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BRITISH ECOLOGICAL SOCIETY Ecological Solutions and Evidence

REGISTERED REPORT STAGE 1

What are the effects of sea lice on wild and farmed Pacific and Atlantic salmon? A systematic map 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.
2. 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. Fisheries and Oceans Canada Aquaculture Directorate requested a knowledge synthesis on the impact of sea lice from net-pen salmon farms on wild Pacific salmon in British Columbia. To ensure a full understanding of this host–parasite system, we propose to first compile a global inventory of studies investigating the effects of sea lice (in the genera *Lepeophtheirus* or *Caligus*) on wild, enhanced or farmed Pacific salmon (Chinook salmon *Oncorhynchus tshawytscha*, coho salmon *O. kisutch*, chum salmon *O. keta*, sockeye salmon *O. nerka* or pink salmon *O. gorbuscha*) or Atlantic salmon (*Salmo salar*), with any outcome related to adult abundance, reproduction or productivity; outcomes at any life stage related to performance, population-level survival or sea lice infestation levels; measures of species-level differences in susceptibility to lice; or how environmental factors (e.g. salinity, temperature, currents) affect sea lice.
3. This systematic map will capture evidence available in published and grey literature. We will search for and identify relevant literature using bibliographic databases, search engines, specialist websites and databases and networking tools. Eligibility screening will be conducted at two stages: (1) title and abstract and (2) full text. Relevant information from included papers will be coded and entered into a database.
4. *Practical implications*. We will use a narrative synthesis and descriptive statistics to describe key characteristics of the evidence base (e.g. number of publications, focal salmon and lice species, life stage of salmon and lice, study objectives, exposure and comparator details, outcomes and study designs). We will identify knowledge gaps to inform future research needs and subtopics (evidence clusters)

that are sufficiently covered to allow for a full systematic review from visual heat maps.

KEYWORDS
aquaculture, evidence map, evidence synthesis, fish farming, management, policy, salmonid, smolt

1 | INTRODUCTION

Wildlife health, especially as it relates to pest/parasite and pathogen transmission among domestic or farmed animals and wild populations, involves many complex and high-profile cases (Stephen, 2022). This ranges from avian influenza in wild and domestic birds and mammals (Harvey et al., 2023) to bovine tuberculosis threatening endangered bison (Gałązka et al., 2023) and to wild deer as reservoirs of SARS-CoV-2 (Kuchipudi et al., 2022). Similarly, sea lice (copepods in the family Caligidae) can be found on marine aquaculture finfish globally and can be transferred between farmed and wild hosts (Costello, 2009) including species listed under the Endangered Species Act (Rowley, 2000).

One group of fishes affected by sea lice is Pacific salmon (*Oncorhynchus* spp.). This ecologically, culturally and economically important group of species has 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). 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).

Sea lice in the genera *Lepeophtheirus* and *Caligus* occur globally. There are 268 species of *Caligus*, of which the majority are marine, but a few live in brackish or freshwater environments (Tavares-Dias & Oliveira, 2023). *Caligus* spp. have been found parasitizing 368 different teleost fishes, and *C. elongatus* is the most general species, occurring on fish in 19 different families (reviewed in Tavares-Dias & Oliveira, 2023). While *L. salmonis* is generally restricted to salmonids (and so is commonly called the 'salmon louse'), in the Pacific Ocean, three-spined stickleback (*Gasterosteus aculeatus*) can also be hosts (Jones et al., 2006) though lice do not appear to reproduce on them (Pert et al., 2012) and three-spined stickleback consume *L. salmonis* attached to juvenile pink salmon (Losos et al., 2010). This species is generally restricted to shallow coastal habitats, and in one study caused the complete removal of the fins from juvenile pink salmon (*O. gorbuscha*; Parker & Margolis, 1964).

In British Columbia (hereafter BC), *Lepeophtheirus salmonis* and *Caligus clemensi* are the most common naturally occurring ectoparasites on farmed and wild Pacific salmon (Beamish et al., 2009; Saksida et al., 2007). In both *C. clemensi* and *L. salmonis*, the planktonic, free-swimming non-infective nauplii hatch from eggs. The two nauplii stages are planktonic and cannot swim directionally but can adjust their vertical depth. The next copepodid stage is infective and, when it finds a fish host, it moults to the first chalimus stage and becomes parasitic, attaching to a fish using a frontal filament, where it will stay through a second chalimus stage in *L. salmonis* or through to a fourth chalimus stage in *C. clemensi* (Hamre et al., 2013). In both species, the next two pre-adult stages are mobile and can move on the host or swim freely, and combined with the final mature stage, are when the most damage is caused to the fish due to feeding on their skin, mucus and blood. 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). The life cycle takes about 6 weeks at 9°C, and adults can live over 6 months (Heuch et al., 2000). *L. salmonis* can mature at 25 days (male) and 30 days (females) on Atlantic salmon (*Salmo salar*), and 40 and 45 days on Chinook salmon (Johnson, 1993), and each female can produce an average of 152–600 eggs per string from the same batch of sperm depending on temperature and which string is counted (the first two strings are typically more variable), and can produce 10–11 strings from the same batch of sperm (Heuch et al., 2000; Johnson & Albright, 1991; Samsing et al., 2016; Stucchi et al., 2011; Ugelvik et al., 2017). *L. 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). There is little data specifically on *L. s. oncorhynchi* fecundity (Brooker et al., 2018); most of the above information refers to *L. s. salmonis* (though Stucchi et al., 2011 recorded a range of 150–500 eggs per string from *L. s. oncorhynchi*). Additionally, there is little data on *C. clemensi*, except that it produces fewer eggs per string (<200) than *L. salmonis* (Johnson & Jones, 2015).

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 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' (https://www.pac.dfo-mpo.gc.ca/aquaculture/reporting-rapports/lice-ab-pou/index-eng.html; Fish Health Program, 2003–2005). 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 mucosal and skin layers 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, political and conservation outcomes; resulting in reduced profits, impacting the welfare of farmed fish and may have negative effects on wild Pacific salmon (Abolofia et al., 2017; Costello, 2009; Liu et al., 2011).

This system is not unique in its complexity, as other wildlife-domestic host–parasite systems have similar challenges. Here, one must consider the dynamics of lice-host transmission, sublethal effects, the variable hydrology and chemistry of coastal waters, the presence of two lice species and a lice species with multiple salmonid and non-salmonid host species that have different susceptibility, migration pathways and life cycles. These complexities are especially relevant when trying to establish causation between the survival of freely migrating juveniles that interact with other wild juvenile and adult salmonids and other host species, and lice from net pens (Arbeider et al., 2023; 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). The main challenge is establishing that the exposure of juveniles to net-pen-origin sea lice is the only thing that differs among populations and thus affects adult returns. Care must be taken in this comparison, as populations can differ in ways that are not related to whether they travel past net-pen farms (e.g. life history, migration routes, timing of migration, size at migration; Beacham et al., 2014; Freshwater et al., 2019). One key question is whether the mortality of lice-affected juveniles is over and above 'normal' levels of mortality (Hedger et al., 2021; Krkošek et al., 2011).

To our knowledge, there has been no comprehensive summary of the evidence base for the effects of sea lice on wild (as defined in DFO, 2005), enhanced and farmed Pacific salmon. To ensure a full understanding of the ecology of this host–parasite farmed-wildlife system, we propose to document and describe the global information on sea lice infestations in Pacific and Atlantic salmon. This broad scope of inclusion will address the primary request of Fisheries and Oceans Canada (i.e. examining the effects of sea lice on wild Pacific salmon in BC; see *Identification of review topic* below) while also ensuring that we can learn from other systems that have experienced similar issues (i.e. Pacific and Atlantic salmon globally). We will use a systematic map[1] approach, adopting best practices from the Collaboration for Environmental Evidence (Collaboration for Environmental Evidence (CEE), 2022) to collate and describe the available evidence evaluating the relationship between wild, enhanced and farmed Pacific salmon (i.e. Chinook salmon *O. tshawytscha*, coho salmon *O. kisutch*, chum salmon *O. keta*, sockeye salmon *O. nerka* or pink salmon *O. gorbuscha*) and Atlantic salmon (*Salmo salar*) globally and sea lice (in the genera *Lepeophtheirus* or *Caligus*).

To help make future evidence-informed decisions, we will identify evidence clusters (subsets of evidence investigating a similar topic within the broader primary question that may be suitable for a full systematic review[2]) and knowledge gaps (topics where research is lacking). Systematic maps can also provide transparent and objective identification of evidence where topics are controversial or high profile (Haddaway & Pullin, 2014), as in the case here with the effects of sea lice on salmon.

1.1 | Identification of review topic and interest-holder engagement

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 collaborating with the Canadian Centre for Evidence-Informed Conservation (CEIC; formerly Centre for Evidence-Based Conservation) to address this need in part by generating a state of knowledge paper on the topic. Before undertaking a comprehensive and quantitative synthesis, we propose a systematic map approach to first accurately describe the evidence base for this topic and identify evidence clusters and knowledge gaps, with the goal to later conduct a systematic review on one or more evidence clusters identified from this mapping approach. This process (i.e. systematic map leading to the end goal of producing a systematic review) will be carried out in phases, each with their own CSAS

[1] A systematic map is an approach that systematically and transparently collects and describes the abundance and distribution of research effort (e.g. research papers), and identifies groups of information (evidence clusters) and knowledge gaps. Although the process is similar to a systematic review, systematic maps do not aim to provide an answer to a particular question, but instead, a summary of the available research (Haddaway et al., 2016; James et al., 2016).

[2] A systematic review is a highly structured form of evidence synthesis where the goal is to answer a specific question as precisely as possible in an unbiased way, ideally including a quantitative synthesis if possible and appropriate. The process includes collating and describing all relevant evidence in a narrative synthesis, which involves the critical appraisal of the included evidence (CEE, 2022; Pullin et al., 2016).

meeting (see Terms of Reference, available at: https://www.dfo-mpo.gc.ca/csas-sccs/Schedule-Horraire/2024/792-eng.html). This research will leverage previous efforts by CEIC for the North Atlantic Salmon Conservation Organization (NASCO), in collaboration with other review and topic experts, on a recent systematic review on the impacts of sea lice in the North Atlantic on wild Atlantic salmon (see Rytwinski et al., 2024).

Evidence synthesis experts from CEIC established and consulted with an Advisory Team 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) to lay out the project plan. The Advisory Team, as well as DFO science advisors and researchers, provided suggestions on where to search for relevant data (especially grey literature), generation of the benchmark list, development of the eligibility criteria for article screening and the data coding strategy. The Advisory Team will continue to engage in the systematic map process. Also, science experts involved in the CSAS process (Phase I held November 26–28, 2024; https://www.isdm-gdsi.gc.ca/csas-sccs/applications/events-evenements/result-eng.asp?year=2024) reviewed and provided input on the project plan, including scope and how to define (a priori) what will constitute an evidence cluster.

2 | OBJECTIVE OF THE PROTOCOL

The objective of this proposed systematic map is to provide a summary of the existing literature base addressing the effects of sea lice on wild, enhanced and farmed Pacific salmon (five species of *Oncorhynchus*) and Atlantic salmon globally. In doing so, we will describe the key characteristics of the available evidence (e.g. number of publications, focal salmon and lice species, life stage of salmon and lice, study objectives, exposure and comparator details, outcomes and study designs) and identify evidence clusters (subsets of evidence that may be suitable for secondary research) and evidence gaps (topics that are underrepresented in the evidence base that require future primary research). As noted above, the primary request by DFO is for scientific research on the effects of sea lice from net-pen salmon farms on wild Pacific salmon in BC, so a further goal of the systematic map will be to indicate whether we can qualitatively or quantitatively assess the effects of sea lice for any identified evidence cluster related to the following Pacific salmon sub-questions of interest: (1) How and to what extent do sea lice affect the performance of juvenile Pacific salmon? (2) Do sea lice (from wild and farmed sources) affect populations of wild Pacific salmon, and if so, to what extent? (3) To what extent do net-pen salmon farms contribute to sea louse loads on wild Pacific salmon? These questions are meant to be read sequentially. Information identified and compiled from Atlantic salmon and other geographic areas for the five focal species of Pacific salmon will be included in the mapping effort but considered supplemental to the primary Pacific salmon evidence base.

2.1 | Primary question

Our primary question is: What are the effects of sea lice on wild and farmed Pacific and Atlantic salmon?

2.2 | Components of the primary question

2.2.1 | Population (subject)

Wild, enhanced 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*) and Atlantic salmon (*Salmo salar*) anywhere in the world.

2.2.2 | Intervention/exposure

Exposure of Pacific or Atlantic salmon to any life stage of sea lice in the genera *Lepeophtheirus* or *Caligus* from Atlantic salmon or Pacific salmon net pens and/or wild sources. This includes direct exposure through experimentation or potential exposure of outward-migrating juveniles through areas with salmon net pens, or exposure of farmed salmon to sea lice.

2.2.3 | Comparator

No exposure to sea lice either between groups of fish in experimental studies, or between sites or over time or to different levels of exposure (e.g. low versus high infestation) for observational studies. However, at this systematic map stage, no studies will be excluded based on the presence or absence of a comparator.

2.2.4 | Outcomes

Measures of change in population status using metrics of adult salmon abundance (e.g. escapement [number of adult recruits minus number removed due to exploitation], abundance, density, CPUE), reproduction (e.g. spawning success, migration success), a recruit-per-spawner index (productivity) or the proportion of adult returns in relation to the number of out-migrating smolts from experimental release studies; measures of change (at any life stage) in (i) individual-level performance metrics (i.e. outcomes that affect fitness: Peiman & Robinson, 2017) related to growth (e.g. length, mass, condition), physiology (e.g. hormones, osmoregulation, immune response), behaviour (e.g. feeding, activity patterns, migration timing/route, swimming ability), histology (e.g. visible injuries, tissue damage), infections, gene expression, predation risk, direct lice-induced mortality (individual survival), (ii) population-level survival or (iii) lice levels (e.g. prevalence, abundance, intensity); measures of species-level differences in susceptibility to

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lice; measures of how environmental factors (e.g. salinity, temperature, currents) affect sea lice; or surrogates thereof.

3 | MATERIALS AND METHODS

The proposed systematic map will follow standards and guidelines from the CEE (2022) and the reporting standards from ROSES (Haddaway et al., 2018) (see Supporting Information 1).

3.1 | Searching for articles

The systematic map will be based on two separate but similar search strategies, both including commercially published and grey literature. First, literature searches targeting Pacific salmon will use standardised search terms across four publication databases, one web-based search engine and 19 specialist websites and databases, as described in more detail below. Second, existing literature searches targeting Atlantic salmon will be leveraged (and updated) from a separate systematic review on the impacts of sea lice in the North Atlantic on wild Atlantic salmon (see Rytwinski et al., 2024; but also described further below). For both search strategies, reference sections of relevant reviews identified from searches will be manually searched to evaluate relevant titles that may not have been found using the search strategies. A call for evidence will be issued to further identify grey literature sources through social media and relevant mailing lists. The Advisory Team and science experts involved in the Phase I CSAS process will also circulate the call for evidence to relevant networks and colleagues.

3.1.1 | Pacific salmon

Search string

A list of potentially relevant English search terms was developed in consultation with the Advisory and Review Teams and broken into two components: the population and the exposure. With this list of search terms, the review team then performed a scoping exercise using Web of Science Core Collections to modify and iteratively refine a set of search strings. The scoping exercise was used to evaluate the sensitivity of the search terms and associated wildcards (Table 1; Supporting Information S2). The comprehensiveness of the search string was then tested using a list of benchmark papers (Supporting Information S2) suggested by the Advisory Team as being relevant for this review.

Searches

Four bibliographic databases (ISI Web of Science Core Collections, Scopus, ProQuest Dissertations & Theses Global and Federal Science Libraries Network) will be searched using Carleton University's institutional subscriptions. No document type, date or language restrictions will be applied during the search. A search in Google Scholar will also be conducted using seven simplified search strings to search for additional published and grey literature (Supporting Information S2). The results of the Google Scholar search (which typically returns tens of thousands of hits) will be sorted by relevance; a reasonably sized subset of results from each of the seven search strings (i.e. either the first 150 or 300 articles based on a scoping exercise of relevance) will be screened.

We will also search websites and portals of organizations and databases relevant to the topic using their built-in search facilities using simplified English search term combinations. For each, the top 30 search results for each simplified search string, sorted by relevance, will be screened for inclusion to ensure the inclusion of a wide range of sources and materials. Where built-in search facilities are not available, we will search the sites 'by hand' (i.e. focusing on any 'Publications' pages and examining site maps where available). The list of websites, online databases and evidence libraries was narrowed to the following in consultation with our Advisory Team:

Websites

1. Fisheries and Oceans Canada (https://www.dfo-mpo.gc.ca/)
2. Pacific Salmon Foundation (https://psf.ca/)
3. Government of Canada (https://publications.gc.ca/site/eng/home.html)
4. Skeena Salmon Data Centre (https://data.skeenasalmon.info/dataset/)
5. Raincoast Research (http://raincoastresearch.org/science-resources/raincoast-studies/)
6. Pacific Salmon Commission (https://www.psc.org/publications/)
7. North Pacific Anadromous Fish Commission (https://www.npafc.org/publications/)
8. North Pacific Marine Science Organization (PICES) (https://meetings.pices.int/publications)
9. Hakai Institute (https://hakai.org/publications/)
10. Salmon Coast Lab (https://salmoncoast.org/research/our-projects/sea-lice-monitoring/)
11. MOWI (https://mowi.com/caw/sustainability/wild-salmonid-lice-monitoring/)
12. Cermaq (https://www.cermaq.ca/public-trust/public-reporting)
13. Cedar Coast Field Station (https://www.cedarcoastfieldstation.org/monitoring-programs/)

TABLE 1 Proposed search string that will be used 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)

Grey literature or pre-print databases

14. AFS Fisheries Grey Literature Database (https://graylitreports.fisheries.org/)
15. bioRxiv (https://www.biorxiv.org/)
16. Open Science Framework (OSF) (https://osf.io/)

Evidence libraries

17. CEE Evidence Synthesis Library (https://environmentalevidence.org/completed-reviews/)
18. Conservation Evidence (www.conservationevidence.com)
19. The CEE Database of Evidence Reviews (CEEDER) (https://environmentalevidence.org/ceeder/)

3.1.2 | Atlantic salmon

The literature searches targeting Atlantic salmon from a separate systematic review effort are fully described in an existing protocol (Rytwinski et al., 2024). For this effort, literature searches were performed in 2023 using three publication databases (ISI Web of Science Core Collections [1451 records identified], Scopus [900 records] and ProQuest Dissertations & Theses Global [1437 records]; searches performed in March 2023) and two search engines (Google Scholar [700 records] and ORIA [293 records]; included articles available up to the end of 2023). English and Norwegian search terms were used to conduct searches (see Table 2). A total of 2784 unique records after duplicate removal were identified from this search strategy.

An updated search will be performed to cover literature published since March 2023 for the three publication databases using Carleton University's institutional subscriptions and since January 01 2024 for Google Scholar. We will also perform a search in the Federal Science Libraries Network database for all years available to align with the search strategy for Pacific salmon. Also, when searching for relevant Pacific salmon literature in the above-mentioned websites and organizational portals/databases, we will screen for inclusion any returned or encountered Atlantic salmon literature. This updated search effort will not only build on and leverage the previous systematic review but also ensure literature relevant to Atlantic salmon in the BC context is captured and included in the mapping exercise.

TABLE 2 Search string used to execute searches for Atlantic salmon literature from Rytwinski et al. (2024), formatted for Web of Science Core Collection.

Component	String
Population	TS=(“Atlantic salmon” OR salmo)
	AND
Exposure	TS=(lepeophtheirus OR “salmon louse” OR “salmon lice” OR “sea louse” OR “sea lice” OR lakselus OR caligus OR skottelus)

3.1.3 | Supplemental searches for Pacific and Atlantic salmon

To supplement the above searches for both Pacific and Atlantic salmon literature, the bibliographies of relevant review articles identified during the search will be hand-searched for any additional relevant articles or datasets that are not already captured by the search strategy. In cases of unpublished references, we will contact authors to request access to the full article. Additionally, a call for evidence targeting grey literature will be circulated using professional networks and association distribution lists (e.g. Canadian Conference for Fisheries Research, American Fisheries Society, Society of Canadian Aquatic Sciences) to solicit articles for inclusion in this synthesis. Furthermore, we will use social media and email to reach out to the community, recognised experts and practitioners for further recommendations and identification of relevant unpublished works. All submissions will be screened using the same strategy (see Section 3.2.1) as literature found in searches.

3.1.4 | Search record databases

A final search record database will be generated for Pacific salmon and for Atlantic salmon separately. These two databases will serve as an archive of all included search results, regardless of relevance. These databases are a direct product of the search strategies and will not be changed during the review process. This means they can be used to update the systematic map archive in the future.

The final search record database for Pacific salmon will be generated from the following steps. First, all articles captured by database and search engine searches will be exported into separate MS-Excel files and saved for backup. Second, all articles found by database searches will then be copied into a single database, where duplicates will be identified and merged. Third, articles from Google Scholar will be kept in a separate database, with duplicates between databases and Google Scholar removed prior to screening.

The final search record database for Atlantic salmon will be generated by following the same steps listed above for the updated literature search results; then those will be combined with the existing deduplicated search records (n=2784 unique records) from the previous systematic review effort.

Note, for both the Pacific and Atlantic salmon databases, further duplicates may be removed at subsequent stages of the review. Here, attempts will be made to avoid double-counting results by identifying situations where a single investigation was 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 documents).

3.2 | Article screening and study eligibility criteria

3.2.1 | Screening process

The two databases containing Pacific and Atlantic salmon articles will be screened separately but following the same screening process. Articles containing relevant information for both Pacific and Atlantic salmon will be captured in both databases. Documents found through databases and search engines will be screened at two stages: (1) title and abstract and (2) full text. Before screening begins, two reviewers using a random subset of 10% or 100 articles (whichever is larger) from database searches will undertake a consistency check. This subset will ensure consistent and repeatable application of the eligibility criteria before articles are moved to the next stage of the review. A comparison of reviewer consistency check results will be performed, with all discrepancies discussed to understand why an inclusion/exclusion decision was made. If necessary, changes will be made to clarify the inclusion criteria. If the level of agreement between reviewers is low (i.e. below 90% agreement), further consistency checking will be performed on an additional set of articles. Following consistency checking (i.e. when agreement is ≥90%), each article will be double-screened by two reviewers at this screening stage. Following title and abstract screening, inclusion/exclusion decisions for each article will be compared between the two reviews and the review team will discuss all discrepancies and come to a decision.

Following title and abstract screening, all articles included will then be screened at full text. We will also perform a consistency check at that stage (using 10% of the articles included at title and abstract) in the same manner as for title and abstract screening. Following consistency checking (i.e. when agreement is ≥90%), each article will be screened by a single reviewer only. Articles or datasets found by other means (e.g. searching bibliographies of relevant reviews, social media) will not be included in consistency checks (under the assumption that the types of articles do not affect consistency) and will enter at the second stage of this screening process (full text). If the reviewer is uncertain whether to include an article at any screening stage, they will tend toward inclusion to the next stage. If there is further doubt, the review team will discuss those articles as a group and come to a decision. If a decision cannot be made by the review team, the query will be brought to the broader Advisory Team for discussion until a decision can be made.

A list of studies excluded at full text will be provided in an additional file, along with the reason for exclusion. Digital media will be screened when they are available online without the need for purchasing the media or having specialised pay-for-use software to view it. The Interlibrary Loans programme at Carleton University and Fisheries and Oceans Canada will be used to obtain hard or digital, full-text copies of articles included at the title and abstract screening stage. Reviewers will not screen articles (at either screening stage) for which they are an author.

3.2.2 | Eligibility criteria

All articles will be screened according to the predefined criteria developed in consultation with the Advisory and Review Teams (Table 3) and will only be included when all criteria are met. Any alteration to criteria made during the review process will be recorded and included in the final report.

3.3 | Study validity assessment

Study validity will not be assessed for this mapping exercise given the broad scope of this topic and the diversity of approaches used to evaluate sea lice effects on salmon. However, meta-data on aspects of study type, design and outcomes will be coded from included studies to provide an overview of the robustness of the evidence. The primary purpose of coding this meta-data is to aid future critical appraisal and more in-depth synthesis of studies for a systematic review(s) on subtopics of interest identified from this systematic map exercise.

3.4 | Data coding strategy

Coding and data extraction will be conducted by the review team following full-text screening. The following main categories of descriptive data will be extracted for all included studies: (1) bibliographic information; (2) study summary and location(s) (e.g. objective(s), country, watersheds for BC studies); (3) study design and comparator details (e.g. comparator type [e.g. comparative, non-comparative, theoretical], study type [e.g. experimental, non-experimental], study design [e.g. [R]CT, BA, CI, BACI, after only], study dates); (4) population details (e.g. focal salmon species, source [wild, enhanced, farmed], life stage); (5) intervention/exposure (e.g. species of parasitic copepod within *Lepeophtheirus* or *Caligus*; life stage; presence/absence of farm(s)); (6) outcome details (e.g. including any outcome measurement related to adult abundance [escapement, abundance, density, CPUE], reproduction [spawning success, migration success], productivity [recruit-per-spawner] or the proportion of adult returns in relation to the number of out migrating smolts from experimental release studies; at any life stage, metrics related to performance [growth, physiology, behaviour, histology, infection, gene expression, predation risk, individual survival], population-level survival or sea lice infestation levels; measures of species-level differences in susceptibility to lice); and measures of how environmental factors affect sea lice (e.g. lice dispersal, survival, reproduction). Depending on the type and variety of included studies, this list may be expanded. Further, coding options within these key variables may also be expanded in a partly iterative process as they are encountered during data coding.

To ensure that data are being extracted in a consistent and repeatable manner, at the beginning of the process, reviewers will

TABLE 3 Article inclusion and exclusion criteria.

Included	Excluded
Population	
Wild, (as defined in DFO, 2005) enhanced or farmed 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*). Wild, enhanced or farmed Atlantic salmon (*Salmo salar*). This is anywhere in the world. Exception: Studies that evaluate environmental factors in relation to sea lice that are not attached to a host (i.e. sea lice are in the water and there is no direct link to any fish species, salmon or otherwise) will also be included at the request of interest holders	Any fish species other than these six species (e.g. steelhead *O. mykiss* will be excluded). Note, during screening, studies that meet all other criteria except they do not mention Pacific or Atlantic salmon by name in the title or abstract, and instead only mention salmon, Salmo or Oncorhynchus, will be moved forward for further consideration at full-text in case they contain relevant information on Pacific or Atlantic salmon
Intervention/exposure	
Exposure of Pacific or Atlantic salmon to any life stage of sea lice (any species in the genus *Lepeophtheirus* or *Caligus*). All life stages of copepods will be considered. This includes direct exposure through experimentation or potential exposure of outward-migrating juveniles through areas with salmon net pens and/or to wild sources. Also, studies that look at environmental (abiotic) effects on sea lice while attached to at least one of the five Pacific salmon species or Atlantic salmon. Exception: Studies that evaluate environmental factors in relation to sea lice that are not attached to a host (i.e. sea lice are in the water and there is no direct link to any fish species, salmon or otherwise) will also be included at the request of interest holders	Copepods or parasitic species in other genera. 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 comparison between (1) groups of fish in experimental studies (e.g. a group of anti-parasitically treated salmon, a control group not exposed to sea lice, a group moved to avoid exposure to sea lice), (2) groups of fish in lab-based studies that are then released into the wild, (3) study sites (control/impact design comparing sites with/without net pens), (4) time (before/after or time-series using time periods with/without net pens). Additionally, this could include comparative studies of different levels of exposure (e.g. low versus high infestation)	No studies will be excluded based on a comparator (or lack thereof)
Outcome	
Measures of change in population status using metrics of adult salmon abundance (e.g. escapement, abundance, density, CPUE), reproduction (spawning success, migration success), a recruit-per-spawner index (productivity) or the proportion of adult returns in relation to the number of out-migrating smolts from experimental release studies Measures of change in individual-level performance metrics at any life stage (defined as outcomes that 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 growth (length, mass, condition), physiology (e.g. hormones, osmoregulation, immune response), behaviour (e.g. feeding, activity patterns, migration timing/route, swimming ability), histology (e.g. visible injuries, tissue damage), infections, gene expression, predation risk and direct lice-induced mortality (individual survival) Measures of population-level survival (any life stage) Measures of the number of lice (any salmon life stage) (prevalence, abundance, intensity) Measures of species-level differences in susceptibility to lice Measure of how environmental factors (e.g. salinity, temperature, currents) affect sea lice while attached to any of the five Pacific salmon species or Atlantic salmon, or while in the water column (e.g. lice dispersal, survival, reproduction)	Studies only evaluating particular methodologies (e.g. eDNA) to assess sea lice infestation pressure, or evaluating environmental factors (e.g. salinity, temperature, currents) with no relation to sea lice
Study design	
Field-based experimental or observational studies or a combination. Purely laboratory experiments or lab experiments with a field component (e.g. exposure to sea lice occurs in a lab but salmon are then released into the field). Studies that used a randomized control trial (RCT) or non-randomized control trial (CT), before/after (BA), before/after/control/impact (BACI), control/impact (CI) or a gradient of exposure, after only without baseline/before time periods, cross-sectional studies that assess the characteristics of a system/group at single point in time, or species comparisons that compare the difference in outcome(s) among species of salmon or sea lice. Also, relevant modelling (theoretical) studies (i.e. individual-based models, population viability analysis, simulated scenarios)	Review or expert opinion papers that do not contain new data or analyses, and policy discussions
Language	
English and French at full text for Pacific and Atlantic salmon	Any study that is not in English or French at full text[a]

[a]Other languages will be considered depending on the feasibility of the translation and depending on the potential relevance of information located during searches.

extract information from a random subset of articles included at full text. Coded information will be compared among reviewers, and any inconsistencies will be discussed with the review team. Modifications to the codebook will be made where needed to ensure reviewers are extracting the appropriate information in the same manner.

3.5 | Study mapping and presentation

A separate narrative synthesis and a coded database (MS-Excel) of all eligible articles in the systematic map will be generated for Pacific salmon and for Atlantic salmon. Descriptive statistics will be used to describe the overall amount (e.g. number of articles, number of studies) and key characteristics (e.g. focal salmon and lice species, life stage of salmon and lice, study objectives, exposure and comparator details, outcomes and study designs) of evidence available. Our narrative synthesis will summarise information in tables and figures.

Knowledge gaps and clusters will be identified using visual heat maps. Noted previously by Hernández Martínez de la Riva et al. (2023), there are currently no standards or guidelines for setting quantitative thresholds to identify knowledge clusters and gaps, leaving threshold definitions to the discretion of the review teams (see Supporting Information S3). Therefore, at the Phase I CSAS meeting, a threshold for an evidence cluster was discussed and defined for this process. For this systematic map, studies of wild Atlantic salmon and each of the five wild Pacific salmon species will initially be mapped separately, with one set of maps for effects of the sea lice genera *Lepeophtheirus* and one set for the lice genera *Caligus*. Separate maps will also be initially created for the effects of these two lice genera on farmed salmon. An evidence cluster will be defined as a group of at least 25 similar cases but could be as low as three cases. If few evidence clusters emerge with more than three cases, species will be grouped further. Evidence clusters that include Atlantic salmon and other sea lice species will be weighted differently than those that include the main species of interest (the five wild Pacific salmon species, and the lice species *Caligus clemensi* and *Lepeophtheirus salmonis*). Given the primary request by DFO is to examine the effects of sea lice on wild Pacific salmon, the Atlantic salmon evidence is meant to support a future deeper synthesis for Pacific salmon.

4 | DISCUSSION

The goal of this systematic map is to identify, collate and describe the information that exists on the effects of sea lice from net-pen salmon farms on wild, enhanced or farmed Pacific and Atlantic salmon globally. Understanding what type of evaluations have been performed, for which salmon species and study settings, the study designs used and what outcome metrics are commonly reported in the literature will help guide further exploration and analysis on this topic. In particular, the proposed systemic map will be used to determine whether there is sufficient evidence to further investigate possible effects of sea lice from net-pen salmon farms on wild Pacific salmon (i.e. identified evidence clusters), as well as to inform management and direct future studies to fill identified knowledge gaps.

AUTHOR CONTRIBUTIONS

All authors conceived the ideas and designed methodologies. Kathryn S. Peiman and Trina Rytwinski 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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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

This article does not contain data. Once the study (i.e. systematic map) is complete, a publicly accessible online version of the systematic map and a queryable database will also be developed.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Supporting Information S1. ROSES for Systematic Map Protocols. Version 1.0.

Supporting Information S2. Search string scoping exercises.

Supporting Information S3. Considerations for defining an evidence cluster.

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