How and to what extent do sea lice affect the performance of juvenile Pacific salmon? A systematic review protocol

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Abstract

1. Wild Pacific salmon are a culturally, ecologically, and economically important group of fishes. Unfortunately, several distinct lineages have already been lost. The abundance of these species varies over interdecadal and centennial time scales due to climatic and local ecosystem complexity and dynamics. Sea lice from net-pen salmon farms (traditional flow-through containment systems) have been linked to negative effects on wild salmon. However, there is debate over the quality of evidence for these claims.
2. To gain a better understanding of this host–parasite system, we completed a systematic map to provide a summary of the existing literature base on the effects of sea lice (in the genera *Lepeophtheirus* or *Caligus*) on wild-caught, hatchery-sourced, and farmed Pacific (Chinook salmon *Oncorhynchus tshawytscha*, coho salmon *O. kisutch*, chum salmon *O. keta*, sockeye salmon *O. nerka*, or pink salmon *O. gorbuscha*) and Atlantic salmon (*Salmo salar*). This approach was intended as a first step, with the goal to later conduct a systematic review on one or more evidence clusters relating to Pacific salmon identified from the mapping approach. Based on the map findings, studies investigating sea lice effects on individual-level performance metrics (e.g., osmotic function and homeostasis, immune function, and survival) in Pacific salmon were identified as subtopics (i.e., knowledge clusters) that had sufficient coverage for further review. Here we present a protocol for a subsequent systematic review that will estimate how and to what extent sea lice affect the performance of juvenile Pacific salmon.
3. This systematic review will use evidence identified during a systematic map process that included commercially published and grey literature available from 1900 to March 2025. This evidence was identified from English-language searches using four publication databases, Google Scholar, 25 specialist websites, hand-searching reference sections of 98 relevant reviews, and networking tools and calls for evidence in English and French to target grey literature (accepting suggestions until November 2025).
4. Studies that evaluate the effect of sea lice (in the genera *Lepeophtheirus* or *Caligus*) on individual-level performance metrics in the five Pacific salmon species mentioned above

found anywhere in the world will be included. Specifically, we will include measures of change related to: (1) a stress response (e.g., glucose, cortisol, heat shock proteins), (2) osmotic function and homeostasis (e.g., osmolality, Na+, haematocrit), (3) immune function (e.g., hypertrophy, macrophage function, immune-related genes), (4) injuries (e.g., visible injuries, tissue damage), (5) growth (e.g., length, mass, condition, specific growth rate), (6) behaviour (e.g., feeding, activity patterns, migration timing/route, swimming ability), (7) survival (number died or consumed by predator), (8) reproduction (e.g., number of eggs laid, estradiol, testosterone), (9) cardio-respiratory function (e.g., cardiac output, heart rate, critical swimming speed), or surrogates thereof.

5. Included studies will undergo critical appraisal of internal and external validity. We will build off the coded and extracted information from the mapping exercise by extracting quantitative information on measured outcomes and further exposure and comparator details, as well as effect modifiers (e.g., sea lice infestation level, time since infestation, size and age of salmon). A narrative synthesis will be used to describe the quantity and characteristics of the available evidence, while quantitative syntheses (i.e., meta-analyses) will be conducted to estimate an overall mean and variance of effect for each outcome category separately (e.g., outcome groups 1-9 listed above) when sufficient numbers of similar studies are available. Further, we will attempt to identify sea lice exposure thresholds which could yield valuable information to help inform management for Canadian stakeholders.

Keywords: aquaculture, evidence synthesis, individual, management, mortality, salmonid, threshold

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Background

Pacific salmon (*Oncorhynchus* spp.) are an ecologically, culturally, and economically important group of species, but they have already lost several distinct ecological, life history, and genetic lineages (Cordoleani et al., 2021; Gustafson et al., 2007; Thompson et al., 2019) and many more are at risk due to commercial bycatch, freshwater habitat loss, barriers to migration, invasive species, pollution, pathogens/disease, hatcheries, climate change, and predators (Chalifour et al., 2022; Crozier & Siegel, 2023). The abundance of these species varies over interdecadal and centennial time scales due to climatic and local ecosystem complexity and dynamics (Rogers et al., 2013), and they have geographically extensive journeys that make monitoring populations challenging (Malick et al., 2017; Ross et al., 2013).

Sea lice on salmon farms have been associated with infestations in wild Pacific salmon populations (Krkošek et al., 2007; Marty et al., 2010; Peacock et al., 2013). In British Columbia (hereafter BC), the salmon louse *Lepeophtheirus salmonis* and the herring louse *Caligus clemensi*, both caligid copepods, are the most common naturally occurring ectoparasites on farmed and wild Pacific salmon (Beamish et al., 2009; Saksida et al., 2007). Sea lice in these genera occur globally, with 268 species of *Caligus* recognised, of which the majority are marine, but a few live in brackish or freshwater environments (Tavares-Dias & Oliveira, 2023). *Caligus* spp. can parasitize 368 different teleost fishes, and *C. elongatus* is the most general species, occurring on fishes in 19 different families (reviewed in Tavares-Dias & Oliveira, 2023). *Lepeophtheirus salmonis* is generally restricted to salmonids and usually occurs in shallow coastal habitats. *Lepeophtheirus salmonis* occurs on both coasts of Canada, with genetically distinct variants occurring in the Atlantic (*L. s. salmonis*) and Pacific oceans (*L. s. oncorhynchi*) (Skern-Mauritzen et al., 2014; Todd et al., 2004).

In both *C. clemensi* and *L. salmonis*, the planktonic, free-swimming non-infective nauplii hatch from eggs. The two nauplius stages cannot swim against the current but can adjust their vertical depth. The following copepodid stage is infective and, when it finds a fish host, it attaches and feeds briefly before molting to the first chalimus stage, which is attached to the fish by a rope-like frontal filament. In *L. salmonis*, the first chalimus stage molts through to a second host-attached chalimus stage (Hamre et al., 2013) and then molts through two sexually differentiated preadult stages to the final sexually mature adult stage. In contrast, *C. clemensi* possesses four chalimus stages, then proceeds directly to the adult stage with no intervening preadult stage. In both species, preadult and adult stages are mobile on the host and may re-enter the water column to find new hosts, and these stages cause the most damage to fish due to their more extensive feeding on host skin, mucus and blood. Additionally, the speed and success of sea lice development is influenced by environmental conditions such as temperature and salinity (reviewed in Jones & Johnson, 2015). For instance, higher temperatures result in more eggs hatching and higher levels of infestations (Samsing et al., 2016).

Sea lice dynamics are inherently complex, shaped by ocean currents and environmental conditions, modulated by the presence and distribution of suitable hosts, and occurring across both wild and farmed salmon. In the fall, returning adult salmon that naturally carry sea lice can transmit these lice to juvenile salmon remaining in coastal waters (Beamish et al., 2007; Gottesfeld et al., 2009), though others argue there is little spatial overlap between adults and juveniles (Krkošek et al., 2007). The transmission from adults to wild or farmed fish is known as 'spill over' (British Columbia Ministry of Agriculture and Lands, nd). Farmed salmon may then amplify and re-infest wild adult or juvenile salmon, termed 'spill back' (Daszak et al., 2000; Groner et al., 2016; Vollset et al., 2023). The mechanism of attachment and feeding activities by sea lice can cause damage to the host's skin and create open wounds on the host. Damage caused by sea lice can increase the susceptibility to co-infection from other pathogens, cause osmotic and other stress, influence behaviour and growth, and in some cases lead to the death of the host (Brauner et al., 2012; Godwin et al., 2015; Johnson et al., 1996; Krkošek et al., 2011; Long et al., 2019; Mages & Dill, 2010; Sutherland et al., 2011). The effects of sea lice infestations in aquaculture span economic, ethical, political, and conservation outcomes, resulting in reduced profits, impacting the welfare of farmed fish, and potentially having negative effects on wild Pacific salmon (Abolofia et al., 2017; Costello, 2009; Liu et al., 2011; Marty et al., 2010).

This system is not unique in its complexity, as other wildlife–domestic host–parasite systems have similar challenges (Morgan et al., 2004). Here, one must consider the dynamics of lice–host transmission, the sublethal effects of sea lice on salmon, the variable hydrology and chemistry of coastal waters, the presence of multiple lice species, some of which have multiple salmonid and non-salmonid host species with different susceptibilities, migration pathways and life cycles. These complexities are especially relevant when trying to establish whether survival of freely migrating juveniles, which interact with other wild juvenile and adult salmonids as well as many other host species, is impacted by lice originating from net pen salmon farms (Arbeider et al., 2024; Beamish et al., 2005; Brooks, 2005, 2009; Brookson et al., 2020; Elmoslemany et al., 2015; Godwin et al., 2015; Nagasawa, 2001; Simenstad et al., 1982).

Syntheses of evidence on the effects of sea lice have progressed further for Atlantic salmon (*Salmo salar*) than Pacific salmon. For example, several meta-analyses have focused on the effects of sea lice on marine survival in Atlantic salmon (e.g. Gargan et al., 2025; Jackson et al., 2013; Krkošek et al., 2013; Vollset et al., 2016; Vollset et al. 2023), and Ives et al. (2023) assessed thresholds for lice-induced sub-lethal effects and direct mortality in juvenile Atlantic salmon. However, even in Atlantic salmon, experts have identified gaps in knowledge, calling for improved understanding of critical lice thresholds for fish, seasonal effects and the interaction between sublethal lice impacts and other stressors (Murphy et al., 2024). Comparatively, there have been fewer evidence syntheses focused on the effects of sea lice on one or more species of Pacific salmon (e.g., Wagner et al., 2008 on Pacific and Atlantic salmon; Brauner et al., 2012 on *O. gorbuscha*; Krkošek et al., 2024 on Pacific salmon [but see Marty et al., 2025]). To our knowledge, there is currently no comprehensive evidence synthesis characterizing the influence of sea lice on Pacific salmon physiology and behaviour. Here, we propose to conduct a global systematic review, including a quantitative synthesis, to better understand how and to what extent sea lice affect the performance of juvenile Pacific salmon. Importantly, we will develop and use a critical appraisal tool to evaluate the validity (internal and external) of all studies. Critical appraisal is an assessment of how well the studies included in the review are conducted and thus, how reliable their findings are (CEE, 2022). In combination with a systematic review, this tool can provide transparent and objective assessments where topics are controversial or high profile (Haddaway and Pullin, 2014, Rytwinski et al., 2021).

Topic identification and stakeholder involvement

Fisheries and Oceans Canada (hereafter DFO) Aquaculture Directorate requested Canadian Science Advisory Secretariat (CSAS) peer-reviewed science advice on the impacts of sea lice from salmon farms to wild Pacific salmon species in BC (see https://www.dfo-mpo.gc.ca/csas-sccs/Schedule-Horraire/2024/792-eng.html). Previous science advice related to this topic was completed in 2022 and focused on the associations between sea lice from Atlantic salmon farms and sea lice infestation on juvenile wild Pacific salmon in BC (see DFO, 2023). DFO is planning to complete a more comprehensive review to provide science advice to DFO managers, which is currently planned to be completed by 2026. To produce this advice, DFO Science has asked for scientific peer-reviewed research about the impact of sea lice from net-pen salmon farms on wild Pacific salmon in BC, with information pulled from other species and geographic areas as appropriate. DFO is currently collaborating with the Canadian Centre for Evidence-Informed Conservation to address this need in part by recently conducting a systematic map (Peiman et al., 2025) to provide a summary of the existing literature base on the effects of sea lice on wild-caught, hatchery-sourced, and farmed Pacific and Atlantic salmon. The focus was on the effects of lice in the genera *Caligus* and *Lepeophtheirus* on the population status, performance, or lice levels of the focal salmon species. The map followed the Collaboration for Environmental Evidence (CEE) guidelines for systematic mapping (CEE, 2022) whereby authors described the quantity and key characteristics of the available evidence and identified evidence clusters and knowledge gaps but did not synthesize results. This approach was intended as a first step, with the goal to later conduct a systematic review on one or more evidence clusters relating to Pacific salmon identified from the mapping approach, and is planned out in phases, each with their own peer-reviewed science advice meeting (see Figure 1; Canadian Science Advisory Secretariat [CSAS] meetings). A total of 413 relevant studies from 344 articles were identified, documenting a range of sea lice impacts on five species of Pacific salmon worldwide. Here, if multiple studies were reported within one article, they were entered as independent lines in the database, with study (case study) being defined as an investigation/experiment of an exposure at a specific study location (but could include multiple study sites) over a similar specified time period.

From the map, the largest evidence cluster was for studies that addressed the sub-question of interest "To what extent do net-pen salmon farms contribute to the sea lice loads on wild Pacific salmon?", in relation to three main outcomes (sea lice prevalence, abundance, and intensity). A smaller evidence cluster was apparent for the sub-question "How and to what extent do sea lice affect the performance of juvenile Pacific salmon?", in relation to outcomes of salmon stress responses, osmotic function and homeostasis, immune function, injuries, growth/condition, behaviour, and survival. The smallest evidence cluster was for the sub-question "Does the exposure to sea lice from net-pen salmon farms have a population-level effect on wild Pacific salmon, and if so, to what extent?" in relation to salmon escapement and productivity. Interest and scientific value of all three questions was acknowledged by the Advisory Team (see below), the participants at the Phase 2A CSAS meeting (held in November 2025), and DFO aquaculture management. After further discussions, it was concluded that there may be alternative methods (instead of systematic review) that are best for the analysis of the evidence cluster associated with sea lice loads. DFO is also exploring options to further review the small evidence base for the population-level effects sub-question (see Figure 1: 'Evidence synthesis' column). Thus, a decision was made by DFO to proceed with a full systematic review of the evidence cluster for "How and to what extent do sea lice affect the performance of juvenile Pacific salmon?" in order to try and advance our understanding of the individual-level effects of sea lice, which would also aid in moving us further along the spectrum of understanding population-level effects.

Evidence synthesis experts from CEIC established and consulted with an Advisory Team during the systematic map process. This group was made up of individuals from the non-profit sector (Pacific Salmon Foundation), government officials (DFO) and academic and research scientists (Simon Fraser University, NORCE Norwegian Research Centre). This same Advisory Team was consulted to lay out the project plan for this systematic review. The Advisory Team, as well as DFO science advisors and researchers, were consulted in the development of the inclusion criteria for article screening, the critical appraisal tool, and data extraction strategy and will continue to participate in this systematic review through to completion. Also, science experts involved in the CSAS process (Phase 2A held November 2025) reviewed and provided input on the critical appraisal tool and project plan (see Figure 1).

Objective of the review

The objective of this proposed systematic review is to clarify how and to what extent sea lice affect the performance of juvenile Pacific salmon (five species of *Oncorhynchus*).

Primary question

How and to what extent do sea lice affect the performance of juvenile Pacific salmon?

Components of the primary question

Subject (population): Wild-caught, hatchery-sourced, or farmed Pacific salmon (any of the following five species: Chinook [king] salmon *O. tshawytscha*, coho [silver] salmon *O. kisutch*, chum [dog, keta] salmon *O. keta*, sockeye [red, blueback] salmon *O. nerka*, pink [humpback] salmon *O. gorbuscha*) anywhere in the world. Although the focus will be on juvenile Pacific salmon, any life stage of salmon will be included.

Intervention/Exposure: Exposure of Pacific salmon to any infective life stage of sea lice in the genera *Lepeophtheirus* or *Caligus*. This includes direct exposure through experimentation, exposure of outward-migrating juveniles through areas with or without salmon net pens, or exposure of farmed salmon to sea lice.

Comparator: No exposure to sea lice either between groups of fish in experimental studies, between sites, or over time, or an exposure to different levels of sea lice (e.g., low versus high infestation).

Outcomes: Measures of change (at any life stage) in individual-level performance metrics (i.e., outcomes that could affect fitness: Peiman & Robinson, 2017) related to a stress response (e.g., glucose, cortisol, heat shock proteins), osmotic function and homeostasis (e.g., osmolality, Na+, haematocrit), immune function (e.g., hypertrophy, macrophage function, immune-related genes), injuries (e.g., visible injuries, tissue damage), growth (e.g., length, mass, condition, specific growth rate), behaviour (e.g., feeding, activity patterns, migration timing/route, swimming ability), survival (number died or consumed by predator), reproduction (e.g., number of eggs laid, estradiol, testosterone), cardio-respiratory (e.g., cardiac output, heart rate, critical swimming speed), or surrogates thereof.

Secondary question

We also propose to address, with quantitative synthesis, the secondary question of:

a) To what extent do factors (e.g., louse species, louse life stage, lice infestation, salmon species, source, age, size, time since infestation, temperature, salinity) influence the relationship between sea lice and performance in Pacific salmon?

And with quantitative and qualitative syntheses:

b) What is the threshold of sea lice exposure above which Pacific salmon responses are detected?

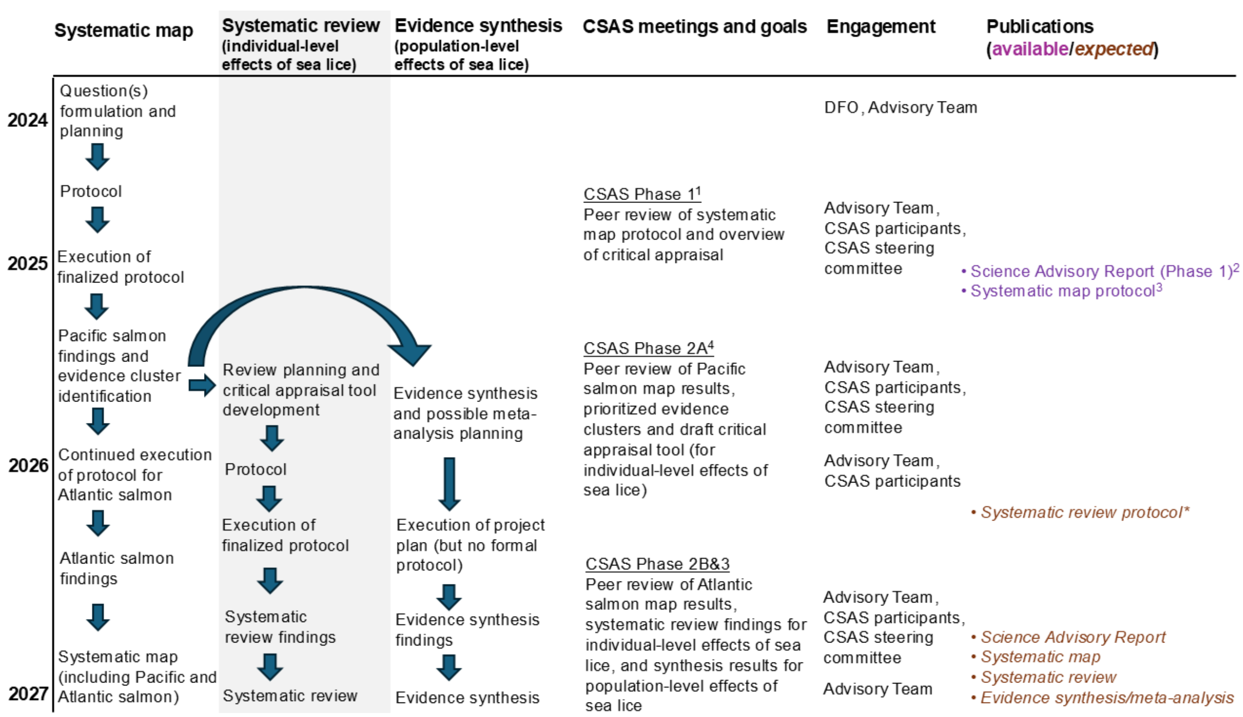

Figure 1. Details of the systematic map process from which the topic of this proposed systematic review was identified (shaded grey area), along with project phases (Canadian Science Advisory Secretariat [CSAS] meetings), engagement, publications (currently available in purple and those anticipated in orange italics, including this document*) and approximate timelines.

[1]DFO Terms of Reference for Phase 1, available at: https://csas-scas.dfo-mpo.gc.ca/meetings-reunions/91fa7193-b4c3-42a2-83b8-be726f3a7957?lang=en

[2]DFO (2025)

[3]Peiman et al. (2025)

[4]DFO Terms of Reference for Phase 2A, available at: https://csas-scas.dfo-mpo.gc.ca/meetings-reunions/fbcdfdc2-793e-4707-b395-caf6068c5e13?lang=en

Materials and Methods

The proposed systematic review will follow, as closely as possible, the standards and guidelines for systematic reviews (CEE, 2022) and RepOrting standards for Systematic Evidence Syntheses in environmental research (i.e., ROSES; see Haddaway et al., 2018) (see Supporting Information 1).

Selection of studies identified in the systematic map

Searching for articles

The evidence on which this systematic review will be based derives from the recently completed systematic map on the effects of sea lice on wild and farmed Pacific and Atlantic salmon (Peiman et al., 2025). The systematic map searched for commercially published (e.g., academic literature from journals or books) and grey literature (e.g., reports, government documents, white papers) using four publication databases (ISI Web of Science Core Collections, Scopus, ProQuest Dissertations & Theses Global, and Federal Science Libraries Network; searches performed in March 2025), Google Scholar (search performed in June 2024) and 25 specialist websites (searches performed in April to May 2025) (see Table 1 for the search string and Supporting Information 2 for full details and search results). The comprehensiveness of the search string was tested using a list of benchmark papers (see Peiman et al., 2025) suggested by the Advisory Team as being relevant for this review. In addition, reference sections of 98 relevant reviews were hand searched for relevant titles that were not found using the search strategy. Calls for evidence were also issued in English and French to target grey literature through relevant mailing lists, social media, and the networks and colleagues of Advisory Team members and science experts involved in the CSAS process (calls performed in February 2025 but accepted suggestions up until November 2025). In summary, the systematic map included all articles available from 1900 to March 2025, with some additional articles until November 2025. The search string used in the systematic map can be found in Peiman et al. (2025) and Supporting Information 2.

Because the searches for articles included in the systematic map were conducted in June 2024 (Google Scholar) and March 2025 (databases), we will not conduct an updated search. However, some articles published after those dates (up until November 2025) were also included if we became aware of them through grey literature suggestions.

Table 1. Search string used in the systematic map (Peiman et al., 2025) to execute searches for Pacific salmon formatted for Web of Science Core Collection.

Component	String
Population	TS=(“Pacific salmon” OR Oncorhynchus OR Chinook OR Chum OR Coho OR Pink OR Sockeye OR King OR Silver OR Dog OR Keta OR Red OR Blueback OR Humpback)
	AND
Exposure	TS=(lepeophtheirus OR “salmon louse” OR “salmon lice” OR “sea louse” OR “sea lice” OR “herring lice” OR “herring louse” OR caligus)

Article screening, initial data coding and study eligibility criteria

Once the peer-reviewed and grey literature were compiled from the systematic map searches, studies were screened at two stages (i.e., title/abstract and full text) using predefined inclusion criteria (see Peiman et al., 2025). Prior to screening articles, a consistency check was performed by three reviewers at each stage on a subset of articles (title/abstract: 30% subset of publication database items; full text: 15% subset of publication database items). Any discrepancies were discussed to understand why an inclusion/exclusion decision was made, and changes were made to clarifying the inclusion criteria when necessary. After consistency checking (i.e., when agreement was ≥90%), each article was still independently double-screened by two reviewers at the title/abstract stage, and by a single reviewer only at the full-text screening stage. Articles excluded at full text will be provided in an additional file, along with reason for exclusion in the final systematic map report. Reviewers did not screen articles (at either screening stage) for which they were an author.

Eligible studies for the systematic map then underwent meta-data coding and extraction for key variables of interest, including: (1) bibliographic information; (2) geographical location; (3) salmon information (species, source, life stage); (4) louse and exposure information (species, life stage, net-pen presence); (5) study design and comparator information (comparator type, study design, study period, duration of monitoring); and (6) outcome details (outcome category and subcategory). Further details of the systematic map search strategy, article screening and study eligibility, and data extraction can be found in the Stage 1 registered report (Peiman et al., 2025).

From the mapping exercise, we identified 67 relevant studies (from 52 articles) relating to the primary question of this systematic review "How and to what extent do sea lice affect the performance of juvenile Pacific salmon?" (see Table 2 for the eligibility criteria specific to this sub-question and the focus of this proposed systematic review and quantitative synthesis). Within this question, the outcome subcategories with the highest number of studies related to osmotic function and homeostasis (n = 16), immune function (n = 19), and survival (n = 19); however, all outcome subcategories will be included in the systematic review and synthesized separately.

Table 2. Article inclusion and exclusion criteria.

Included	Excluded
Population	
Wild-caught[1], hatchery-sourced[2], or farmed[3] Pacific salmon of the following five *Oncorhynchus* species: Chinook salmon (*O. tshawytscha*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), sockeye salmon (*O. nerka*), and pink salmon (*O. gorbuscha*) anywhere in the world. Although the focus will be on juvenile Pacific salmon, any life stage of salmon will be included.	Any fish species other than these five Pacific salmon species (e.g., steelhead *O. mykiss,* Atlantic salmon *Salmo salar*) were excluded.
Intervention/exposure	
Exposure of Pacific salmon to any life stage of sea lice (any species in the genus *Lepeophtheirus* or *Caligus*). This includes direct exposure through experimentation or potential exposure of outward-migrating juveniles through areas with net pens and/or to wild lice sources, or exposure of farmed salmon to sea lice.	Copepods in other genera, or other parasitic species. Salmon diseases not related to sea lice (e.g., pancreas diseases, salmonid rickettsial septicaemia, viral hemorrhagic septicemia, infectious haematopoietic necrosis virus, gill diseases).
Comparator	
No exposure to sea lice which could include a control group(s) not directly exposed to sea lice, non-infected salmon collected from the wild, or time periods prior to exposure (before exposure data). Additionally, this will include comparative studies of different levels of exposure (e.g., low versus high infestation; referred to as alternative comparisons) or among species.	No studies will be excluded based on a comparator (or lack thereof).
Outcome	
Measures of change in individual-level performance metrics at any life stage (defined as outcomes that could affect fitness, i.e. the ability of an organism to perform actions that directly or indirectly influence energy gain for growth, survival and reproduction: Peiman & Robinson, 2017). This will include outcomes related to stress response (e.g., glucose, cortisol, heat shock proteins), osmotic function and homeostasis (e.g., osmolality, Na+, haematocrit), immune function (e.g., hypertrophy, macrophage function, immune-related genes), injuries (e.g., visible injuries, tissue damage), growth (e.g., length, mass, condition, specific growth rate), behaviour (e.g., feeding, activity patterns, migration timing/route, swimming ability), survival (number died or consumed by predator), reproduction (e.g., number of eggs laid, estradiol, testosterone), cardio-respiratory (cardiac output, heart rate, critical swimming speed), or surrogates thereof. Outcomes will be recorded as binary (e.g., presence/absence of skin injuries) or continuous data (e.g., growth rate), as reported in the study.	Studies only considering changes in population-level metrics (e.g., abundance, survival, escapement, productivity), sea lice infestation (number of lice on salmon; e.g. lice prevalence, abundance, intensity), evaluations of particular methodologies (e.g., eDNA) to assess sea lice infestation pressure or effects of environmental factors on sea lice (e.g., salinity, temperature, currents) will be excluded.

Table 2 continued.

Included	Excluded
Study design	
Experimental (manipulated exposure) or observational (natural exposure) studies occurring in the field and/or laboratory. Studies that used a randomized or non-randomized control trial (R)CT, control/impact (CI) or a gradient of exposure with a no-lice control group, before/after (BA), before/after/control/impact (BACI), after only without before time periods, cross-sectional studies that assess the characteristics of a group at a single point in time, comparisons of different levels of exposure (e.g., low versus high infestation; alternative comparisons) or species comparisons that compare the difference in outcome(s) among species of salmon. Also, relevant modelling (theoretical) studies (i.e., individual-based models, simulated scenarios exploring model dynamics; no parameter estimation).	Review or expert opinion papers that do not contain new data or analyses, and policy discussions.
Language	
English and French at full text.	Any study that is not in English or French at full text.

[1] Salmon collected in the wild, including wild salmon that have spent their entire life cycle in the wild and originate from parents that were also produced by natural spawning and continuously lived in the wild, first-generation wild salmon, salmon that originate directly from managed spawning channels (enhanced salmon), salmon that originate from other enhancement activities, such as habitat restoration, or unmarked hatchery-raised salmon; [2] Salmon taken directly from a hatchery (i.e., they are hatched from eggs that are fertilized in captivity and raised in captivity) or hatchery-marked salmon caught in the wild; [3] Salmon raised (or still in the hatchery with the intent of being farmed) and managed in controlled net-pen salmon farms (traditional flow-through containment systems) for aquaculture purposes (food); also referred to as commercial hatcheries.

Study validity assessment

Articles found to be relevant to this review (n=52) will then undergo a study validity assessment. This critical appraisal will be carried out on a study-by-study basis rather than article-by-article; meaning if a single article reported more than one experiment/observation, these will be regarded as separate studies. For example, if a single article used different designs/experimental setups (e.g., described a case study using an RCT), separate study validity assessments will be recorded. The focus of the assessment will be on the internal study validity (i.e., reliability/susceptibility of each study to bias). External validity (study generalizability) will be captured with a series of external validity questions described further below.

Data will be extracted from each relevant study in a detailed and transparent manner and entered in a MS-Excel worksheet. The information from the assessments will be used to describe studies in the narrative synthesis for both internal and external validity, and in sensitivity analyses during the quantitative synthesis (if performed, and only in relation to internal validity). Critical appraisal will be done independently by at least two reviewers, with a comparison of assessments at the end to discuss any discrepancies. Final decisions regarding uncertain cases will be taken by the review team as a whole. No studies will be excluded from the systematic review based on validity assessment; however, a sensitivity analysis will be carried out to investigate the influence of internal validity categories in the quantitative analysis when the evidence-base allows. Reviewers will not assess studies for risk of bias for which they are an author.

Critical appraisal will incorporate FEAT (focused, extensive, applied and transparent) principles as recommended by Frampton et al. (2022) and the recommendation guidelines from the CEE (2022). A critical appraisal tool was initially developed by modifying the Critical Appraisal Tool version 0.3 (prototype) (CEE, 2022; Konno et al., 2021). This tool was further refined in consultation with the Advisory Team and participants at the Phase 2A CSAS meeting (held in November 2025) to ensure that it accurately identified and reflected the risks of bias for this topic/evidence base. A draft of the critical appraisal tool can be found in Supporting Information 3.

For internal validity, studies will be classified on three levels of overall risk of bias: low risk of bias, medium risk of bias, or high risk of bias. To meet these criteria, articles will be assessed on up to eight criteria (in addition to a pre-filter question – described below) depending on the study design used, including: (1) risk of confounding biases prior to the exposure (i.e., baseline imbalances due to the selection of fish or sites in studies before exposure to sea lice) (all study designs), (2) risk of post-exposure selection biases (i.e., non-random or non-systematic sampling) (all study designs), (3) risk of misclassified comparison biases (i.e., lacking well defined exposure and comparators) (observational studies only), (4) risk of performance bias (i.e., deviations from the intended exposure) (experimental studies only), (5) risk of detection biases (i.e., use of an inappropriate outcome for the intended assessment of causal effect) (all study designs), (6) risk of outcome reporting bias (i.e., missing data) (all study designs), (7) risk of outcome assessment bias (i.e., inappropriate statistical methods) (all study designs) and (8) risk of 'other' performance biases post-exposure (i.e., deviations from the original study design/setup during the study investigation period) (experimental studies only). Prior to assessing criteria 1 to 8, articles will be assessed on a pre-filter question (i.e., Does the study use a comparative study design?), with comparative studies moving forward for further assessment, and non-comparative studies (e.g., time series without before exposure data [after-only], species comparisons, theoretical studies) being assessed as having high risk of bias without requiring further assessment. Questions within each criterion will be answered as “Yes”, “No”, “Unclear” or “Not applicable”, and the combined influence of these questions will be used to determine if each criterion has high, medium or low risk of bias. To determine the overall risk of bias (internal validity), if any of the criteria for a given study design type are identified as having a high risk of bias, the overall risk of bias for the study will be *high*. If no criteria are at high risk of bias, but at least one criterion is identified as having medium risk of bias, the overall risk of bias for the study will be *medium*. Studies with *low* risk of bias will therefore have no criteria with high or medium risk of bias (Konno et al., 2021).

External validity will be assessed separately from internal validity using three study generalizability questions with interest in applying the results of studies representative of the effects of sea lice on wild juvenile Pacific salmon: (1) Are the subjects (fish population) representative of the wild population?; (2) Does exposure to sea lice occur in the wild (field-study)?; and (3) Are the subjects (fish population) juvenile salmon? Three answer categories will be used to define external validity for the four questions: *green (high external validity), orange (medium external validity or red (low external validity).* The information from this external validity assessment will be used to describe all studies in the narrative synthesis only (i.e., regardless of internal validity), and as such, no studies will be excluded from the systematic review based on the external validity assessment.

Data coding and extraction strategy

Building off the coded and extracted information from the mapping exercise, performance studies that used a comparative study design (i.e., includes a no lice treatment control group [(R)CT, CI, BA] or an alternative comparison group e.g., low lice-infestation) will undergo quantitative data extraction and further data coding for quantitative synthesis. This information will be used in meta-analysis to address our primary and secondary questions. Some outcome data that will be recorded include sample size (used by authors for reported outcome means or from review team calculations using raw data), outcome means (e.g., mean survival of a species for the exposure and comparator groups) and measures of variability (e.g., standard deviation, standard error, confidence intervals of outcome means). When information is present in tables or graphs, all information will be extracted; if it is not possible to interpret the information from graphs, the corresponding author will be contacted (via email) if time permits, or imaging software (i.e., WebPlotDigitizer, Rohatgi, 2024) will be used. When only raw data are included in the article, the Review Team will calculate summary statistics and will record how the calculations were conducted and what information was used.

Additional information will also be extracted or coded, including: (1) the initial exposure level of sea lice treatment i.e., number (or mean) of lice applied at time zero, lice:fish ratio, or lice per gram (for direct exposure studies), (2) the developmental stage of louse at time of initial exposure for direct exposure studies (or at time of collection for naturally infected fish, if applicable), (3) date/time of size measure for fish, (4) number of fish per tank/experimental enclosure, (5) number of tanks/experimental enclosure for each group, (6) salinity (dissolved salt concentration in parts per thousand (PPT), (7) effect modifiers (see Table 3 below), and (8) study validity assessment results.

All the above extracted data will be recorded and combined with the extracted information from the mapping exercise in an MS-Excel spreadsheet and made publicly available with the final published (open-access) report. Reviewers will not extract data from studies for which they are an author. At the beginning of the data extraction process, two reviewers will independently extract information from a subset of articles (n=8 articles). To ensure that data are extracted in a consistent and repeatable manner, extractions will be compared, and any inconsistencies will be discussed. If any disagreements occur, the entire Review Team will discuss them to reach consensus. Modifications will be made to the extraction form where needed to ensure that reviewers extract data and interpret studies in the same manner. Following this consistency check process, each remaining article will be extracted by a single reviewer; however, extracted information will be cross-checked by second reviewer (i.e., second person will be aware of first person's extractions) and any differences will be resolved through discussion Attempts will be made to avoid double-counting results by identifying situations where a single investigation is described in multiple documents (e.g., the findings of a report later published as a peer-reviewed journal article, annual update reports of the same monitoring project, or data from a single project re-analysed in multiple journal articles).

Potential effect modifiers and reasons for heterogeneity

Potential reasons for heterogeneity will be identified to obtain a better understanding of the factors that are associated with variation in effects among studies. The review team will extract data on potential effect modifiers from articles using author-reported information or specific external sources. Effect modifiers were selected after consultation with the Advisory Team and CSAS participants (Table 3). Additional effect modifiers may be identified and extracted from studies as the review proceeds. Additions will be included with Advisory Team and CSAS participants consultation.

Data synthesis and presentation

A narrative synthesis of all eligible articles in the systematic review will be generated. The synthesis will aim to be as visual as possible, describing the validity of the results and summarizing findings in figures and tables. The goal of this review is to determine how and to what extent sea lice affect the performance of juvenile Pacific salmon (primary question) and, as such, we will aim to conduct quantitative synthesis. Separate analyses will be conducted for each outcome subcategory (e.g., stress response, immune function, survival) in response to natural or experimental sea lice exposure, to investigate whether lice-infections have a consistent overall effect on each performance metric type (by comparison of mean responses of infected and uninfected/baseline exposure groups). Note, we are only assessing whether sea lice had a measurable effect on performance, not whether the study also linked the performance metric to an adverse fitness-level effect on salmon. In the case that meta-analyses are possible (given sufficient sample size of studies), study effect sizes will be standardized (i.e., standardized mean difference) and weighted appropriately. When there are sufficient sample sizes and variation, we will combine Pacific salmon and sea lice species together in random-effect models (most likely using multi-level meta-analytic models to handle non-independence among effect sizes) and explore heterogeneity among species (salmon and/or sea lice) with meta-regression. Risk of publication bias will be assessed through funnel plots and fail-safe numbers, supplemented with multi-level meta-regression approaches to test the small-study effect for dependent effect sizes

(Nakagawa et al., 2022). Further, sensitivity analysis using study validity categories will be carried out when possible. We will produce forest plots to visualize effect sizes and 95% confidence intervals from individual studies. To investigate potential reasons for heterogeneity (secondary question a), depending on the availability of the data, meta-regression will also be performed where sufficient studies report common sources of heterogeneity.

To address our secondary question (b) related to identifying thresholds, we will attempt two types of analyses. First, we will attempt, where possible, to explore the quantitative relationship between study effect sizes and sea lice infestation using mixed-effects models that fit linear and non-linear exposure-response curves (i.e., dose-response meta-analysis or DRMA models). We will model each outcome subgroup separately for outcome metrics that are continuous (and where possible, for each species of salmon and/or sea lice separately, and accounting for fish size), and estimate the 'dose-response threshold' as the exposure level at which the upper bound of the 95% confidence interval of a DRMA regression does not overlap with the line of no effect (i.e., no difference between exposure and comparator groups). This threshold will identify the minimum exposure that produces a statistically significant difference between exposure and comparator groups (see Figure 2A for a hypothetical depiction). Similar dose-response analyses will be attempted for binary metrics where possible and appropriate. All analyses will be conducted in R (R Core Team, 2023) using the *rma.mv* function in the 'metafor' package (Viechtbauer, 2010).

To supplement the above quantitative approach, we will use a secondary approach to identify a threshold of lice-induced effects on Pacific salmon, following methods described by Ives et al. (2023). To determine the lowest level of lice (T1) at which substantial systemic sub-lethal impacts are observed, we will examine studies for the threshold below which only minor lesions or cellular damage occurs (i.e., limited to the area around the louse feeding site and superficial in nature) versus above which whole-body responses that impact the welfare and physical condition of the host (e.g., physiological effects such as cardiac output; considering all outcome subcategories together) are detectable. This definition is independent of the response magnitude (i.e., the effect of sea lice may reduce a salmon's performance, but the reduction may not be measurable e.g., presence/absence of skin injuries). To identify T1, each relevant comparison from a given study (i.e., a single study could report more than one relevant comparison, e.g., different performance metrics within the same or different outcome subgroups) will be coded for the presence or absence of a detected effect by comparing exposure and comparator groups. Specifically, if the original study detected a statistically significant change in performance of the exposure group as compared to the comparator group, then the investigated comparison would be coded as a '1' (presence of a detected effect); otherwise, the comparison would be coded as a '0' (absence of a detected effect) if the exposure group was not significantly different from the comparator group. This information will then be summarized to visualize the range of sea lice infestation and to identify T1 (where possible, for each species of salmon and/or sea lice separately and accounting for fish size) (see Figure 2B for a hypothetical depiction). In doing so, this will allow us to use more of the data (i.e., it is not restricted to separate outcome subcategories or only those with sufficient sample sizes for quantitative synthesis); however, it is a less robust approach, similar to vote counting, since it is not based on quantitative effect sizes and ignores the uncertainty around the effect estimate (Bushman & Wang, 2009; Koricheva & Gurevitch, 2013). As such, we will only use this T1 threshold approach to supplement the more robust exposure-response curves described above, and to compare findings with Ives et al. (2023).

Table 3. Sources of potential heterogeneity extracted from eligible studies.

Predictor variable	Description	Predictions
Lice		
Species	*Caligus clemensi, Caligus rogercresseyi*, or *Lepeophtheirus salmonis*	Exploratory (no prediction).
Life stage	Copepodid, chalimus, preadult, adult	Lice in later life stages are more damaging for fish (Jakob et al., 2013). Therefore, average sea lice effects will be greater for salmon exposed to preadult/adult sea lice life stages than for salmon exposed to copepodid/chalimus stages.
Infestation level	Number of attached lice per gram of salmon body weight	Lice feed on the blood, mucus, and skin of salmon. Therefore, for a given size of salmon, average sea lice effects will be greater for salmon exposed to more lice per gram of fish than for salmon exposed to fewer lice per gram of fish.
Time since infestation	Number of days since the salmon were exposed to the lice	Lice have larger effects the longer they are attached (Finstad et al., 2000). Therefore, average sea lice effects will be greater for salmon exposed to lice for longer periods than for salmon exposed for shorter periods.
Salmon		
Species	*Oncorhynchus tshawytscha* (chinook), *O. kisutch* (coho), *O. keta* (chum), *O. nerka* (sockeye), or *O. gorbuscha* (pink)	Salmon species vary in their innate resistance to salmon lice. Therefore, the average sea lice effects on salmon (ranked smallest to largest effects) will be coho < pink < chinook < chum < sockeye (Braden, 2015; Jones, 2011; Jones et al., 2007)
Age	Juvenile, subadult, adult	Juvenile salmon have a larger surface area to volume ratio than older fish. Therefore, average sea lice effects will be greater for juveniles than for older salmon.

Table 3 continued.

Predictor variable	Description	Predictions
Size	Mass or length	At least for some species (e.g., pink salmon), innate resistance develops as they grow (Sutherland et al., 2011). For example, pink salmon are more susceptible to lice when they are smaller than 0.5g (Sackville et al., 2011). Therefore, for a given species of salmon, average sea lice effects will be larger for smaller fish than for bigger fish.
Source	Wild-caught, hatchery-sourced, farmed	Exploratory (no prediction)
Environmental conditions		
Temperature	Water temperature (°C)	Salmon metabolism and sea lice development are affected by temperature (Godwin et al., 2020; Medcalf et al., 2021). Therefore, average sea lice effects will be greater for salmon exposed to higher temperatures than for salmon exposed to lower temperatures.

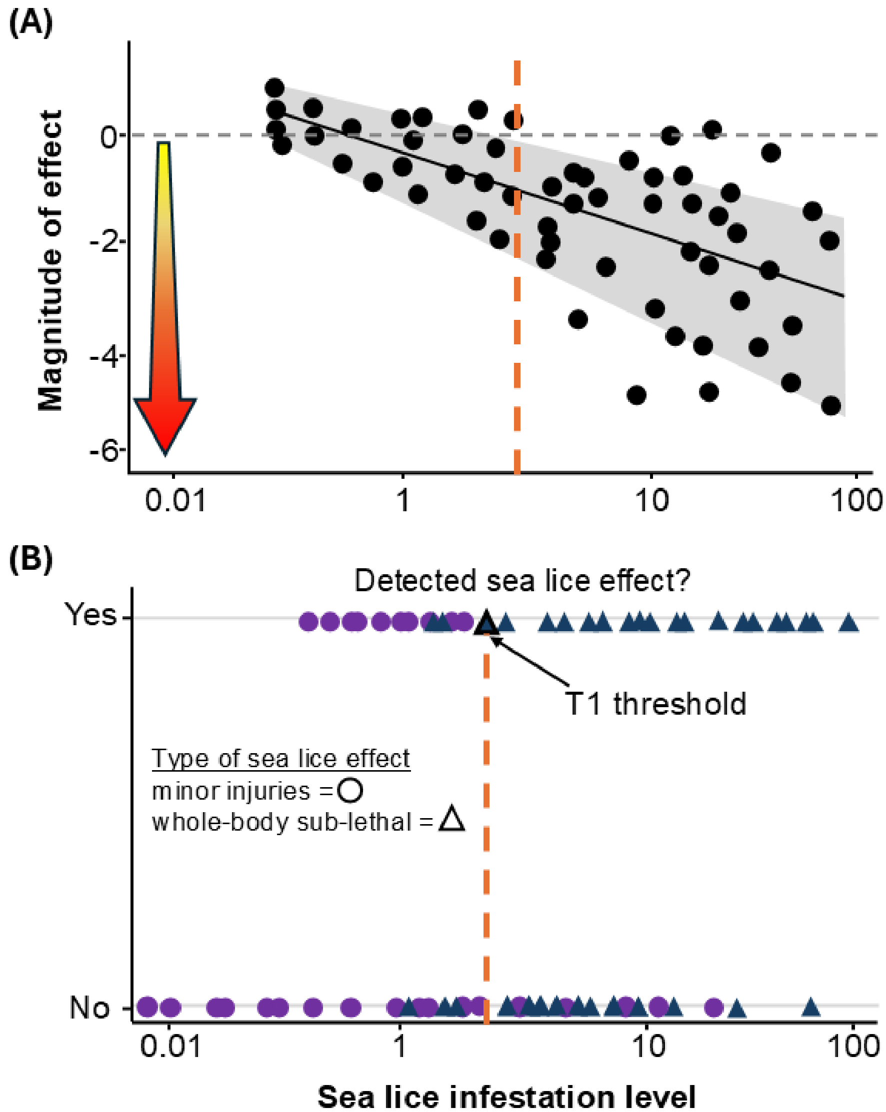

Figure 2. Hypothetical depiction of the meta-analysis and threshold synthesis. (A) analysis of continuous data that characterizes the relationship between sea lice exposure and magnitude of an effect (where zero is the line of no effect indicating no difference between the exposure and comparator group). The orange dashed line represents the dose-response threshold, where the 95% confidence interval (in gray) from a dose-response meta-regression model no longer overlaps with zero. Endpoints will be determined for each outcome subgroup separately. (B) detection of sea lice effects (i.e., 'Yes' line on y-axis) that identifies sea lice exposure threshold, where the orange dashed line represents the lowest level of lice (T1) below which only minor lesions or cellular damage occurs versus above which whole-body sub-lethal responses that are predicted to impact the welfare and physical condition of the host salmon are detectable. Here, endpoints will be determined for all outcome subgroups combined. Where possible and appropriate (A and B) analyses will account for fish size and the developmental stage of louse and be performed for each species of salmon and/or sea lice separately.

Supporting Information

Supporting Information 1. ROSES reporting form for systematic review protocols.

Supporting Information 2. Search strategy and results.

Supporting Information 3. Draft critical appraisal form. Includes a draft of the critical appraisal tool for internal and external study validity assessment.

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Authors' contributions

All authors conceived the ideas and designed methodologies. KSP and TR led the writing of the manuscript. All authors provided comments and revisions. All authors contributed critically to the drafts and gave final approval.

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Competing interests

The authors declare that they have no competing interests.

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