems in farm production, including sea lice outbreaks (IPCC 2023). While some marine species may experience range expansions or contractions due to changing environmental conditions, the specific responses of most sea lice species remain unexplored. Here, we

examine the response of the most harmful sea lice species in salmon farming to climate change, specifically in relation to shifts in ocean temperatures.

There are 608 species of ectoparasitic copepods in the worldwide genera *Caligus* and *Lepeophtheirus* (Walter & Boxshall 2025a,b). These sea lice have non-feeding planktonic early life-stages, of which the copepodid stage attaches to a fish host and moults into a feeding chalimus that anchors itself to the host skin (Costello 1993). During the chalimus and especially the subsequent mobile pre-adult and adult stages, the lice feed on the hosts' skin, mucous, and blood, and at high densities, kill the host (Costello 2006).

The 3 most prominent sea lice species impacting the salmon aquaculture industry are *Caligus elongatus* von Nordmann, 1832 in the North Atlantic, *C. roger-*

*Corresponding author: amy.mackintosh@nord.no

cresseyi Boxshall & Bravo, 2000 in Chile, and *Lepeophtheirus salmonis* Krøyer, 1837, known as the salmon louse, in the North Atlantic and Pacific Oceans. While *Caligus* species are not host specific, *L. salmonis* is specific to salmonid species (Costello 2006, Hemmingsen et al. 2020). Other sea lice species may occasionally cause problems on salmonids and other farmed species, such as tuna, but remain of lesser consequence (Costello 2006). Not only do these species disfigure and stress salmonids, exposing them to additional pathogens, but they also require expensive treatments to control infestations, costing the global salmon farming industry approximately US\$480 million in 2006 (Costello 2009b) and US\$436 million in Norway alone in 2011 (ca. 8.7% of revenue) (Abolofia et al. 2017). More recently, the cost of sea lice treatments was estimated to be US\$4.3 billion across Norway, Scotland, Canada, and Chile from 2013 to 2019 (Just Economics 2021).

The tolerance of sea lice, particularly *L. salmonis*, to temperature has been widely reported, with many laboratory studies showing an increase in sea lice generation time with warmer conditions (Costello 2006, Hamre et al. 2019) (Fig. 1; Table S1 in the Supplement at www.int-res.com/articles/suppl/q017p175_suppl.pdf). For *L. salmonis*, optimal development

rates have been recorded around 10 to 15°C, with reduced capacity below 5°C and above 18 to 20°C (Hamre et al. 2019). Similarly, the optimal temperature for *C. elongatus* was reported to be around 14°C (Hogans & Trudeau 1989). Temperature has also been found to impact sea lice infectivity, swimming activity, and energetic capacity, which can further affect the likelihood of host–parasite contact and settlement success (Skern-Mauritzen et al. 2020, Sandvik et al. 2021).

However, laboratory studies conducted on already stressed lice may only reflect controlled short-term responses and not the longer-term dynamics observed in the natural environment. Additionally, these results could be influenced by local population adaptations, making it difficult to generalise across the entire species' range. Furthermore, because sea lice larvae do not feed during their planktonic life-stage, their settlement success and survival is primarily limited by the availability of suitable salmon hosts and favourable water temperatures (Boxaspen 2006, Costello 2006). Given the sensitivity of sea lice to temperature, it could be useful for industry planning to understand how climate change may alter their distribution and potential for interaction with farmed salmon. However, to date only *C. rogercresseyi*'s envi-

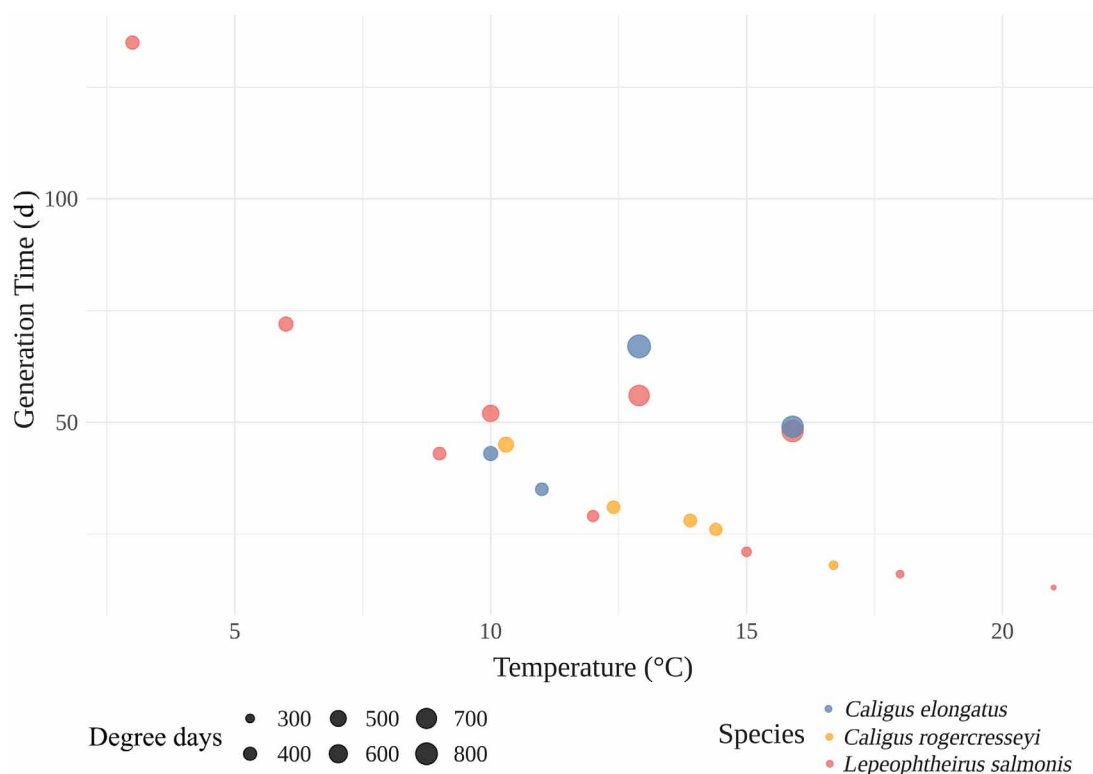


Fig. 1. Relationship between temperature and generation time for each of the 3 sea lice species, with the size of the points corresponding to the degree days. Data available in Table S1

ronmental suitability has been assessed under various climate scenarios, with end-of-century projections indicating habitat expansion into southern Chile, largely driven by rising ocean temperatures (Lepe-Lopez et al. 2021). A comprehensive assessment of the environmental niches of additional sea lice species is needed to fully understand their potential responses to climate change.

Apart from treatment costs and loss of production, high sea lice infestation rates on farms have impacted wild salmon populations, particularly in regions where farmed and wild salmonids overlap during vulnerable life stages (Krkošek et al. 2005, Costello 2009a, Forseth et al. 2017). In Canada, sea lice infestations on wild juvenile pink and chum salmon *Oncorhynchus gorbuscha* (Walbaum, 1792) and *O. keta* (Walbaum, 1792), respectively, have been associated with proximity to salmon farms, with juveniles in farm-free regions experiencing lower infestations in comparison to those near farms (Krkošek 2010). Concerns over sea lice impacts on wild salmon have contributed to farm closures in British Columbia and the denial of a salmon farm license in Ireland, while in Norway, farms are required to reduce production if lice levels exceed certain thresholds (Greaker et al. 2020, Krkošek et al. 2024).

Here, we used a maximum entropy (MaxEnt) model to estimate the thermal niche and project the future distribution of *L. salmonis*, *C. elongatus* and *C. rogercresseyi* under present-day conditions and 3 end-of-century climate change scenarios: SSP1-1.9, SSP3-7.0, and SSP5-8.5. In doing so, we aimed to identify regions where climate change may decrease or increase sea lice infestations, posing major challenges to the salmon aquaculture industry.

2. MATERIALS AND METHODS

2.1. Species occurrence data

Empirical occurrence records of *Lepeophtheirus salmonis*, *Caligus elongatus* and *C. rogercresseyi*, were obtained from the Global Biodiversity Information Facility (GBIF.org 2023), the Ocean Biodiversity Information System (OBIS 2024a), and additional literature sources (Table S2). This included points from countries with recorded sea lice outbreaks, including Canada. From the collated data, duplicate occurrence points, points without coordinates, points with geographic uncertainty greater than 10 km, those outside the known range of the species, and likely identification errors (from existing literature)

were removed. The study area encompassed the known distribution of each species: the northern hemisphere for *L. salmonis*, the North Atlantic for *C. elongatus*, and the southern coasts of Chile and Argentina for *C. rogercresseyi*. In total, we obtained 344 spatially unique occurrence records for *L. salmonis*, 50 records for *C. elongatus*, and 24 records for *C. rogercresseyi*.

2.2. Environmental data

We obtained sea surface temperature (SST) data (0 m depth) at 0.05° resolution for present-day conditions (period 2010 to 2020), and end-of-century projected conditions (period 2090 to 2100) from Bio-ORACLE v3.0 (Assis et al. 2024). Specifically, the environmental predictor variables used to construct the models were minimum, mean, and maximum SST (°C). Three shared socioeconomic pathways (SSP) scenarios were considered: (1) SSP1-1.9, the 'sustainability' scenario that avoids exceeding 1.5°C of warming, in line with the goals of the Paris Agreement (UNFCCC 2015); (2) SSP3-7.0, the 'regional rivalry' scenario, under which CO₂ emissions double by 2100 resulting in a warming of 3.6°C; and (3) SSP5-8.5, the 'fossil fuel development' scenario, where CO₂ emissions double by mid-century and continue increasing thereafter, leading to a warming of 4.4°C by 2100 (Meinshausen et al. 2020, Schoeman et al. 2023).

2.3. Thermal suitability models

The environmental suitability for present-day and for future climate scenarios was estimated using the maximum entropy model, performed with the 'Maxnet' R implementation, which fits species' occurrence records against environmental data (Phillips et al. 2017, Vignali et al. 2020). As the algorithm uses presence-only data, a set of background points (340 000 for *L. salmonis*, 50 000 for *C. elongatus*, and 10 000 for *C. rogercresseyi*) were randomly generated across the study area of each species, representing locations where species presence is not reported but likely to occur. The study area for *L. salmonis* largely covered the northern hemisphere (179° W to 155° E, 30 to 80° N), *C. elongatus* across the North Atlantic (80° W to 45° E, 30 to 80° N), and *C. rogercresseyi* around the south coast of South America (80 to 60° W, 35 to 60° S). Each presence and background point was then matched to its corresponding minimum, mean, and maximum SST, based on its geographic location. To

partition the data for cross-validation, spatially structured folds were generated using the block method, via the `get.block` function (Kass et al. 2021). This divided the presence and background points into 4 distinct spatial blocks, minimising spatial autocorrelation. The model was trained using 3 of the 4 blocks (80% of the data), with the fourth block (20%) used for testing. This process was repeated 4 times, with each iteration using a different block for testing and the remaining blocks for training.

Model tuning was carried out by performing a grid search to optimise the hyperparameters, which enhance model performance and control complexity, and regularisation multipliers, which penalise complex response curves to reduce overfitting. The feature class 'lq', or linear quadratic, was the selected hyperparameter for final model calibration for each of the species models, as it provided a balance between model interpretability and predictive performance. The regularisation multiplier of 1 was chosen for *C. elongatus* and *C. rogercresseyi*, and a multiplier of 2 was chosen for *L. salmonis*, to maintain accuracy while minimising overfitting.

The model performance was evaluated on the testing data using multiple metrics including the area under the receiver operating characteristic curve (AUC), the true skills statistics (TSS, using MaxTSS), and the accuracy at a threshold that maximised the sum of sensitivity and specificity.

The selected models were used to project present-day and future environmental suitability under the 3 SSP climate scenarios. The outputs were visualised as continuous probability maps, ranging from 0 (unsuitable) to 1 (highly suitable), and difference maps, which highlighted the areas in future scenarios with increasing or decreasing suitability compared to the present-day projections. The shifting environmental suitability of each lice species was then visually compared to the shifting environmental suitability of the 3 highest aquaculture-producing salmonid species: *Salmo salar*, *Oncorhynchus mykiss*, and *O. kisutch*. These projection maps were derived from a point process modelling framework adopted by MPA Europe and made publicly available (OBIS 2024b) and modelled using MaxEnt for SSP1-1.9, SSP3-7.0, and SSP5-8.5 to 2100.

2.4. Thermal niche

To assess sea lice species' thermal suitability, response curves were generated for each of the temperature variables from the thermal suitability models,

with the shaded areas representing the 95% confidence intervals. Suitability was scaled between 0 and 1, with higher values indicating more favourable conditions. We then evaluated the temperature range of each species using the overall range, the mean, and the 10th and 90th percentiles of the temperature values — the latter representing the preferred thermal range used by Aquamaps (Kaschner et al. 2019). The preferred thermal niche values for the salmonid host species were sourced from Aquamaps for comparison with the sea lice species preferred niche. Finally, we collected data on the generation times of the lice species at various temperatures from previous studies to support our thermal niche results (Hogans & Trudeau 1989, Tully 1989, Johnson & Albright 1992, Piasecki & MacKinnon 1995, González & Carvajal 2003, Bravo 2010, Hamre et al. 2019).

2.5. Data analysis

All analyses were performed using R Statistical Software (v4.4.1; R Core Team 2024) and R Studio (Posit Team 2023). The R packages used include 'biooracler' (Fernandez 2025), 'blockCV' (Valavi et al. 2019), 'dismo' (Hijmans et al. 2024), 'fuzzySim' (Barbosa 2015), 'ggplot2' (Wickham 2016), 'raster' (Hijmans 2025), 'rgbif' (Chamberlain & Boettiger 2017), 'robis' (Provoost & Bosch 2022), and 'SDMtune' (Vignali et al. 2020).

3. RESULTS

3.1. Overview

The generation times of all 3 species of sea lice shorten with increasing mean experimental temperature (Fig. 1; Table S1). Thus, within the temperature range of a species there will be greater production of lice larvae at warmer temperatures. Additionally, the experimental temperatures all fell within the response curve of the mean variable, for each species (Fig. 2).

The environmental suitability models revealed distinct thermal preferences for each sea lice species, with *Caligus rogercresseyi* favouring slightly warmer temperatures than *C. elongatus* and *Lepeophtheirus salmonis*. Under present-day conditions, *L. salmonis* was predicted to find high thermal suitability in the North Atlantic and Pacific, *C. elongatus* in northern Europe and the eastern USA, and *C. rogercresseyi* along the southern coast of South America. Future

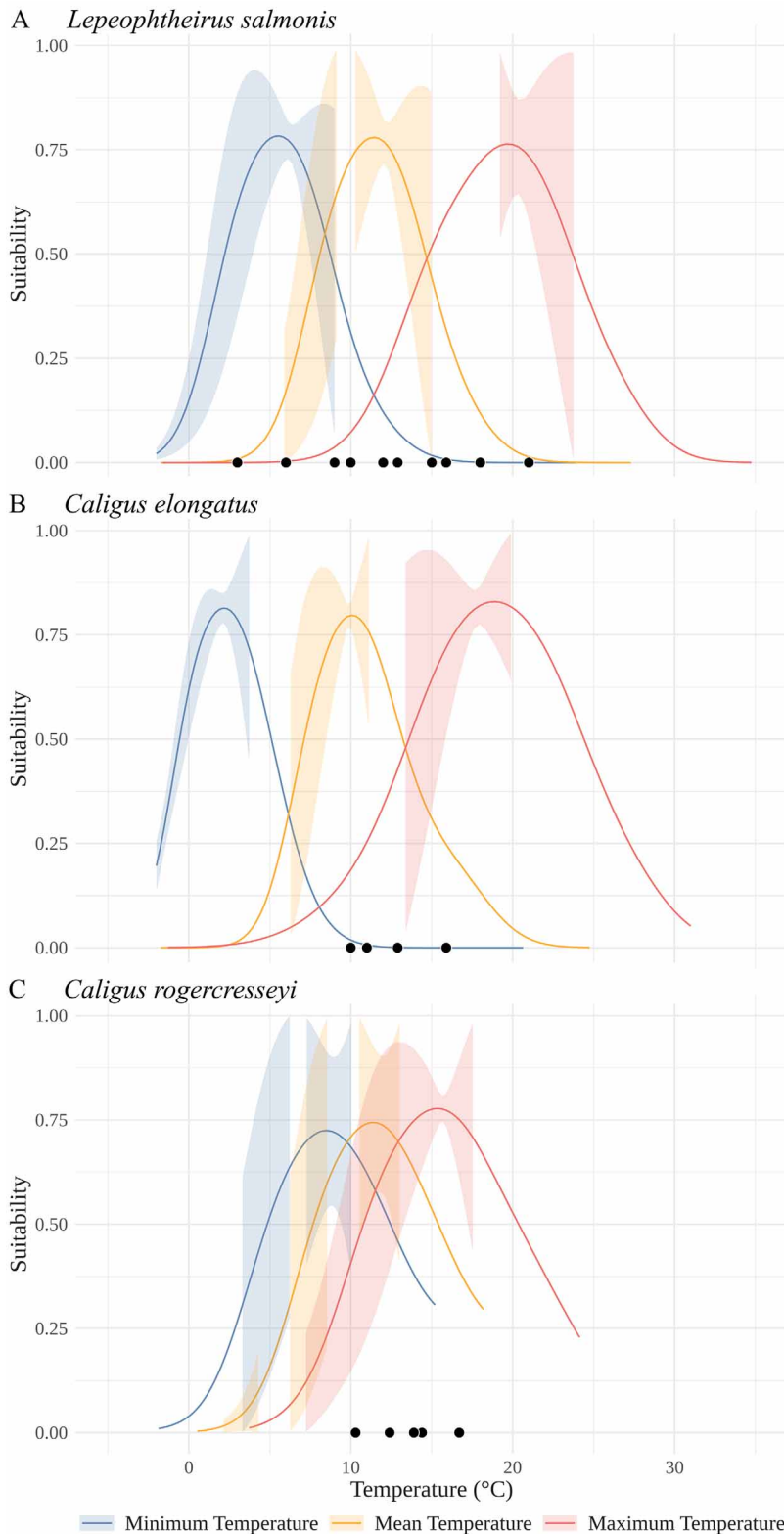


Fig. 2. Modelled variable response for minimum, mean, and maximum sea surface temperature of (A) *Lepeophtheirus salmonis*, (B) *Caligus elongatus*, and (C) *Caligus rogercresseyi*. Solid line represents suitability; shaded areas indicate 95% confidence interval. Black points on x-axis correspond to the temperature values from laboratory studies from the literature (Fig. 1; Table S1)

climate scenarios projected poleward shifts in suitable thermal habitat for all species, with varying degrees of expansion and contraction in different regions.

3.2. *L. salmonis*

For *L. salmonis*, maximum SST was the most influential temperature metric (explaining 48% of the variation) followed by minimum SST (explaining 41%) and mean SST (explaining 11%). The preferred temperatures (10th and 90th percentiles), based on occurrence records, ranged from 7.1 to 11.1°C in the mean temperature variable (Table 1; Table S3). The response curves from the thermal suitability model indicated that suitability peaked at 5.8°C for the minimum, 11.5°C for the mean, and 19.4°C for the maximum SST variable (Fig. 2A).

Model performance was good with a TSS of 0.76, a threshold of 0.34, a sensitivity of 0.92, a specificity of 0.84, and an AUC of 0.92. Under present-day conditions, our analysis revealed that high thermal suitability was concentrated along the North Atlantic coasts, around northern Europe, and the Pacific coast of North America (Fig. 3). Regions in white represent areas with no environmental suitability for *L. salmonis* distribution and were primarily the Mediterranean, the Arctic, and the tropics. Under the sustainability scenario SSP1-1.9, the same areas experienced similar environmental conditions to present, with the degree of suitability increasing slightly at higher latitudes and decreasing slightly at lower latitudes (Fig. 3; Fig. S1). Under the regional rivalry scenario SSP3-7.0, the thermal suitability shifted towards higher latitudes, with the degree of high suitability increasing across the North Pacific Ocean and decreasing in lower latitude areas including along the east and west coasts of the USA, the coasts of China and South Korea, in the Black Sea, and along the coast of

Table 1. Summary of the mean thermal suitability for each of the parasite species from the present study and that of the 3 highest-producing salmonid host species from Aquamaps, based on their respective occurrence records (Kaschner et al. 2019)

	Min. temp. (°C)	Preferred min. (10 th)	Preferred max. (90 th)	Max. temp. (°C)
<i>Lepeophtheirus salmonis</i>	2.1	7.1	11.1	12.0
<i>Caligus elongatus</i>	4.9	6.8	11.9	12.2
<i>Caligus rogercresseyi</i>	7.2	11.0	12.8	12.9
<i>Oncorhynchus kisutch</i>	1.8	4.4	12.4	27.1
<i>Oncorhynchus mykiss</i>	3.1	6.4	16.0	20.4
<i>Salmo salar</i>	-0.6	5.0	12.8	20.1

northern Europe. Finally, under a fossil-fuelled development scenario SSP5-8.5, the suitability expanded dramatically across higher latitudes and into the Arctic. Areas with high suitability in previous scenarios experienced increased suitability, especially along the Alaskan and Canadian coasts, as well as in Scandinavia and Russia. Conversely, lower latitudes continued to experience a decrease in thermal suitability.

3.3. *C. elongatus*

Mean temperature was the dominant predictor, contributing 46% to the model's explanatory power, while minimum temperature accounted for 44% and maximum temperature for 10%. The preferred temperatures (10th and 90th percentiles) ranged from 6.8 to 11.9°C in the mean SST variable (Table 1; Table S3). The response curves from the thermal suitability model indicated that suitability peaked at 2.0°C for the minimum, 10.0°C for the mean, and 18.8°C for the maximum SST (Fig. 2B).

The final model had a TSS of 0.83, a threshold of 0.15, a sensitivity of 0.96, a specificity of 0.87, and an AUC of 0.94. Present-day projections of thermal suitability found the highest thermal suitability along the coastlines of northern Europe and eastern USA, while areas with no suitability included the Mediterranean, southern North Atlantic, and Arctic (Fig. 4). Under the sustainability scenario, SSP1-1.9, key regions maintained high suitability with only minor expansions at high latitudes and contractions within the Baltic Sea. Under the regional rivalry scenario, SSP3-7.0, regions of high suitability expanded further into high-latitude regions, particularly in the North Sea, Barents Sea and in the western North Atlantic. Additionally, regions unsuitable for *C. elongatus* expanded across the Mediterranean, Baltic Sea and southern North Atlantic (Fig. S2). Under the fossil-fuelled development sce-

nario, SSP5-8.5, high suitability areas continued to expand across the North Atlantic and into the Arctic, while suitability was reduced in lower latitude regions including the eastern USA, northern Europe and the Baltic Sea.

3.4. *C. rogercresseyi*

Mean temperature was the dominant predictor variable, explaining 43% of the model, followed by maximum temperature (explaining 31%) and minimum temperature (explaining 26%).

The preferred temperatures (10th and 90th percentiles) from the occurrence records ranged from 11.0 to 12.8°C in the mean SST variable (Table 1; Table S3). The response curves from the thermal suitability model indicated that suitability peaked at 8.3°C for the minimum, 11.4°C for the mean, and 15.3°C for the maximum SST variable (Fig. 2C).

The selected model had a TSS of 0.76, a threshold of 0.56, a sensitivity of 0.92, a specificity of 0.84, and an AUC of 0.66. The present-day projections showed high suitability concentrated along the southern coast of South America, particularly within the fjords of Chile (Fig. 5). Projections under SSP1-1.9 followed a similar trend, but with slight reductions along the eastern coast of South America (Fig. S3). Under SSP3-7.0, the high suitability shifted southwards to include the southern tip of South America, while suitability at lower latitudes decreased. Lastly, under SSP5-8.5, the high suitability at the southern tip of South America intensified, as did the decreased suitability at lower latitudes.

4. DISCUSSION

Overall, we projected a poleward expansion and intensification of thermal suitability for all 3 sea lice species across increasing climate scenarios. This expected response pattern of marine species was largely influenced by increasing ocean temperatures, which drive population movements to remain within suitable environmental niche conditions (Hastings et al. 2020, Dahms & Killen 2023). As such, salmon farms located in higher latitudes may experience increased infestations of salmon lice as conditions become more favourable. The degree of projected poleward shifts of *Caligus elongatus* and *Lepeophtheirus salmonis* reflects the increased rate of ocean surface warming

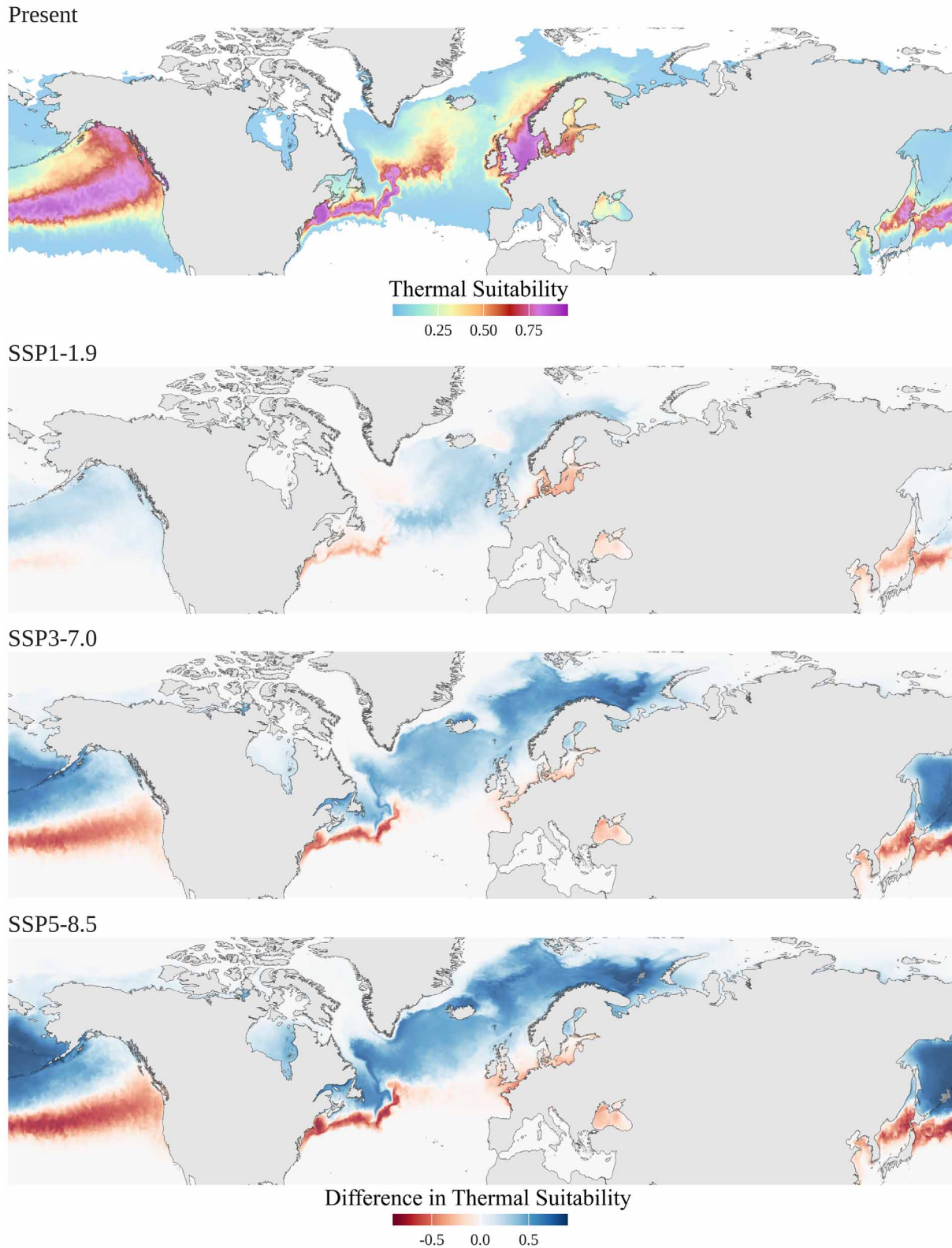


Fig. 3. Projected thermal suitability for *Lepeophtheirus salmonis* across the northern hemisphere under present-day conditions and the projected changes in thermal suitability under 3 climate change scenarios (SSP1-1.9, SSP3-7.0, SSP5-8.5). Under present-day conditions, the thermal suitability ranges from 0 (unsuitable, white in colour) to 1 (highly suitable, purple). Under projected climate scenarios, a decrease in thermal suitability is indicated in red, an increase in blue, and no change in white

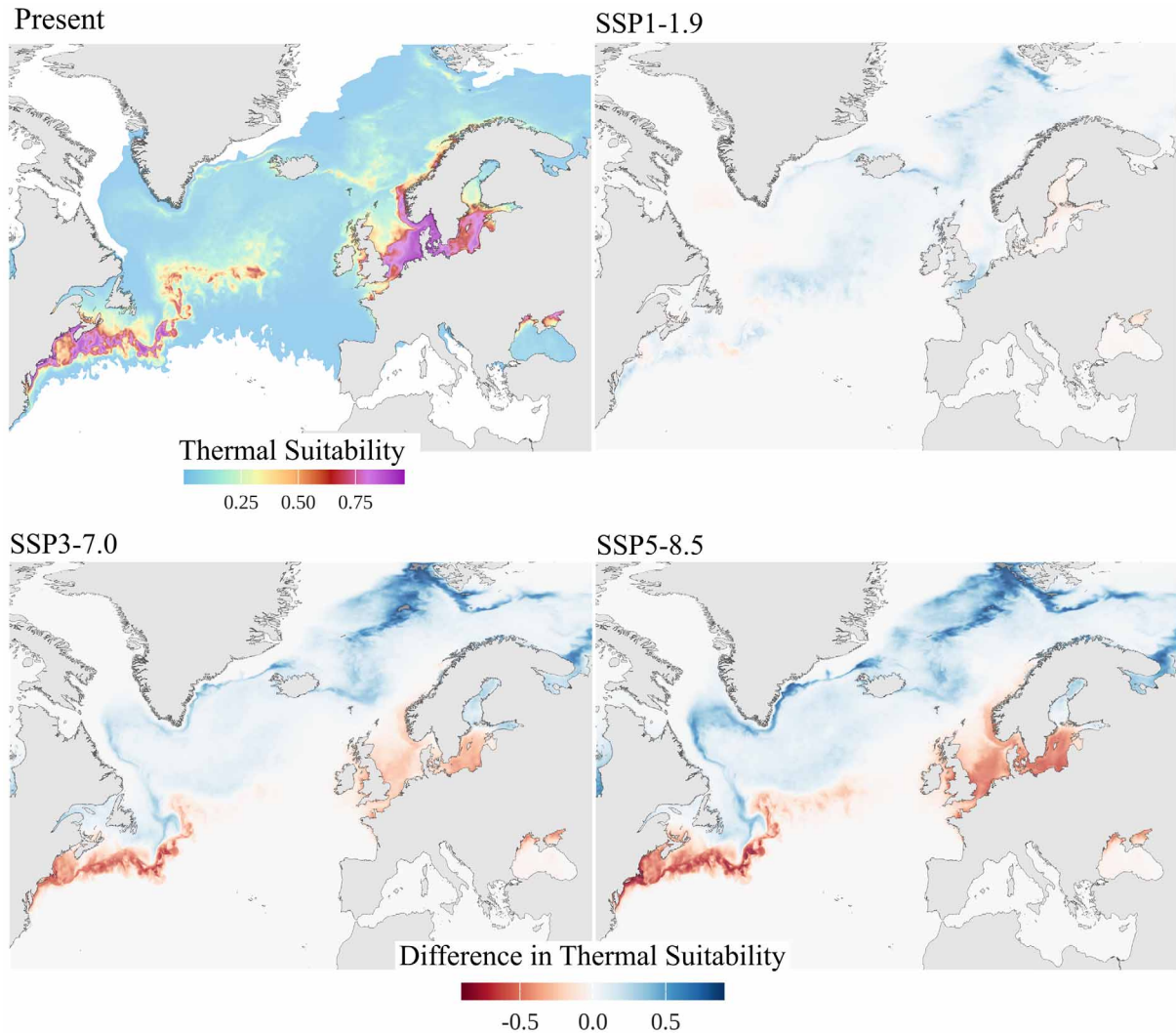


Fig. 4. Projected thermal suitability for *Caligus elongatus* across the North Atlantic under present-day conditions and the projected changes in thermal suitability under 3 climate change scenarios (SSP1-1.9, SSP3-7.0, SSP5-8.5). See Fig. 3 for colour scale description

in the northern hemisphere (Chaudhary et al. 2021, Dahms & Killen 2023). This is consistent with previous projections of species richness in Arctic regions, where thermal conditions are becoming increasingly suitable as climate scenarios intensify, particularly around northern Norway and Svalbard (Gordó-Vilaseca et al. 2023, 2024). The broad thermal tolerances of the northern hemisphere species also support their expansion potential across a wide range of environmental conditions (Figs. 3 & 4).

Our models indicated that the average temperature of the mean variable of SST were between 9 and 12°C across all 3 species (Table S3), which aligns with previous observations (Table S1). *C. rogercresseyi* exhibits a narrower thermal range than the northern hemisphere species, suggesting a more pronounced

response to ocean surface warming. This is reflected by the notable poleward shift under the SSP3-7.0 and SSP5-8.5 scenarios, consistent with previous projections (Lepe-Lopez et al. 2021).

SST is a key driver of sea lice development, growth, infection pressure, and reproduction. Warmer temperatures have been shown to increase the number of hatched eggs, reduce generation times, and increase the infectivity of copepodids, promoting population growth and infection pressure (Hamre et al. 2019, Dalvin et al. 2020, Skern-Mauritzen et al. 2020, Sandvik et al. 2021). These responses can lead to more frequent and severe outbreaks that are harder to control and more expensive to manage (Overton et al. 2019, Murray et al. 2022). With our projections of shifting thermal suitability, these findings suggest that

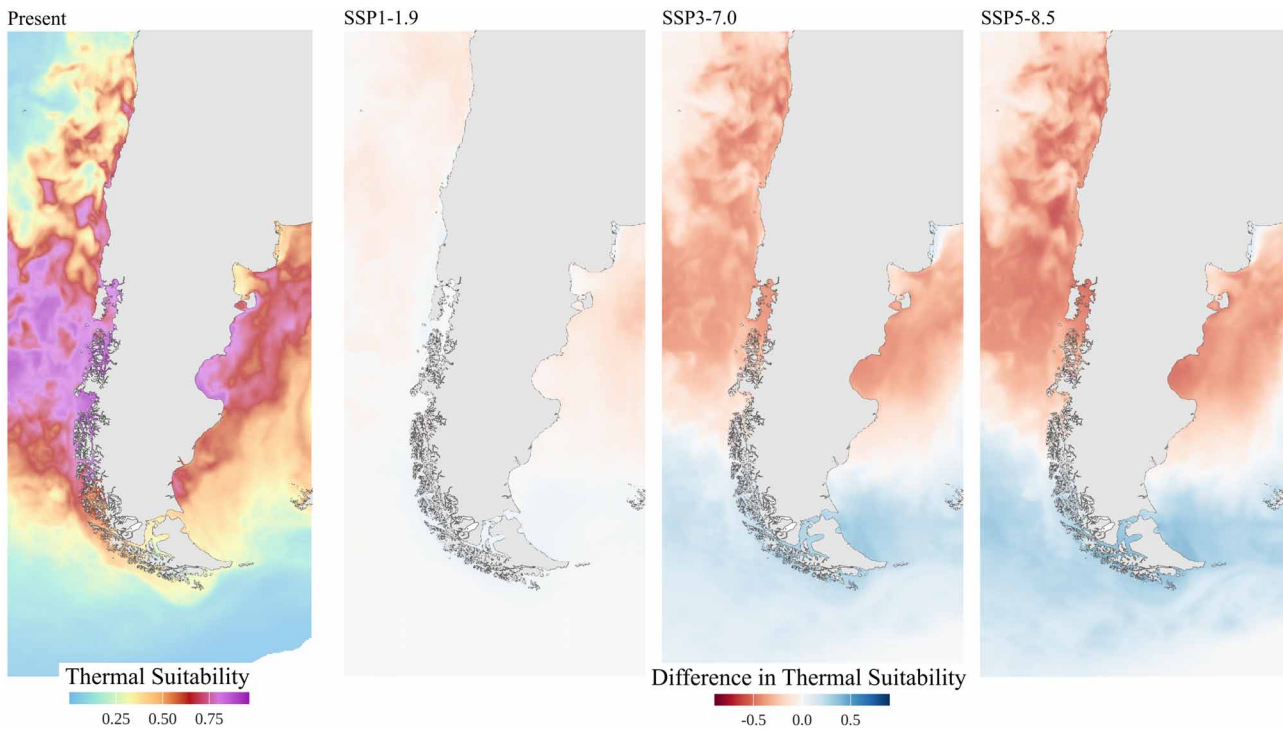


Fig. 5. Projected thermal suitability for *Caligus rogercresseyi* across the southern coast of South America under present-day conditions and the projected changes in thermal suitability under 3 climate change scenarios (SSP1-1.9, SSP3-7.0, SSP5-8.5).

See Fig. 3 for colour scale description

warming could increase the likelihood of lice outbreaks in existing and emerging aquaculture regions.

Because *Caligus* species occupy a wide range of hosts, their distribution is unlikely to be limited by their hosts' distribution under present or future climate change conditions. However, the salmon louse *L. salmonis* is salmonid-specific, and presently, its distribution overlaps with its hosts across the northern hemisphere. The projected distributions and thermal suitability of the 3 highest aquaculture-producing salmonid species — *Salmo salar*, *Oncorhynchus kisutch*, and *O. mykiss* — align with that of *L. salmonis*, further reinforcing that infestations will remain viable as both species shift polewards (Table 1).

As salmon farming moves into new regions, sea lice will follow. In Canada, Ireland, Norway, and Scotland, the declines of wild salmonid populations have been linked to sea lice infestations from nearby farms (Butler 2002, Costello 2009a, Torrissen et al. 2013). Countries reporting low rates of infestations may have sea lice present, but limited farming of host species prevents the development of epidemics (Costello 2009a). Expanding salmon farming in these regions may facilitate higher rates of infestations in both farmed and wild populations (Sandvik et al. 2021). This is exacerbated as warming accelerates sea lice develop-

ment, particularly at the colder edge of their distribution (Tully 1989, Groner et al. 2019). Additionally, sea lice infestations have been found to increase host susceptibility to diseases, such as infectious salmon anaemia virus, as the parasites compromise the hosts' immune system resulting in increased mortalities (Barker et al. 2019).

Although the projected thermal suitability for *L. salmonis* and *C. elongatus* in the Baltic Sea indicates the conditions there may be thermally optimal, the region's very low salinity likely prevents the presence of these species (Holopainen et al. 2025). Reduced salinity was previously identified as a constraint on sea lice population dynamics (Stien et al. 2005). Although adult *L. salmonis* can tolerate low salinities for only up to 14 d when attached to a host, studies show that salmon in low-salinity environments experience the lowest levels of sea lice infestations (Jones & Hargreaves 2007, Ljungfeldt et al. 2017). Freshwater exposure is, therefore, commonly used by both farms and wild populations to treat salmon lice infestations (Powell et al. 2015). However, the use of extensive freshwater treatments has raised concerns about the potential for sea lice to evolve tolerance to low salinities, as they have to pesticides (Ljungfeldt et al. 2017, Groner et al. 2019).

In preliminary analyses, the inclusion of salinity variables in the model revealed unrealistically low salinity niche estimates we attributed to the coarse spatial resolution of the environmental data. Consequently, salinity was excluded from the final analysis. Using only surface temperature variables (at 0 m) also limits the model projections, as sea lice larvae undergo a vertical migration in the water column influenced by light and seasonality (Johnsen et al. 2016, Nelson et al. 2018). Thus, incorporating finer-resolution salinity variables and temperature depth layers could improve the accuracy of the model projections.

Considering our projections and their implications, we recommend that farms implement lice management strategies, such as fallowing and separating farm sites by 30 km, to mitigate the spread of sea lice between farms (Costello 2009a). A complementary option is to invest in the aquaculture development of species less impacted by salmon lice. In Chile, *O. kisutch* has been found to have lower abundances of *C. rogercresseyi* due to their immune response (Lepe-Lopez et al. 2021). In British Columbia, *O. kisutch* and *O. tshawytscha* have lower sea lice intensities than other salmon species, with the development of *L. salmonis* found to be slower on *O. tshawytscha* than on *S. salar* (Johnson & Albright 1992, Johnson 1993, Beamish et al. 2005). Shifting the focus to farming less affected salmonid species may reduce the overall presence of sea lice species, due to reduced host availability. Farming of non-salmonids is also possible.

This paper presents the first projections of thermal suitability shifts of *L. salmonis* and *C. elongatus* under changing climatic conditions and projections of *C. rogercresseyi* that affirm previous literature (Lepe-Lopez et al. 2021). These findings emphasise the need for proactive management plans, including targeted mitigation strategies enforced by governments to protect cross infestation of wild fish. Mitigating sea lice infestations not only facilitates the sustainable expansion of an already successful aquaculture industry but could also benefit wild salmonid populations. Overall, our results indicate that climate change and rising ocean surface temperatures facilitate the poleward movement of the 3 most problematic sea lice species in salmonid aquaculture, in parallel with providing new opportunities to farm salmonids in higher latitudes.

Acknowledgements. We thank the 2 anonymous referees for their helpful suggestions that improved our paper. This paper forms part of A.L.M.'s PhD thesis. This study received Portuguese national funds from FCT-Foundation for Science and Technology (FCT) through the projects UIDB/04326/2020 (<https://doi.org/10.54499/UIDB/04326/2020>), UIDP/04326/2020 (<https://doi.org/10.54499/UIDP/04326/2020>), LA/P/0101/2020 (<https://doi.org/10.54499/LA/P/0101/2020>), and the Individual Call to Scientific Employment Stimulus 2022.00861.CEECIND/CP1729/CT0003 (<https://doi.org/10.54499/2022.00861.CEECIND/CP1729/CT0003>).

2020), UIDP/04326/2020 (<https://doi.org/10.54499/UIDP/04326/2020>), LA/P/0101/2020 (<https://doi.org/10.54499/LA/P/0101/2020>), and the Individual Call to Scientific Employment Stimulus 2022.00861.CEECIND/CP1729/CT0003 (<https://doi.org/10.54499/2022.00861.CEECIND/CP1729/CT0003>).

LITERATURE CITED

- ✦ Abolofia J, Asche F, Wilen JE (2017) The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. *Mar Resour Econ* 32:329–349
- ✦ Assis J, Fernández Bejarano SJ, Salazar VW, Schepers L and others (2024) Bio-ORACLE v3.0. Pushing marine data layers to the CMIP6 earth system models of climate change research. *Glob Ecol Biogeogr* 33:e13813
- ✦ Barbosa AM (2015) fuzzySim: applying fuzzy logic to binary similarity indices in ecology. *Methods Ecol Evol* 6: 853–858
- ✦ Barker SE, Bricknell IR, Covello J, Purcell S, Fast MD, Wolters W, Bouchard DA (2019) Sea lice, *Lepeophtheirus salmonis* (Krøyer 1837), infected Atlantic salmon (*Salmo salar* L.) are more susceptible to infectious salmon anaemia virus. *PLOS ONE* 14:e0209178
- ✦ Beamish RJ, Neville CM, Sweeting RM, Ambers N (2005) Sea lice on adult Pacific salmon in the coastal waters of Central British Columbia, Canada. *Fish Res* 76:198–208
- ✦ Boxaspen K (2006) A review of the biology and genetics of sea lice. *ICES J Mar Sci* 63:1304–1316
- ✦ Bravo S (2010) The reproductive output of sea lice *Caligus rogercresseyi* under controlled conditions. *Exp Parasitol* 125:51–54
- ✦ Butler JRA (2002) Wild salmonids and sea louse infestations on the west coast of Scotland: sources of infection and implications for the management of marine salmon farms. *Pest Manag Sci* 58:595–608
- ✦ Chamberlain SA, Boettiger C (2017) R Python, and Ruby clients for GBIF species occurrence data. *PeerJ Prepr* 5: e3304v1
- ✦ Chaudhary C, Richardson AJ, Schoeman DS, Costello MJ (2021) Global warming is causing a more pronounced dip in marine species richness around the equator. *Proc Natl Acad Sci USA* 118:e2015094118
- ✦ Costello MJ (1993) Review of methods to control sea lice (Caligidae: Crustacea) infestations on salmon (*Salmo salar*) farms. In: Boxhall GA, Defaye D (eds) *Pathogens of wild and farmed fish: sea lice*. Ellis Horwood, Chichester, p 219–252
- ✦ Costello MJ (2006) Ecology of sea lice parasitic on farmed and wild fish. *Trends Parasitol* 22:475–483
- ✦ Costello MJ (2009a) How sea lice from salmon farms may cause wild salmonid declines in Europe and North America and be a threat to fishes elsewhere. *Proc Biol Sci* 276: 3385–3394
- ✦ Costello MJ (2009b) The global economic cost of sea lice to the salmonid farming industry. *J Fish Dis* 32:115–118
- ✦ Dahms C, Killen SS (2023) Temperature change effects on marine fish range shifts: a meta-analysis of ecological and methodological predictors. *Glob Chang Biol* 29: 4459–4479
- ✦ Dalvin S, Hamre LA, Skern-Mauritzen R, Vågseth T, Stien L, Oppedal F, Bui S (2020) The effect of temperature on ability of *Lepeophtheirus salmonis* to infect and persist on Atlantic salmon. *J Fish Dis* 43:1519–1529

- Fernandez S (2025) biooracler: import environmental ocean data from Bio-Oracle via ERDDAP. R package version 0.0.0.9000, commit 218bffcadb1acb1489b1f7a44ded58a30277757. <https://github.com/bio-oracle/biooracler>
- FAO (Food and Agricultural Organization) (2024) The state of world fisheries and aquaculture 2024. FAO, Rome
- Forseth T, Barlaup BT, Finstad B, Fiske P and others (2017) The major threats to Atlantic salmon in Norway. *ICES J Mar Sci* 74:1496–1513
- GBIF.org (Global Biodiversity Information Facility) (2023) <https://www.gbif.org/> (accessed June 2024)
- González L, Carvajal J (2003) Life cycle of *Caligus rogercresseyi*, (Copepoda: Caligidae) parasite of Chilean reared salmonids. *Aquaculture* 220:101–117
- Gordó-Vilaseca C, Stephenson F, Coll M, Lavin C, Costello MJ (2023) Three decades of increasing fish biodiversity across the north-east Atlantic and Arctic Oceans. *Proc Natl Acad Sci USA* 120:e2120869120
- Gordó-Vilaseca C, Costello MJ, Coll M, Jüterbock A, Reiss H, Stephenson F (2024) Future trends of marine fish biomass distributions from the North Sea to the Barents Sea. *Nat Commun* 15:5637
- Greaker M, Vormedal I, Rosendal K (2020) Environmental policy and innovation in Norwegian fish farming: resolving the sea lice problem? *Mar Policy* 117:103942
- Groner ML, Laurin E, Stormoen M, Sanchez J, Fast MD, Revie CW (2019) Evaluating the potential for sea lice to evolve freshwater tolerance as a consequence of freshwater treatments in salmon aquaculture. *Aquacult Environ Interact* 11:507–519
- Hamre LA, Bui S, Oppedal F, Skern-Mauritzen R, Dalvin S (2019) Development of the salmon louse *Lepeophtheirus salmonis* parasitic stages in temperatures ranging from 3 to 24°C. *Aquacult Environ Interact* 11:429–443
- Hastings RA, Rutterford LA, Freer JJ, Collins RA, Simpson SD, Genner MJ (2020) Climate change drives poleward increases and equatorward declines in marine species. *Curr Biol* 30:1572–1577.e2
- Hemmingsen W, MacKenzie K, Sagerup K, Remen M, Bloch-Hansen K, Dagbjartarson Imsland AK (2020) *Caligus elongatus* and other sea lice of the genus *Caligus* as parasites of farmed salmonids: a review. *Aquaculture* 522:735160
- Hijmans R (2025) raster: geographic data analysis and modeling. R package version 3.6-31. <https://CRAN.R-project.org/package=raster>
- Hijmans R, Phillips S, Leathwick J, Elith J (2024) dismo: species distribution modeling. R package version 1.3-16. <https://cran.r-project.org/web/packages/dismo/>
- Hogans WE, Trudeau DJ (1989) Preliminary studies on the biology of sea lice, *Caligus elongatus*, *Caligus curtus* and *Lepeophtheirus salmonis* (Copepoda: Caligoida) parasitic on cage-cultured salmonids in the lower Bay of Fundy. Canadian Technical Report of Fisheries and Aquatic Sciences 1488-5379 No. 1715. Fisheries and Oceans Canada, St. Andrews
- Holopainen R, Kantala T, Korkea-aho T, Heikkinen P, Oksanen A, Orell P, Viljamaa-Dirks S (2025) Survey of the invasive alien pink salmon (*Oncorhynchus gorbuscha*) for infective agents in the Fennoscandian Rivers Tana and Neiden. *Fish Res* 281:107187
- IPCC (Intergovernmental Panel on Climate Change) (2023) Climate change 2022 — impacts, adaptation and vulnerability. Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 1st edn. Cambridge University Press, Cambridge
- Johnsen I, Asplin L, Sandvik A, Serra-Llinares R (2016) Salmon lice dispersion in a northern Norwegian fjord system and the impact of vertical movements. *Aquacult Environ Interact* 8:99–116
- Johnson SC (1993) A comparison of development and growth rates of *Lepeophtheirus salmonis* (Copepoda: Caligidae) on naive Atlantic (*Salmo salar*) and chinook (*Oncorhynchus tshawytscha*) salmon. In: Boxhall GA, Defaye D (eds) Pathogens of wild and farmed fish: sea lice. Ellis Horwood, New York, NY, p 68–80
- Johnson SC, Albright L (1992) Comparative susceptibility and histopathology of the response of naive Atlantic, chinook and coho salmon to experimental infection with *Lepeophtheirus salmonis* (Copepoda: Caligidae). *Dis Aquat Org* 14:179–193
- Jones SRM, Hargreaves NB (2007) The abundance and distribution of *Lepeophtheirus salmonis* (Copepoda: Caligidae) on pink (*Oncorhynchus gorbuscha*) and chum (*O. keta*) salmon in Coastal British Columbia. *J Parasitol* 93:1324–1331
- Just Economics (2021) Dead loss: the high cost of poor sea lice control in salmon farming. Report commissioned by Changing Markets Foundation. www.justeconomics.co.uk/dead-loss
- Kaschner K, Kesner-Reyes K, Garilao C, Rius-Barile J, Rees T, Froese R (2019) AquaMaps: predicted range maps for aquatic species. World wide web electronic publication, version 10/2019. www.aquamaps.org (accessed October 2024)
- Kass JM, Muscarella R, Galante PJ, Bohl CL and others (2021) ENMeval 2.0: redesigned for customizable and reproducible modeling of species' niches and distributions. *Methods Ecol Evol* 12:1602–1608
- Krkošek M (2010) Sea lice and salmon in Pacific Canada: ecology and policy. *Front Ecol Environ* 8:201–209
- Krkošek M, Lewis MA, Volpe JP (2005) Transmission dynamics of parasitic sea lice from farm to wild salmon. *Proc Biol Sci* 272:689–696
- Krkošek M, Bateman AW, Bass AL, Bugg WS and others (2024) Pathogens from salmon aquaculture in relation to conservation of wild Pacific salmon in Canada. *Sci Adv* 10:eadn7118
- Lepe-Lopez M, Escobar-Dodero J, Zimin-Veselkoff N, Azat C, Mardones FO (2021) Assessing the present and future habitat suitability of *Caligus rogercresseyi* (Boxshall and Bravo, 2000) for salmon farming in Southern Chile. *Front Vet Sci* 7:615039
- Ljungfeldt LER, Quintela M, Besnier F, Nilsen F, Glover KA (2017) A pedigree-based experiment reveals variation in salinity and thermal tolerance in the salmon louse, *Lepeophtheirus salmonis*. *Evol Appl* 10:1007–1019
- Meinshausen M, Nicholls ZRJ, Lewis J, Gidden MJ and others (2020) The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci Model Dev* 13:3571–3605
- Murray A, Falconer L, Brown L, Clarke D, Kennerley A (2022) Climate change impacts on marine aquaculture relevant to the UK and Ireland. *MCCIP Science Review* 2022
- Nelson EJ, Robinson SMC, Feindel N, Sterling A, Byrne A, Pee Ang K (2018) Horizontal and vertical distribution of sea lice larvae (*Lepeophtheirus salmonis*) in and around salmon farms in the Bay of Fundy, Canada. *J Fish Dis* 41:885–899

- ✦ OBIS (Ocean Biodiversity Information System) (2024a) Inter-governmental Oceanographic Commission of UNESCO. obis.org. (2023) (accessed June 2024)
- OBIS (2024b) Species distribution dashboard for MPA Europe, version 0.1.0. Zenodo. <https://shiny.obis.org/distmaps> (accessed December 2024)
- ✦ Overton K, Dempster T, Oppedal F, Kristiansen TS, Gismervik K, Stien LH (2019) Salmon lice treatments and salmon mortality in Norwegian aquaculture: a review. *Rev Aquacult* 11:1398–1417
- ✦ Phillips SJ, Anderson RP, Dudík M, Schapire RE, Blair ME (2017) Opening the black box: an open-source release of Maxent. *Ecography* 40:887–893
- ✦ Piasecki W, MacKinnon BM (1995) Life cycle of a sea louse, *Caligus elongatus* von Nordmann, 1832 (Copepoda, Siphonostomatoida, Caligidae). *Can J Zool* 73:74–82
- ✦ Posit Team (2023) RStudio: integrated development environment for R. Posit Software, PBC, Boston, MA. www.posit.co/
- ✦ Powell MD, Reynolds P, Kristensen T (2015) Freshwater treatment of amoebic gill disease and sea-lice in seawater salmon production: considerations of water chemistry and fish welfare in Norway. *Aquaculture* 448:18–28
- ✦ Provoost P, Bosch S (2022) robis: Ocean biodiversity information system (OBIS) client. R package version 2.11.3. <https://CRAN.R-project.org/package=robis>
- R Core Team (2024) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- ✦ Sandvik AD, Dalvin S, Skern-Mauritzen R, Skogen MD (2021) The effect of a warmer climate on the salmon lice infection pressure from Norwegian aquaculture. *ICES J Mar Sci* 78:1849–1859
- ✦ Schoeman DS, Gupta AS, Harrison CS, Everett JD and others (2023) Demystifying global climate models for use in the life sciences. *Trends Ecol Evol* 38:843–858
- ✦ Skern-Mauritzen R, Sissener NH, Sandvik AD, Meier S and others (2020) Parasite development affect dispersal dynamics; infectivity, activity and energetic status in cohorts of salmon louse copepodids. *J Exp Mar Biol Ecol* 530–531:151429
- ✦ Stien A, Bjørn PA, Heuch PA, Elston DA (2005) Population dynamics of salmon lice *Lepeophtheirus salmonis* on Atlantic salmon and sea trout. *Mar Ecol Prog Ser* 290: 263–275
- ✦ Torrissen O, Jones S, Asche F, Guttormsen A and others (2013) Salmon lice – impact on wild salmonids and salmon aquaculture. *J Fish Dis* 36:171–194
- ✦ Tully O (1989) The succession of generations and growth of the caligid copepods *Caligus elongatus* and *Lepeophtheirus salmonis* parasitising farmed Atlantic salmon smolts (*Salmo salar* L.). *J Mar Biol Assoc UK* 69:279–287
- ✦ UNFCCC (United Nations Framework Convention on Climate Change) (2015) The Paris Agreement. <https://unfccc.int/process-and-meetings/the-paris-agreement>
- ✦ Valavi R, Elith J, Lahoz-Monfort JJ, Guillera-Aroita G (2019) BLOCK CV: an R package for generating spatially or environmentally separated folds for *k*-fold cross-validation of species distribution models. *Methods Ecol Evol* 10:225–232
- ✦ Vignali S, Barras AG, Arlettaz R, Braunisch V (2020) SDMtune: an R package to tune and evaluate species distribution models. *Ecol Evol* 10:11488–11506
- ✦ Walter TC, Boxshall G (2025a) World of copepods database. *Caligus Müller OF 1785*. www.marinespecies.org/aphia.php?p=taxdetails&id=135566 (accessed May 31, 2025)
- ✦ Walter TC, Boxshall G (2025b) World of copepods database. *Lepeophtheirus von Nordmann, 1832*. www.marinespecies.org/aphia.php?p=taxdetails&id=135568 (accessed May 31, 2025)
- Wickham H (2016) ggplot2: elegant graphics for data analysis. Springer, New York, NY

Editorial responsibility: Kevin Glover,
Bergen, Norway

Reviewed by: M. Parent and 2 anonymous referees

Submitted: February 4, 2025; Accepted: July 24, 2025

Proofs received from author(s): October 7, 2025

This article is Open Access under the Creative Commons by Attribution (CC-BY) 4.0 License, <https://creativecommons.org/licenses/by/4.0/deed.en>. Use, distribution and reproduction are unrestricted provided the authors and original publication are credited, and indicate if changes were made