The state of evidence on salmon farming: an umbrella review

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Abstract

Background:
The global expansion of salmon aquaculture has transformed marine food systems, offering economic benefits while amplifying environmental and socio-economic challenges. The shift from wild-caught to farmed salmon has led to widespread concerns, including disease transmission, genetic introgression, pollution, and conflicts with Indigenous communities. Additionally, salmon feed supply chains have global implications, such as overfishing in West Africa. Although many studies exist, research is fragmented and dispersed across disciplines, and the influence of industry funding raises questions about bias. This umbrella review synthesises existing systematic reviews on salmon farming to evaluate the scope, quality, and findings of the secondary literature on its environmental, economic, and social impacts.
Methods:
This review follows guidelines from the Collaboration for Environmental Evidence (CEE) and the ROSES reporting standards. Systematic reviews were identified via searches in Scopus, Web of Science, and Lens.org using a structured, validated search strategy. Inclusion criteria focused on reviews explicitly targeting Atlantic or Pacific salmon aquaculture (including rainbow trout). Metadata were extracted on study methods, topical focus, production stages, and funding sources. Review quality was assessed using the CEESAT critical appraisal tool, and visualisations were produced to identify gaps in coverage and assess methodological rigour.
Results:
Out of 327 unique records, 37 reviews were included. Most reviews focused on production-related topics (e.g. fish health, sea lice, feed supply), with very few addressing environmental or social impacts. No reviews met the threshold for high methodological rigour, and only four were rated as moderate quality; the remainder were judged as low or exceptionally low quality. Common weaknesses included absence of a priori protocols, lack of critical appraisal, poor reporting of screening and extraction methods, and inappropriate synthesis techniques such as vote counting. Industry co-authorship was present in 7 reviews, and 8 were industry-funded. Research on sustainability was hindered by methodological inconsistency and limited transparency.
Conclusions:
Despite a growing body of literature on salmon aquaculture, high-quality evidence syntheses remain rare. Most systematic reviews are methodologically flawed and overly focused on productivity, with limited assessment of environmental or socio-economic externalities. Greater attention is urgently needed to unbiased, interdisciplinary, and high-quality evidence synthesis - especially on the broader impacts of salmon farming. We call for enhanced rigour in review methods, transparent reporting, and increased scrutiny of industry influence on research agendas.

Keywords

Salmon farming, mariculture, aquaculture, systematic reviews, salmo, salmonid, oncorhyncus

Background

The global expansion of salmon aquaculture has reshaped marine food systems, creating economic opportunities while also raising significant environmental and socio-economic concerns. Historically, wild salmon fisheries sustained Indigenous communities, supported commercial and recreational fishing, and played a vital role in regional food security (Mills 1991; Lackey et al. 2006). However, due to declining wild populations—both Atlantic salmon (Dadswell et al. 2022) and Pacific salmon (Nehlsen et al. 1991; Lackey 2003)—and the increasing commercial viability of aquaculture, salmon farming has emerged as a dominant force within the seafood sector. Today, Atlantic salmon dominate global aquaculture production, with Norway, Chile, Canada, and Scotland leading production efforts (Naylor et al. 2003; Paisley et al. 2010; Lien 2015). Notably, salmon farming now occurs on every continent except Africa (Asche and Bjorndal 2011).

Industry Growth and Economic Contributions

Salmon aquaculture has expanded rapidly since the 1980s, driven by technological advancements, shifting market dynamics, and the increasing global demand for fish protein (Leitritz and Lewis 1980; Pennell and Barton 1996). Norway's salmon exports, valued at 17.7 billion USD in 2022, illustrate the industry's significance (ResourceTrade.earth 2024). Chile, despite lacking native salmon populations, has become a key global producer, exceeding one million tonnes of production in 2020 (Bjorndal and Aarland 1999; SNP 2020). While proponents argue that farmed salmon contributes to food security (Asche and Bjorndal 2011), critics highlight its primary consumption as a luxury product in wealthier nations, questioning its role in addressing global protein needs (Belton et al. 2020).

Environmental and Ecological Concerns

The intensification of salmon farming has spurred widespread environmental concerns. Key issues include disease transmission to wild populations (Hindar et al. 2006; Quiñones et al. 2019), high mortality rates linked to parasites and environmental stressors (Aaunsmo et al. 2008; Overton et al. 2019; Oliveira et al. 2021), and habitat degradation caused by nutrient pollution (Bloecher et al. 2024). Additionally, escapes of farmed salmon threaten the genetic integrity of wild stocks (Bradbury et al. 2020), while antibiotic overuse raises concerns about antimicrobial resistance (Lozano-Munoz et al. 2021). Further downstream impacts stem from feed supply chains, including the depletion of West African fisheries for fishmeal and fish oil (Feedback 2024) and the deforestation associated with soy production for feed (Anmarkrud 2023).

Climate Change and Sustainability Challenges

Climate change presents a growing challenge to salmon aquaculture. Rising ocean temperatures exacerbate disease susceptibility (Calado et al. 2021) and disrupt production through extreme

weather events, increasing infrastructure vulnerability and plastic pollution (Global Ghost Gear Initiative 2021; Falconer et al. 2022). Ocean acidification further threatens the industry by altering salmon physiology and food web dynamics (Pernet and Browman 2021). While industry stakeholders seek adaptive strategies, the long-term sustainability of salmon farming remains a contentious issue, with evidence suggesting failures in environmental and welfare certification schemes (Environment+Energy Leader 2024).

Social and Regulatory Dimensions

Beyond environmental concerns, salmon farming has profound socio-economic implications. Conflicts with Indigenous and artisanal fishing communities continue to escalate (Hiedanpää et al. 2020; Randin 2024), while opposition to farm expansion grows due to concerns over noise, odour, and ecosystem impacts (Karlsen et al. 2015; Weitzman et al. 2022). Occupational hazards within the industry have also drawn scrutiny, particularly following recent worker fatalities (BBC 2024). Regulatory frameworks vary by region, with certification schemes such as the Aquaculture Stewardship Council (ASC) and the Marine Stewardship Council (MSC) aiming to ensure sustainability (Rector et al. 2023). However, concerns persist regarding industry influence over regulatory bodies and certification processes (DeSmog 2024).

Industry Transparency and Public Accountability

The salmon industry's approach to scrutiny has raised critical questions about transparency and accountability. Journalists and activists investigating environmental and welfare issues frequently face legal challenges and restricted access, as exemplified by cases involving Don Staniford (Salmon Business 2024). Investigations have uncovered falsified records relating to animal welfare and environmental standards (Fish Farming Expert 2019; WeAreAquaculture 2023), underscoring the need for independent oversight.

The Role of Research: Identifying Biases and Knowledge Gaps

Academic research on salmon farming is extensive yet often fragmented and dispersed across disciplines, limiting holistic understanding. Funding from industry stakeholders poses a risk of bias, shaping research agendas and outcomes in ways that may favour commercial interests. Preliminary analysis indicates that 7.4% of funding statements in a Lens.org search explicitly reference industry funding, though 90% lack indexed funding disclosures. This highlights the necessity of synthesising independent research to provide a balanced assessment of the environmental, economic, and social ramifications of salmon farming.

Rationale for an Umbrella Review and Stakeholder Engagement

Despite the breadth of literature on salmon farming, there remains a lack of comprehensive synthesis. Existing reviews often focus on narrow geographical regions (e.g., Quiñones et al. 2019) or adopt narrative rather than systematic approaches (e.g., Chávez et al. 2019). An umbrella review consolidating systematic reviews across multiple domains is needed to bridge these gaps, map research effort across economic, environmental, and social dimensions, and inform evidence-based policy and practice. This review aims to provide an integrated perspective on salmon farming's sustainability, highlighting areas requiring further investigation and independent scrutiny.

Key informant interviews were conducted during question formulation with individuals and groups involved in salmon farming research and activism, aiming to ensure shared definitions of the species included. As a largely academic exercise focusing purely on academic literature, further stakeholder engagement was deemed unnecessary.

Objectives

The aim of this review was to assess the body of secondary research focusing on salmon (Atlantic and Pacific) farming, understanding the topics covered and quality of the syntheses.

Primary question: What is the nature of the academic evidence base on salmon farming in the form of systematic reviews?

The review has the following key components:

Population: Global aquaculture (excluding hatchery-reared fish for release in sports fishing or population enhancement)

Phenomenon: Atlantic and Pacific salmon (including rainbow trout, see details in inclusion criteria below) as a core focus, excluding studies where relevant salmon species are just one of a number of other species incidentally reported within the abstract.

Study type: Systematic reviews published in academic journals

Methods

This overview has been conducted according to an *a priori* published protocol (Haddaway et al. 2025), and following the general guidance for evidence reviews outlined by the Collaboration for Environmental Evidence (CEE 2022). The review is reported according to the ROSES reporting standards for evidence syntheses (Haddaway et al. 2018). There have been no deviations from the protocol.

Searching

Bibliographic database searching

We searched for systematic reviews across three bibliographic resources, Web of Science (including Core Collections (1900-2025), Current Contents Connect (1998-2025), Derwent Innovations Index (1980-2009), Grants Index (1953-2025), KCI-Korean Journals Database (1980-2025), MEDLINE (1950-2025), ProQuest Dissertations & Theses (1637-2025), and SciELO (2002-2025), searched on 16/02/2025), Lens.org and Scopus (both searched on 18/02/2025). We used the search string outlined in Table 1 and Additional File 1. Since we are focusing on academic research literature, we have searched only in English.

Table 1. Bibliographic database search strings.

Substring	String terms
#1	title/abstract/keywords: (salmon OR salmo OR oncorhynchus OR salmonid OR trout OR salmonid OR salmoniformes)
#2	title/abstract/keywords: (aquaculture OR mariculture OR *cultur* OR farm* OR rearing)
#3	title/abstract/keywords: ("scoping review" OR "literature review" OR "systematic review" OR "systematic map" OR "systematic mapping" OR "systematically review" OR "systematically reviewed" OR "review of the literature" OR "evidence review" OR "review of the evidence" OR "rapid evidence assessment" OR "rapid review" OR "evidence synthesis" OR "systematic literature" OR "review of the literature")
#4	title: (salmon OR salmo OR oncorhynchus OR salmonid OR trout OR salmonid OR salmoniformes) AND (aquaculture OR mariculture OR *cultur* OR farm* OR rearing) AND (“a review”)
#5	(#1 AND #2 AND #3) OR #4

Search results were exported and combined, before being deduplicated first in EndNote using the method outlined by Bramer et al. (2016) and then in the web application Rayyan.ai. During deduplication in EndNote, clearly irrelevant titles that are not research articles (e.g. reference lists or book reviews) were removed prior to exporting the results to Rayyan. The subsequent unique results were then screened as outlined below.

Testing comprehensiveness

In order to assess the comprehensiveness of our search string we assembled a list of 6 reviews of known relevance, and identified whether our string returned these records, which it did, indicating sufficiency. This benchmark list of articles is provided in the appendix.

Citation chasing

We performed forward (citing articles) and backward (cited articles) citation chasing in Lens.org, based on the final set of included reviews possessing DOIs (n=37/39), yielding 3,439 records from backwards citation chasing and 864 records from forward citation chasing. These results were then filtered by the review terms in line 3 of the search string above to retain only those records that are reviews. The resulting records were deduplicated against the original search results, and the remaining unique records were screened as outlined below.

Search update

Since this review was completed within a short period (searches conducted in February 2025) and the publication rate for the field is very low, we did not plan to conduct a search update.

Screening for eligibility

We screened records at two levels: title and abstract, and full text. We performed an initial consistency check with 50 titles and abstracts, and 5 full texts to ascertain reviewer agreement between two reviewers (NRH and MDLR) and ability to use the inclusion criteria. At title and abstract level, an initial screening of 50 records revealed 7 conflicts, which were resolved immediately on discussion. All excludes from the initial screening (by NRH) were then double checked (by MDLR). This resulted in 11 conflicts, which were then appraised (by NRH) at full text, with no conflicts requiring inclusion. At full text screening, a random subset of 18 articles (10%) were screened blind by both reviewers. A single conflict occurred but was immediately resolved on clarification of the type of review involved (finally excluded). The fates of all screened articles at full text assessment are provided in Additional File 2.

We used the following inclusion criteria:

Population: Aquaculture worldwide

Phenomenon: Atlantic salmon (*Salmo salar*), which forms 90% of farmed salmon across the world, as well as Pacific salmon that includes several species commonly referred to as salmon - i.e. steelhead salmon (*Oncorhynchus mykiss,* including the rainbow trout which is a form that solely resides in freshwater), coho salmon (*Oncorhynchus kisutch*), chinook salmon (*Oncorhynchus tshawytscha*), pink salmon (*Oncorhynchus gorbuscha*), sockeye salmon (*Oncorhynchus nerka*), masu salmon (*Oncorhynchus masou*) and chum salmon (*Oncorhynchus keta*). Salmon had to be a core focus of the

review, either within the search string or an explicit *a priori* focus. We thus excluded studies where relevant salmon species were just one of a number of other species incidentally reported within the abstract (and results).

Study type: Systematic reviews - defined as any article referring to itself as a "scoping review", "literature review", "systematic review", "systematic map", "systematic mapping", "systematically review", "systematically reviewed", "review of the literature", "evidence review", "review of the evidence", "rapid evidence assessment", "rapid review", or "evidence synthesis". We also included reviews that had explicit methods sections described, that claimed to be comprehensive, or that synthesised data quantitatively.

Coding and extracting meta-data

We coded and extracted meta-data for all included full texts using the schema outlined in Table 2. Before coding and meta-data extraction, a subset of 3 studies were used for trial data extraction by two reviewers. Conflicts were discussed in detail but no further modifications to the schema or definitions were necessary. All relevant information was obtainable without the need to obtain data from authors.

Table 2. Coding and meta-data schema used on all included full texts.

Field	**Description**
Author-year	First author surname - publication year
Title	Article title
Source-volume-pages	Journal - volume - start and end pages
Geographical focus	Countries or regions covered by the review
Authors' method name	The type of review as described by the authors (e.g. "systematic review")
Review type	Evidence map / Narrative synthesis / Quantitative synthesis / Qualitative synthesis
Cited methodology	Authors' reference to methodology used in the review
Species	Atlantic salmon, Rainbow trout, Coho salmon, Chinook salmon, Chum salmon, Sockeye salmon, Pink salmon, Not stated - salmon, Not stated - trout, Not stated - salmon and/or trout
Study objectives	Objectives as described by the authors
Production stage	Feed supply chain, Hatchery, Land-based grow out, Sea-transfer, Sea-cage, Harvest, In-vitro, Salmon supply chain, Consumption, Legislation and policy, Not stated
Topic (hierarchical and clustered, see Additional File 3 for	Broad topic: Business and economy, Consumption, Impacts, Production, Research methods Subtopic: Companies, Customer preference, Economy, Legislation, Public image,

clustering)	Supply chains, Contaminant, General, Mislabelling, Palatability, Quality, Safety, Environmental impacts, Mitigation, Social impacts, Aquaculture facility, Feed, Fish biology, Fish health, Fish welfare, Management, Pathology, Methodology, Research stage Feature: Companies, Customer preference, Economy, Legislation, Public image, Supply chains, Contaminant, General, Mislabelling, Palatability, Quality, Safety, Biodiversity impacts, Escapes, Impacts on native fish, Nutrient load, Chemicals, Wild versus farmed, Management, Output processing, Social impacts, Equipment, Hydrodynamics, Type, Additives, Alternatives, Contaminants, Conventional, Anatomy, Development, Fish behaviour, Histology, Life stage, Outcome, Reproduction, Species, Gut health, Immunity, Injury, Toxicity, Pain, Stress, Treatment, Externalities, Fish by-products, Fish identification, Practices, Production stage, Productivity, Sustainability, Illness, Impacts, Organism, Prevention, Sea lice, Literature review, Modelling, Monitoring, Research stage Component: Companies, Customer preference, Economy, Legislation, Public image, Supply chains, Contaminant, General, Mislabelling, Palatability, Quality, Safety, Biodiversity impacts, Escapes, General, Impacts on native fish, Nutrient load, Chemicals, Wild versus farmed, Escape mitigation, Waste treatment, Water treatment, Social impacts, Equipment, General, Hydrodynamics, Closed, Land-based, Location, Polyculture, Pond-based, Sea-based, Additives, Alternatives, Contaminants, Conventional, General, Management, Supply chains, Anatomy, Developmental problems, Fish behaviour, General, Histology, Life stage, Genetic modification, Genetics, Sex control, Outcome, Reproduction, Atlantic salmon, Chinook salmon, Chum salmon, Coho salmon, Pink salmon, Rainbow trout, Sockeye salmon, General, Gut health, Immune response, Injury, Toxicity, General, Pain, Stress, Anaesthetic, Stress treatment, Externalities, Fish by-products, Fish identification:, General, Farm management, Maximising productivity, Predator deterrent, Production stage, Productivity, Sustainability, General, Illness, Impacts, Organism, Antiseptic, Disinfectant, Vaccination, General, Impacts, Species, Treatment, Anti-parasitic, Antibiotic, Antibiotic resistance, Antimicrobial, General, Insecticide, Nematicide, General, Literature review, Modelling, Monitoring, Research stage
Included studies	Number of studies included in the review
Institute(s)	Affiliation institutions of all author
Funder	Reported funding body/bodies

Assessing study reliability

We used the CEESAT critical appraisal tool (CEE 2020) for assessing evidence review methodological quality, which involves 16 questions about the methods used across planning, searching, screening, data extraction, critical appraisal and synthesis of systematic reviews. The CEESAT tool assigns a grade based on explicit criteria for each question, resulting in judgements of red, amber, green or gold. All reviews were assessed by two reviewers (NRH and HC) independently, before all discrepancies were discussed in detail and an agreement made on the final score for each question.

We made the following minor modifications to CEESAT to reflect a more pragmatic approach to judging reliability, and recognising inconsistencies in the current wording of CEESAT:

- Question 2.1 - The protocol does not need to be published by a journal for “Gold” (i.e. self publication *a priori* is acceptable)
- Question 4.2 - Where 2 or more reviewers independently screened all records BUT failed to report the results of consistency checking, a judgement of “Green” was awarded (i.e. they were not penalised to “Red” for failing to report consistency if each record was screened by 2 or more reviewers)
- Question 7.2 - Where reviews extracted study findings and presented the direction and significance of effect but did NOT perform critical appraisal (AND even if they present magnitude of effect) they were given a “Red” judgement to account for studies that both perform and facilitate vote-counting
- Question 8.3 - Reviews will be judged as “Green” even if the limitations text focuses purely on the limitations of the review methods and there is no discussion of the limitations of the evidence base

We then used the following criteria in Table 3 to assign a reliability judgement across all CEESAT questions for each review.

Table 3. Article-level reliability judgements given according to the 16 CEESAT questions for each included review.

Reliability	**Description**
Exceptionally low	Where 10 or more questions are judged to be "Red"
Low	Where a review scores “Red” on one or more of the following critical criteria: 3.1 (Search repeatability); 3.2 (Comprehensiveness of resources); 4.1 (Clarity of eligibility criteria); 5.1 (Critical appraisal of study validity); 6.2 (Reporting extracted data).
Moderate	When a review has no “Red” judgements for critical questions (3.1, 3.2, 4.1, 5.1, 6.2) and between 1 and 4 “Red” scores for non-critical questions (50% of non-optional responses)
High	Everything else (no “Red” scores)

Synthesis and visualisation

We will visualise the included reviews based on key variables extracted from the syntheses, as well as based on the CEESAT assessments, which will be provided in a detailed table sorted by broad-scale topic. Visualisations will display both the number and quality of syntheses across categorical variables.

Demonstrating procedural independence

No authors of this review were involved with the conduct of any included literature reviews, meaning that preventing decisions on our own work was not a relevant concern.

Results

The review process

The review process and the fate of all considered records is outlined in Figure 1. Our database searches yielded a total of 653 results and 327 unique records. A total of 180 records were retained after title and abstract screening, with 10 unobtainable at full text and 34 records remaining after full text screening. A list of all records excluded at full text screening with exclusion reasons is provided in Additional File 3.

A set of 39 full texts deemed to initially be relevant were subjected to citation chasing. In all, 37 out of these 39 reviews had DOIs and were entered into citationchaser (Haddaway et al. 2022), yielding 3,439 records from backwards citation chasing and 864 records from forward citation chasing. Finally, only one article was relevant at title and abstract and had not already been screened. This record was relevant at full text and retained, making a total of 35 articles and 37 reviews included in the final database.

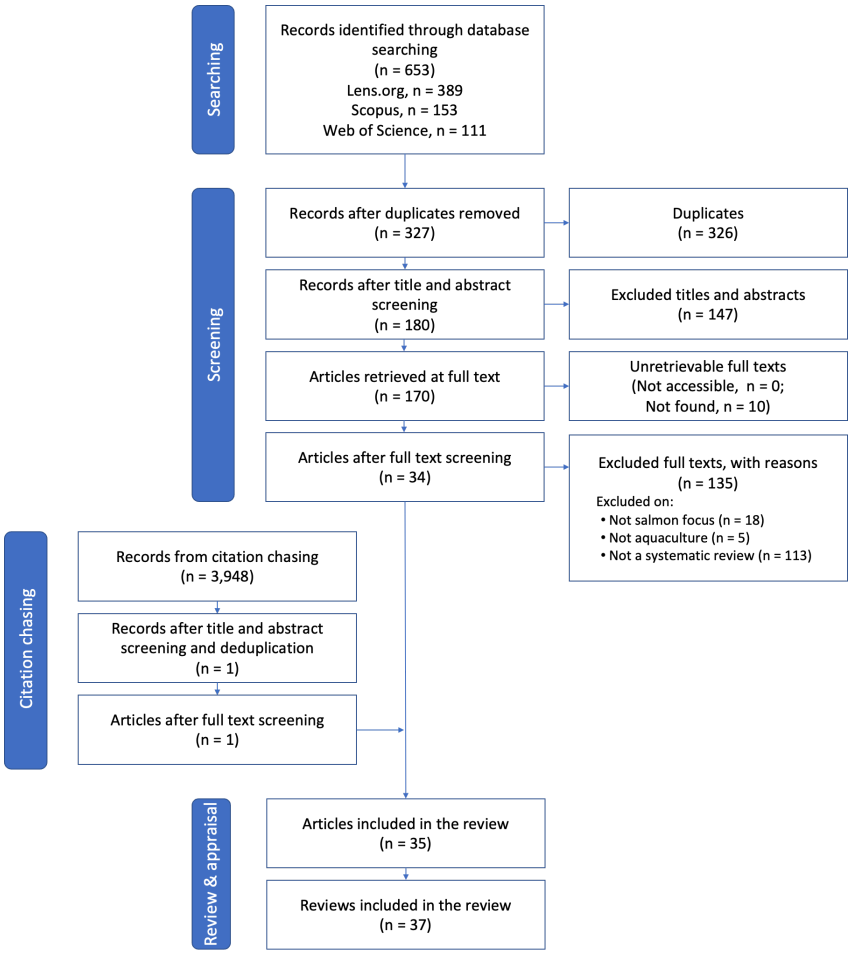

Figure 1. Adapted ROSES flow diagram showing fate of records through the umbrella review process.

The evidence base

The full datasheet for all included reviews is provided in Additional File 3. Research interest via evidence synthesis has increased roughly in line with other fields and primary research in recent years (Figure 2). The vast majority of reviews were published after 2015, with 5 reviews per year published between 2022 and 2024.

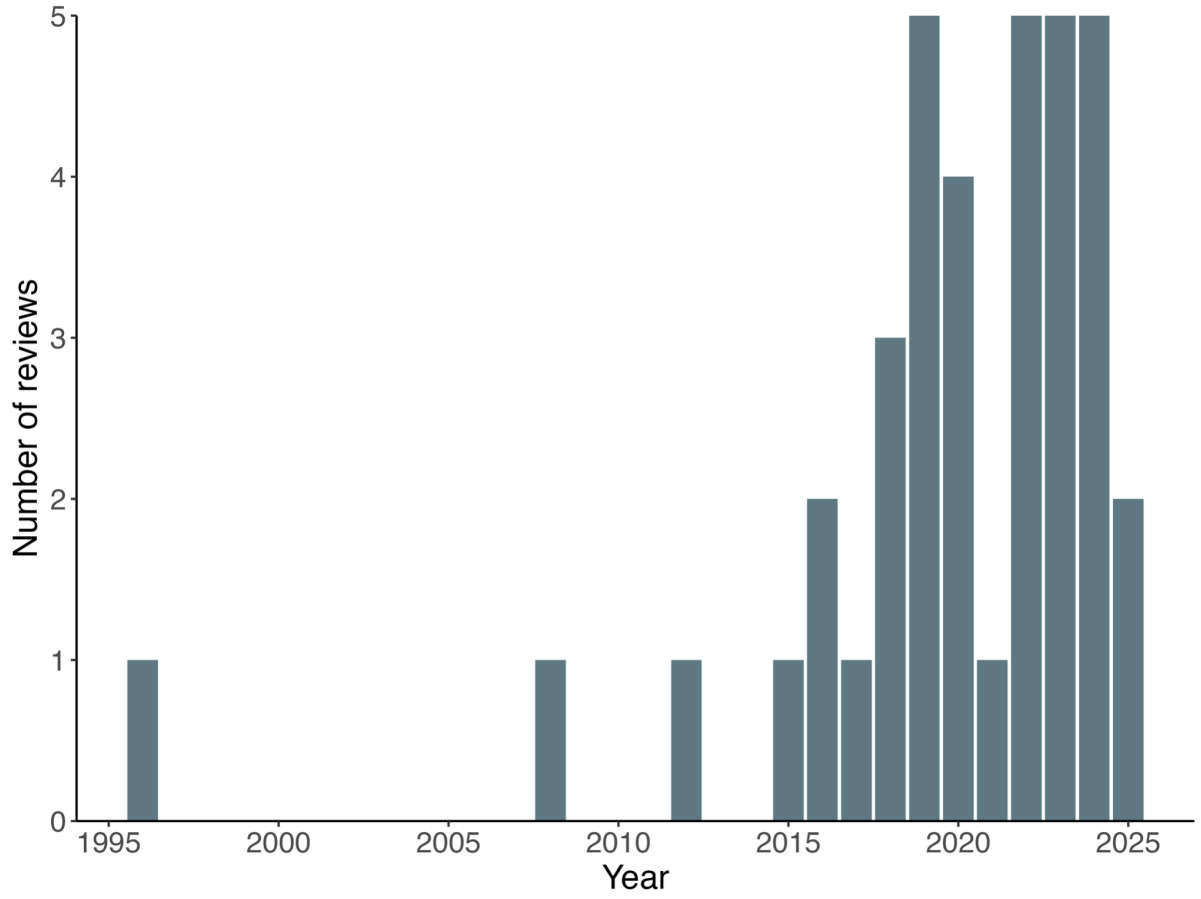

Figure 2. Number of included reviews by publication year.

The academic journals “Aquaculture” and “Reviews in Aquaculture” were the two most commonly represented outlets, each with 5 reviews (Figure 3). One other journal, “Aquaculture Environment Interactions”, featured 3 reviews, whilst other journals each featured 1 to 2 reviews.

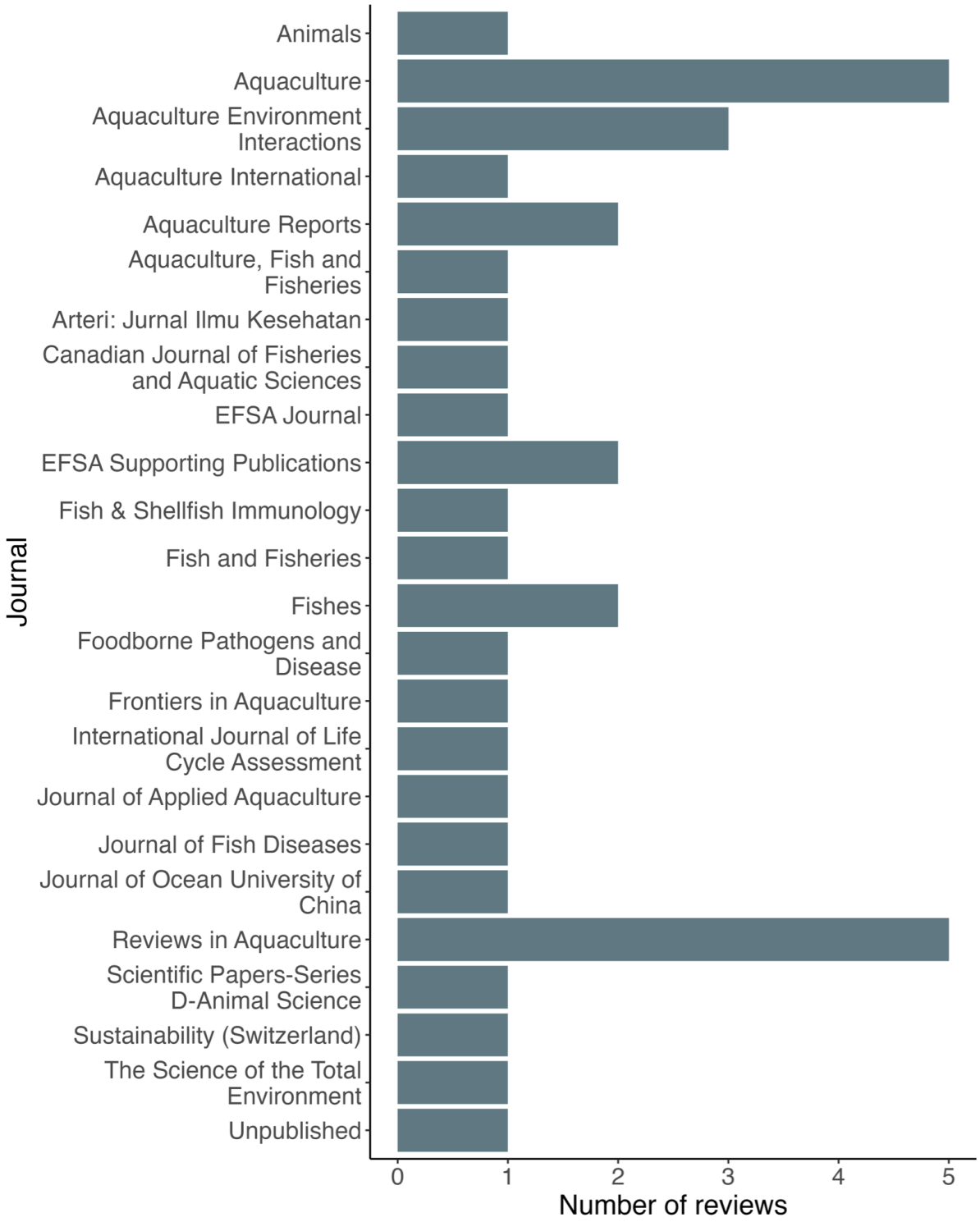

Figure 3. Journals featuring the included reviews by review count.

Authors most commonly hailed from the major salmon producing nations (Norway, n=18; Canada, n=8; United Kingdom, n=4), with other countries represented by 3 or fewer authors (Figure 4).

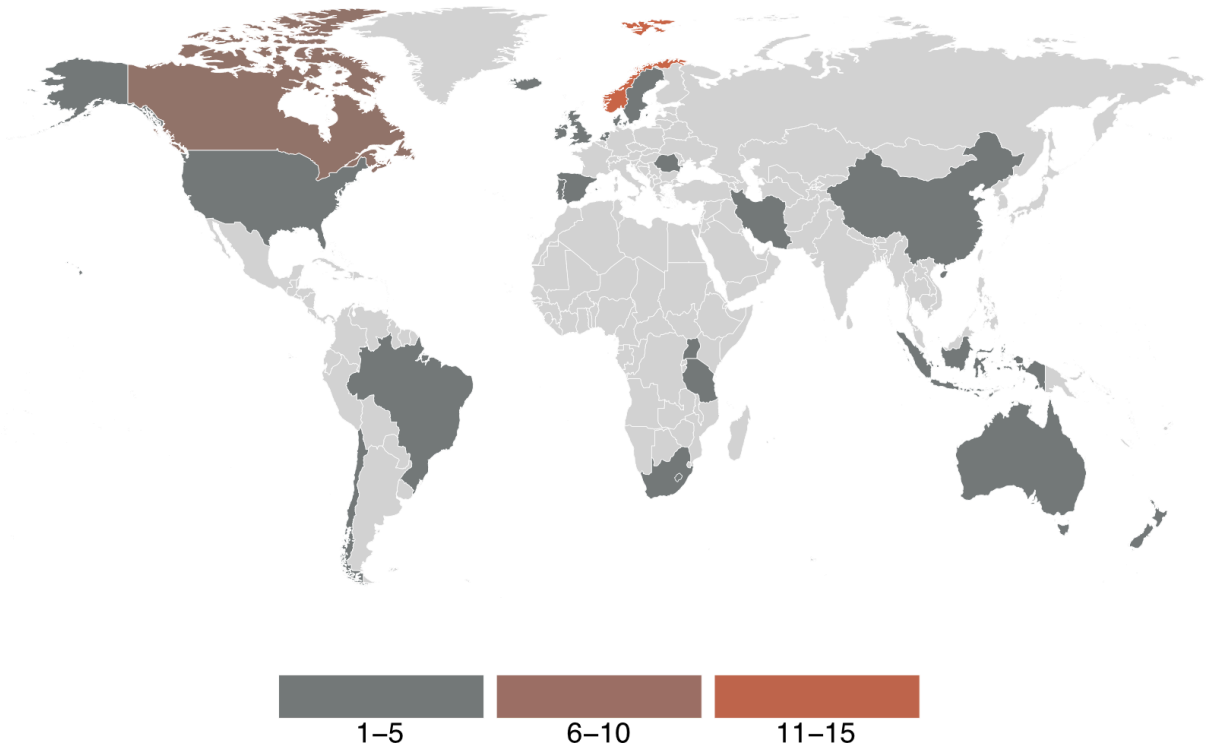

Figure 4. Included reviews across author affiliation country.

Most reviews were generalised across producing countries or regions without geographic restriction (Figure 5), with three reviews focusing on Norway specifically, and Southern Africa, the UK (Scotland), North America and Europe each the focus of 1 review.

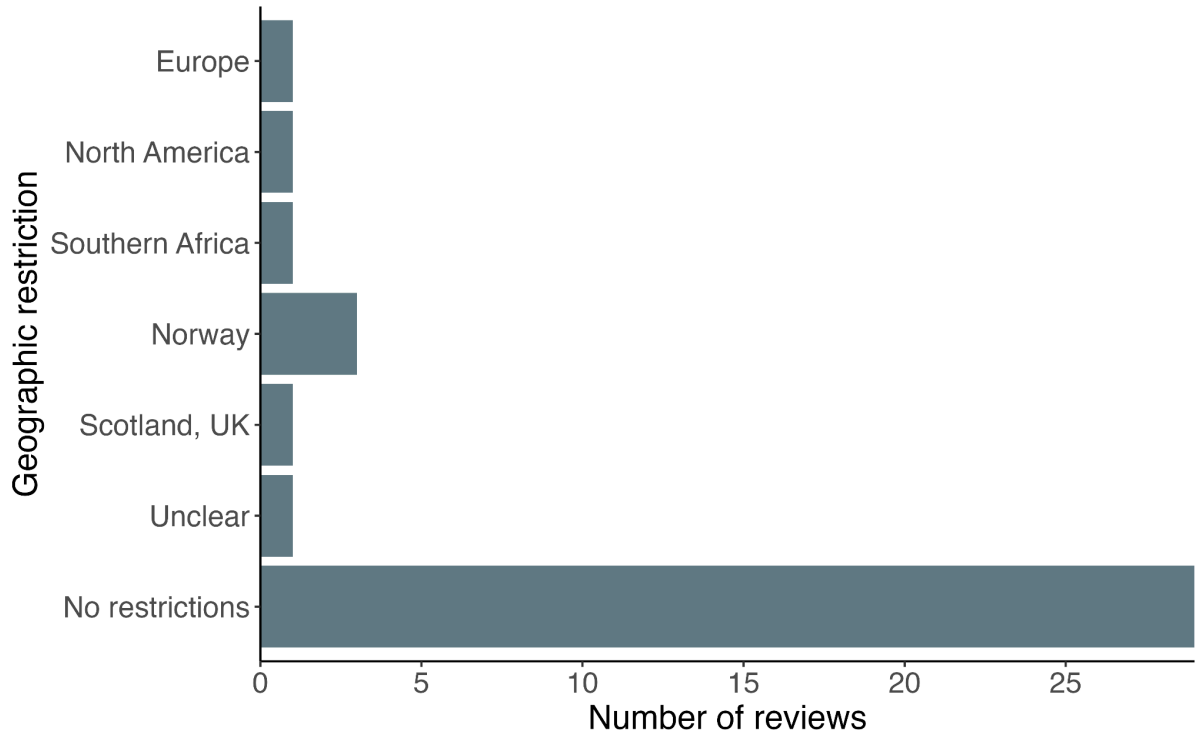

Figure 5. The number of reviews by geographical focus.

The majority of reviews were narrative syntheses (n=13) or quantitative syntheses (involving some form of meta- or other analysis, n=13), with 11 reviews that aimed to map the evidence base without synthesising study findings (Figure 6).

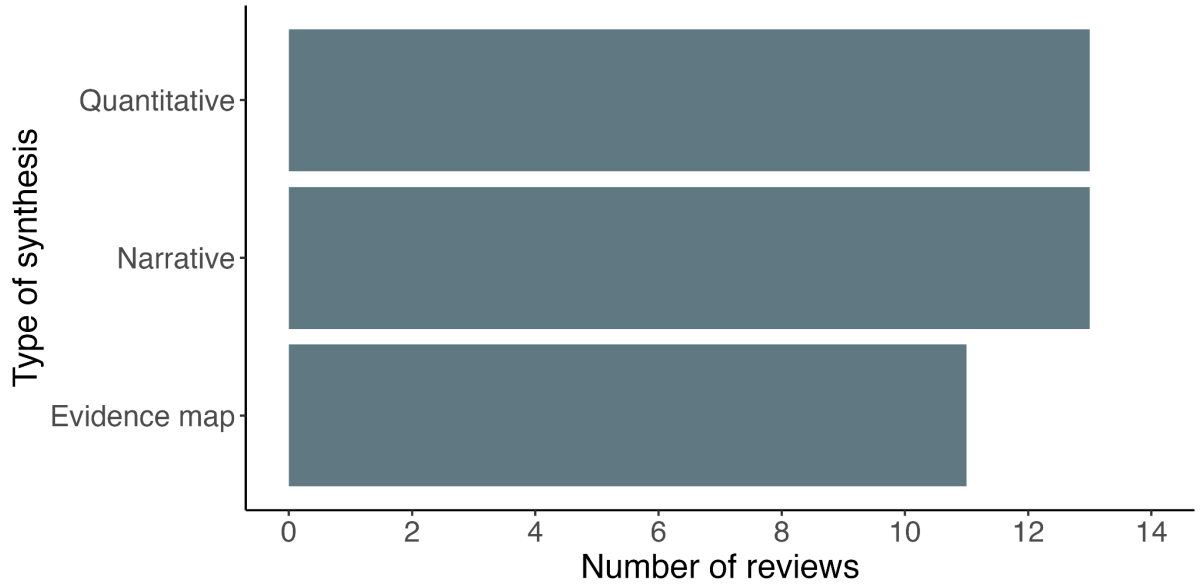

Figure 6. Number of reviews by synthesis type.

In line with their economic importance, Atlantic salmon (*S. salar*, n=23) followed by rainbow trout (*O. mykiss*, n=9) were the most frequently studied species (Figure 7). Relevance to an unspecified salmon and/or trout species was commonly made (n=11), with other salmon species all mentioned fewer than 4 times each.

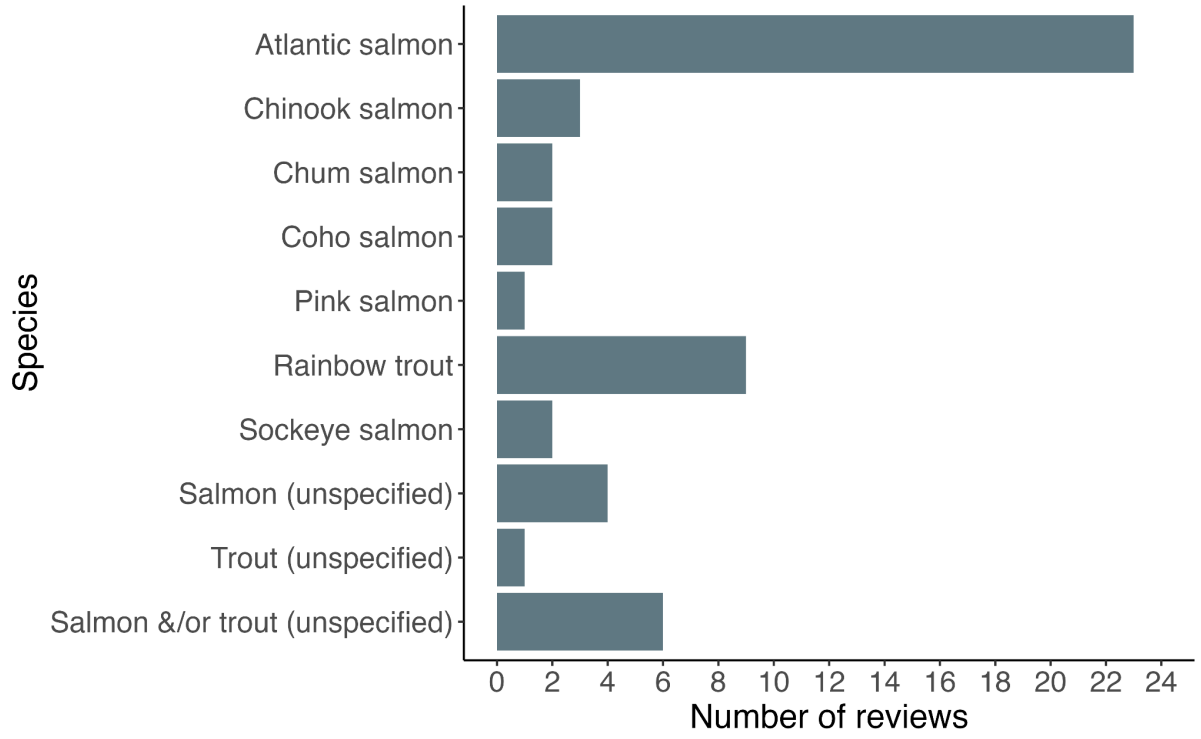

Figure 7. Number of reviews by study species.

The most common production stage was sea-cage grow-out (n=15, Figure 8), followed by feed supply chains (the focus of several life-cycle analyses, n=7). Salmon supply chains and consumption were also represented by multiple reviews (n=4 and 4, respectively). Some 15 reviews did not mention the production stage or were relevant across stages.

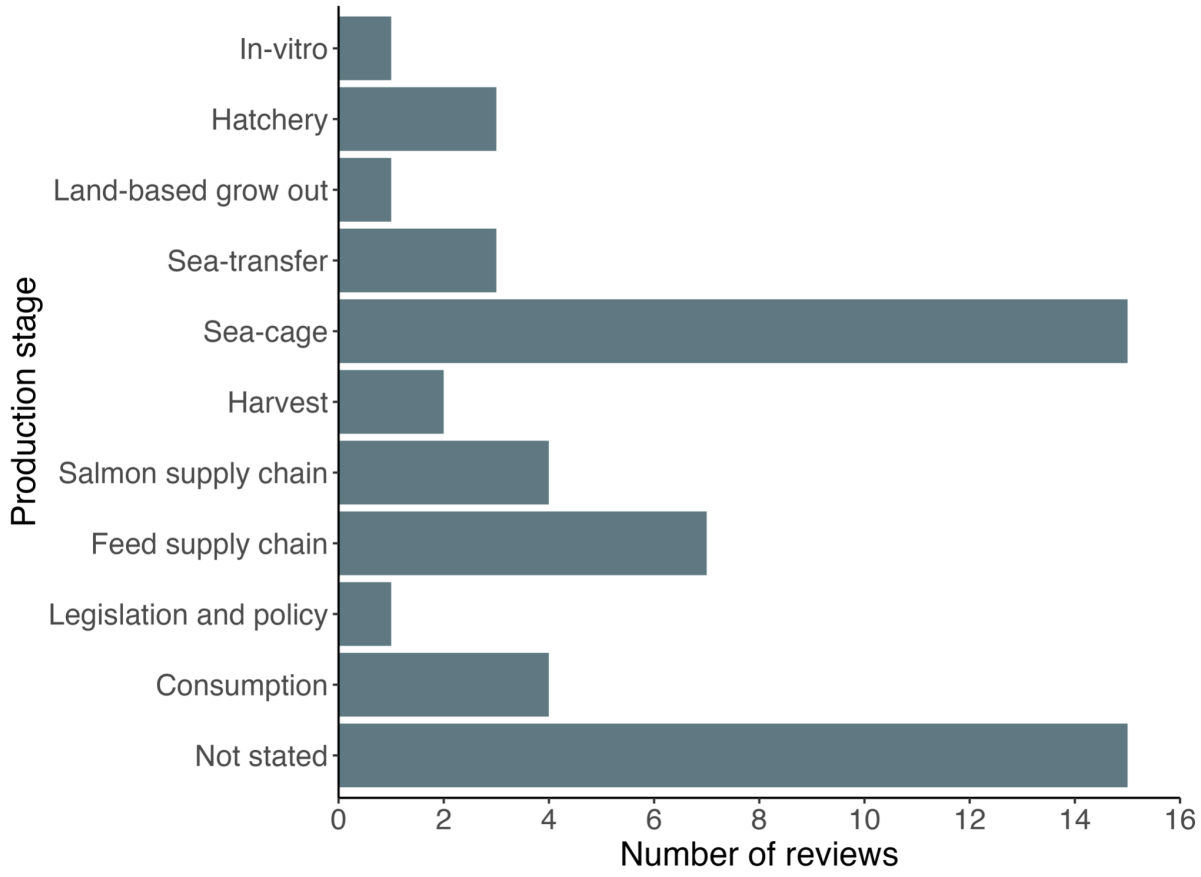

Figure 8. Number of reviews by production stage.

The number of included primary studies in each review was generally low, with 16 reviews including 50 or fewer studies (Figure 9). Thirteen reviews included between 51 and 300 studies. One review, a scoping review, included a much larger number of studies (1,760 included studies). A total of 9 reviews failed to report the number of included studies.

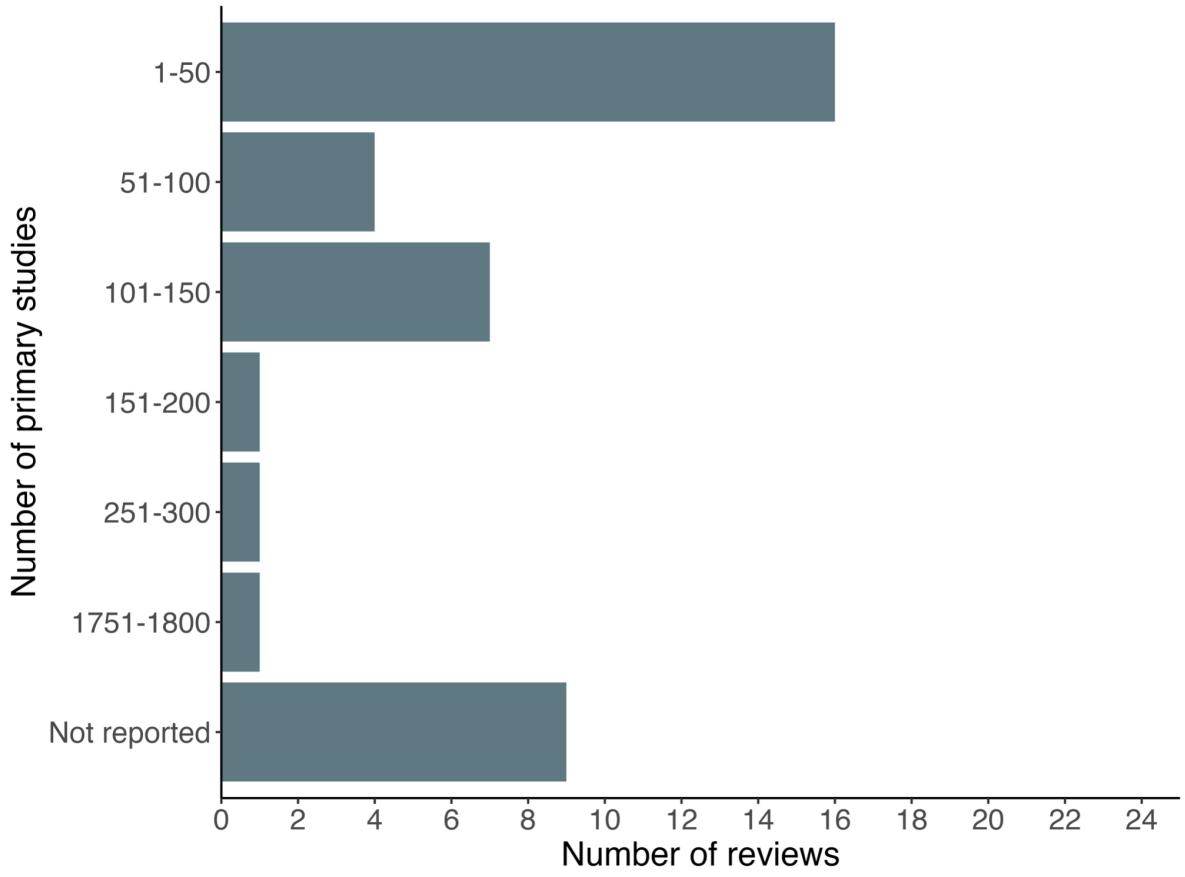

Figure 9. Number of primary studies included in the reviews.

The most common funder for the reviews was a government funding body (n=13), followed by an industry research body (n=8), and with funding not reported (n=6). Furthermore, an analysis of co-author affiliations demonstrated that 7 reviews included industry partners as co-authors, with 10 total industry partners listed as co-authors across these articles. Companies listed as co-authors were: AquaGen AS, Bakkafrost Scotland, BioMar Group, Blue Genomics Chile, Cermaq Finnmark AS, Marine Prospects AS, Mowi Scotland, Nofirma, Nordlaks Oppdrett AS, and Scottish Sea Farms Ltd.

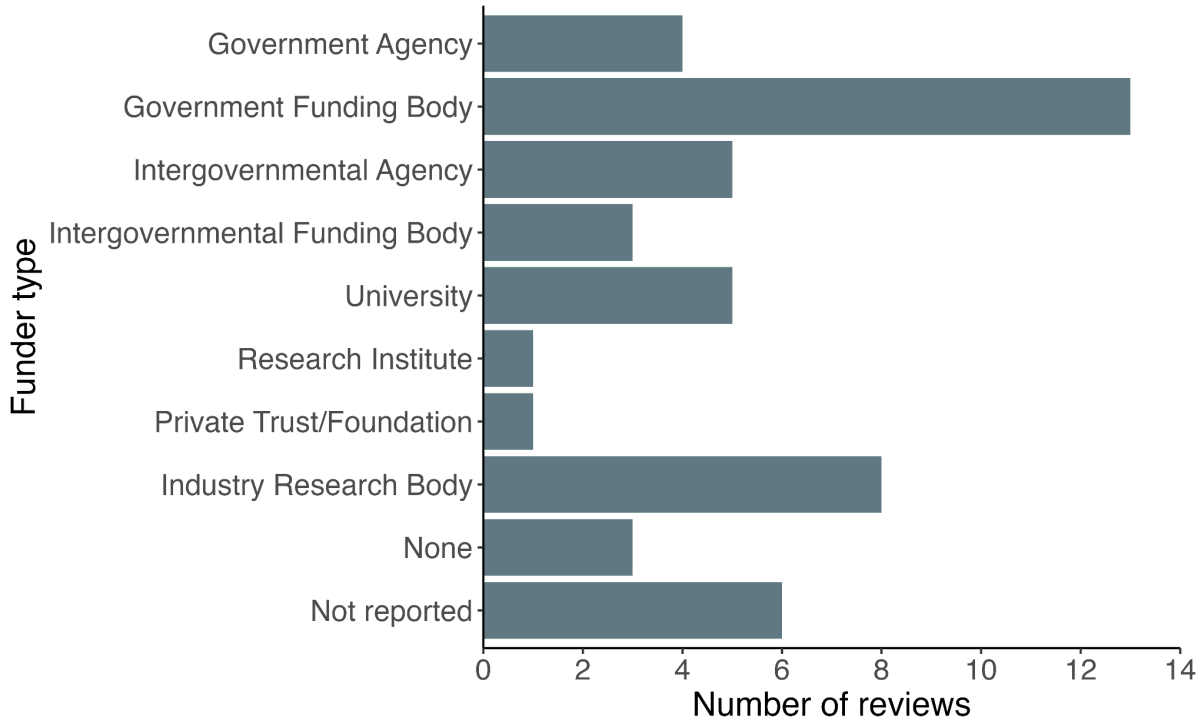

Figure 10. Review funder type across the included reviews.

Production subjects were the most commonly investigated (Figure 11), with pathology and sea lice, specifically, contributing the greatest research attention. Environmental impacts and research methodology were also described across multiple reviews.

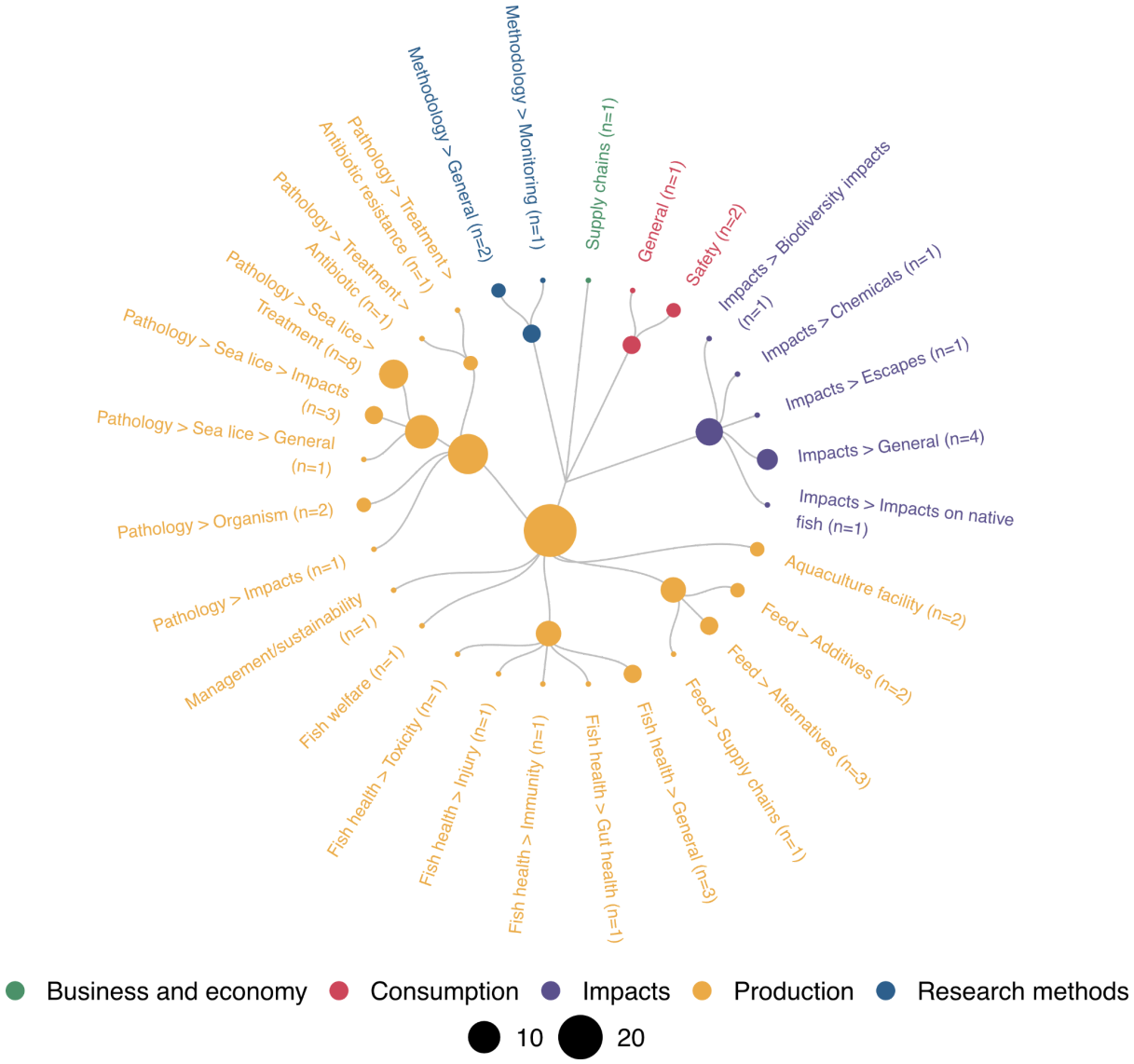

Figure 11. Study subjects referenced within the included reviews.

The majority of reviews focused on Atlantic salmon (n=17) and rainbow trout (n=7) production (Figure 12). Beyond production, other species were represented poorly with just single studies across other categories of subjects.

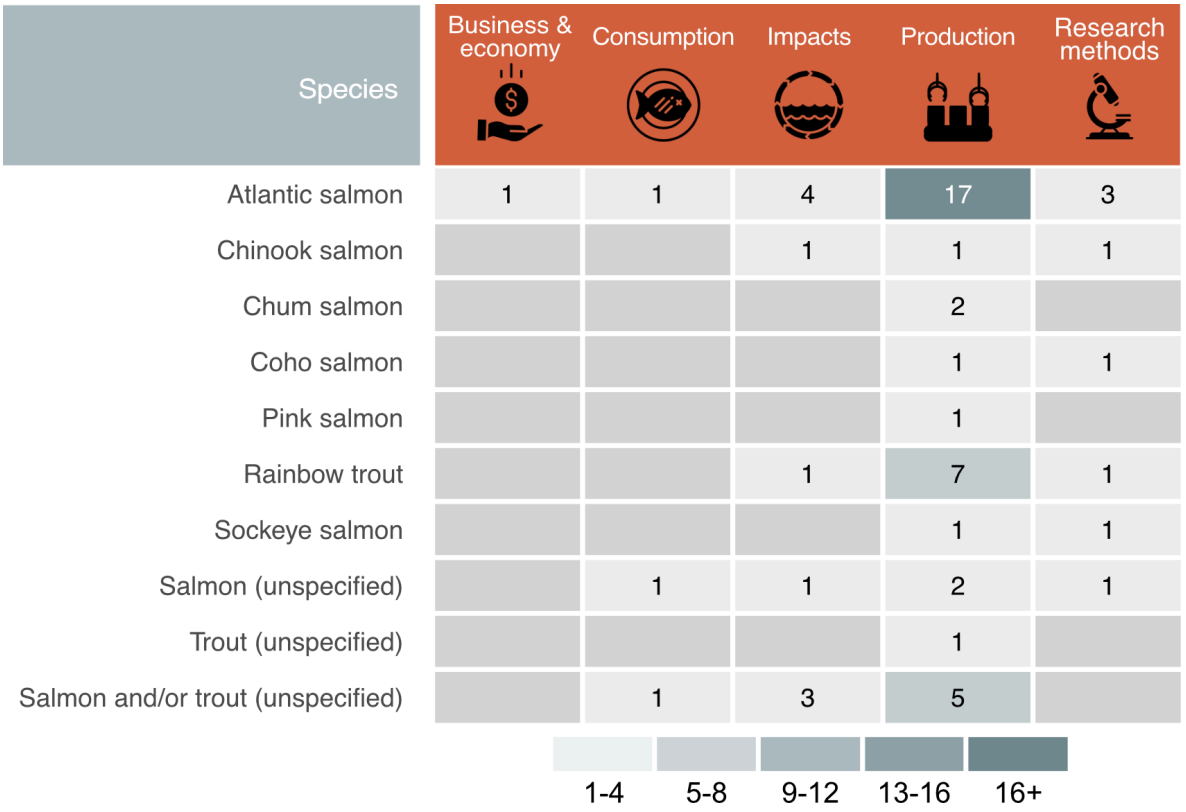

Figure 12. Study subject by species in the included reviews.

As described above, most research focused on production outcomes, and Figure 13 demonstrates that government funding bodies supported 11 of these reviews, industry research bodies 9 and intergovernmental agencies 5, while a wide diversity of funders supported the remaining ones (e.g. universities and a research institute). Other funders also contributed to research into impacts and research methods, with government funding bodies supporting 4 reviews on impacts and 2 on research methods. Industry also supported 1 review on impacts.

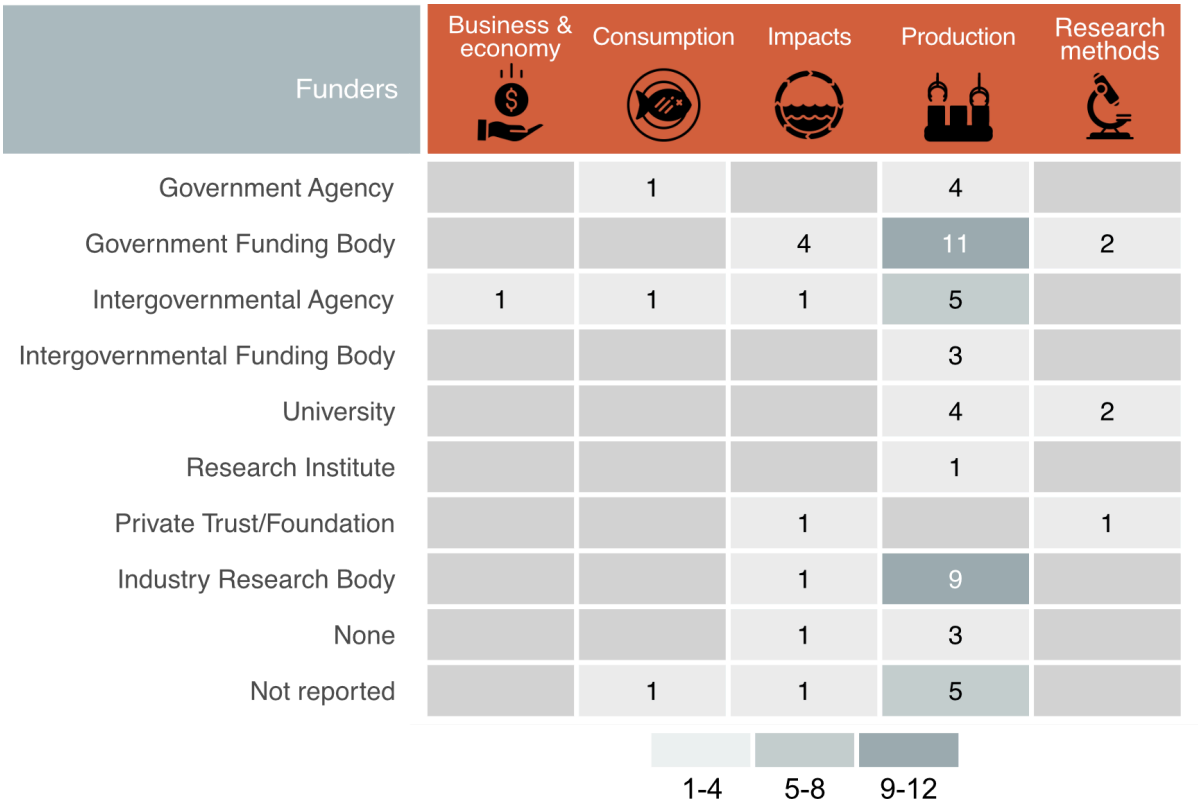

Figure 13. Review funder by outcome focus of the included reviews.

Review rigour

We have summarised the results of our study validity assessment in Figure 14, and provide judgements for all questions across each review in Figure 15. In the following text we have described the status of the evidence base in terms of rigour across each of the 8 steps of the review process and the 16 questions included in the CEESAT appraisal.

In summary, only 4 reviews were judged to be of moderate rigour, whilst none obtained a high rigour rating. In contrast, a total of 9 reviews were judged to be of exceptionally low rigour, and the remaining 23 reviews were deemed to be of low rigour.

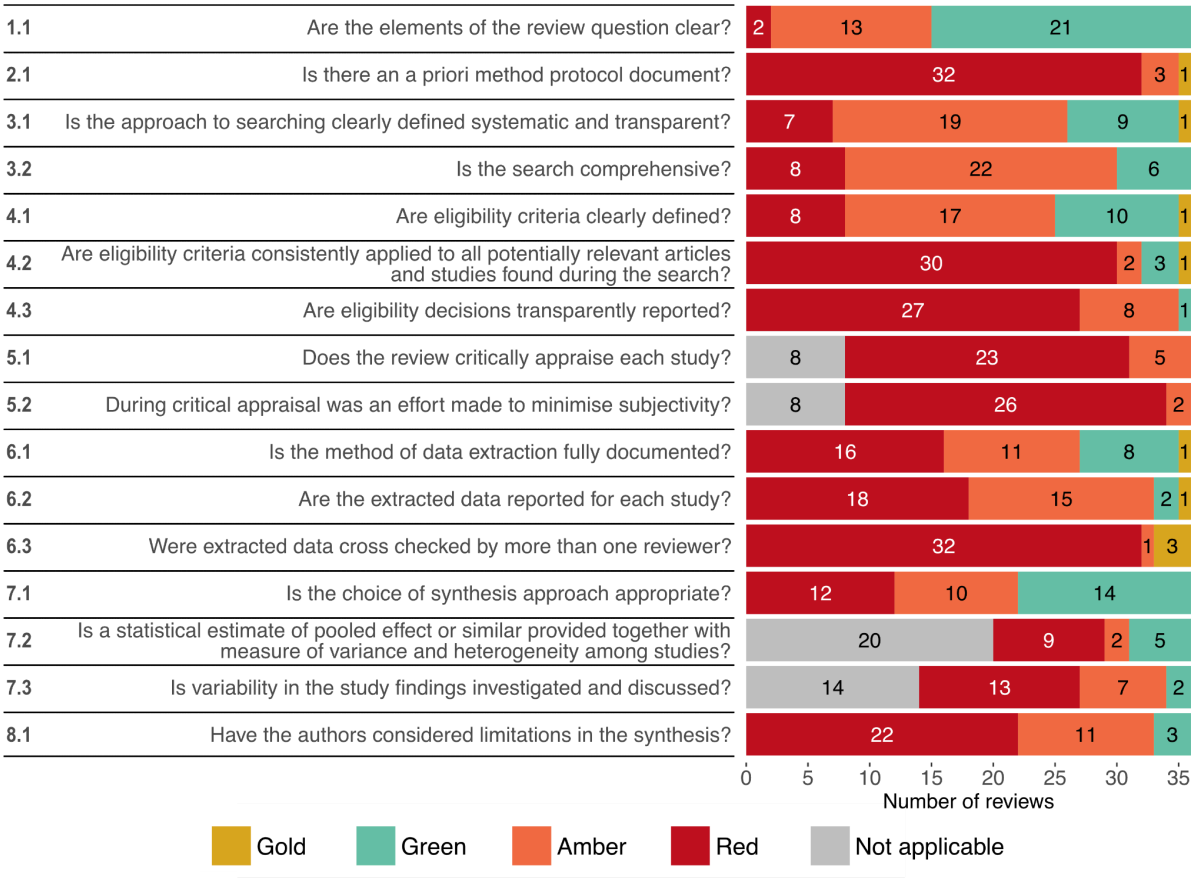

Figure 14. Summary of the judgements for review reliability for each CEESAT question.

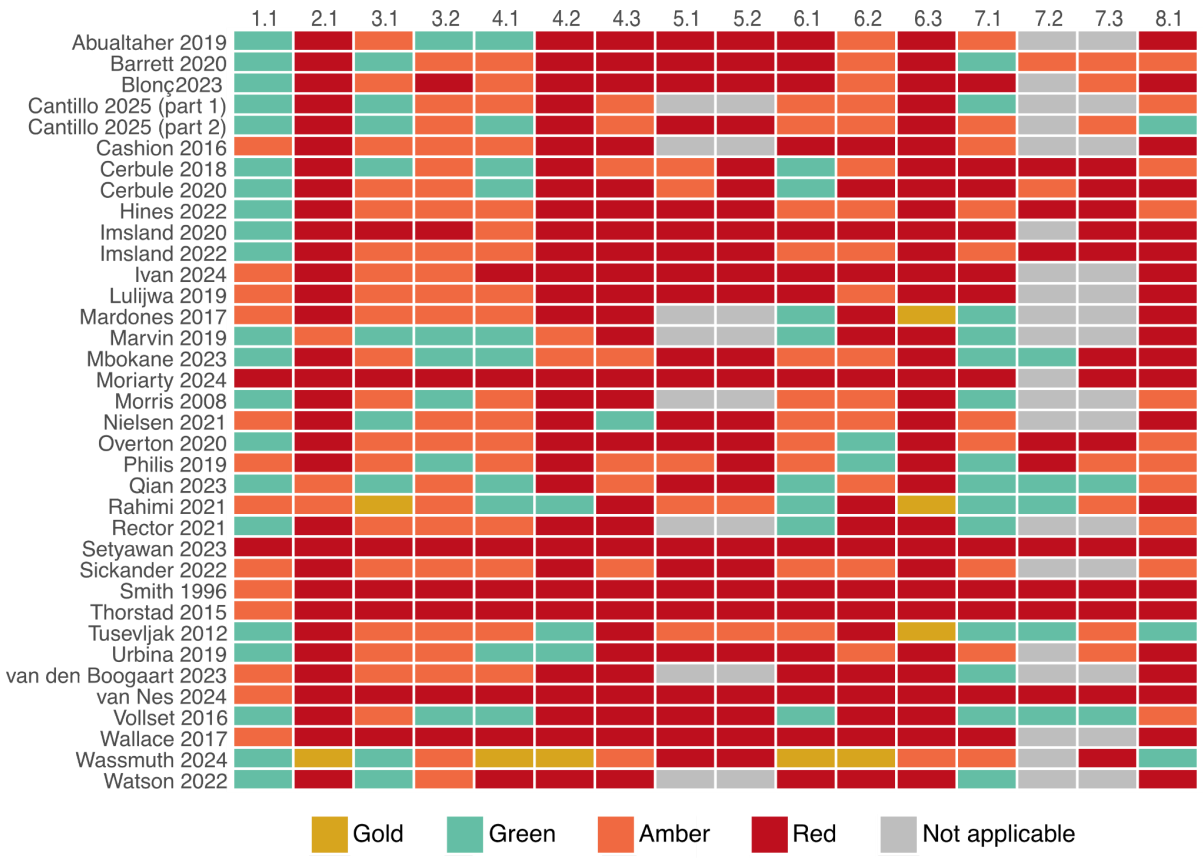

Figure 15. CEESAT scores and overall reliability judgement score for all included reviews.
Our analysis shows that reviews in the field were conducted and reported poorly, with 285 "Red" judgements showing considerable methodological failings, and only 9 "Gold" judgements of high rigour. Grey cells indicate 'not applicable' for cases where evidence mapping or narrative synthesis was performed.

The question

Just over half (58%, n=21) of the reviews provided a question that was clear and well-defined, although no reviews had used an established framework for systematic review questions, such as PICO/PECO. Some 36% of the reviews (n=13) described their question vaguely in terms that allowed the broad concepts to be understood, but 2 reviews failed to define their question or scope.

The protocol

Only one review made reference to a protocol (whether *a priori* or not), with a further 3 reviews (8%) providing sufficient detail for the methods to be ex post inferred. However, the majority (89%, n=32) failed to make use of a protocol document outlining the planned methods and also failed to provide sufficient methodological detail to allow replicability.

The search

Some 9 reviews (25%) provided search details in a way that was replicable, with a further 19 (53%) giving some information about their searches. However, 7 reviews gave no details of their search methods at all, with just one review providing these methods in an *a priori* protocol. Similarly, only 6

reviews (17%) searched across an appropriate number of resources (i.e. more than 2 bibliographic databases and searching for grey literature), with the remainder either searching only 1 or 2 databases or omitting grey literature (61%, n=22), or providing no information about where searches were performed (22%, n=8).

Screening for eligibility

The criteria for primary study inclusion were clear ("Green", n=10) or inferrable ("Amber", n=17) for the majority of reviews (75%), with 8 reviews failing to define criteria at all and one review pre-specifying inclusion criteria in an *a priori* protocol. However, consistency checking or dual screening was rarely performed, with the majority (83%, n=30) giving no details of any cross-reviewer verification. Reporting of screening decisions was particularly poor across reviews, with 75% (n=27) giving no details of the number of screened or included studies and a further 22% (n=8) giving both the number of exclusions and a list of included studies.

Critical appraisal of study validity

For narrative and quantitative reviews, critical appraisal should have been performed (it is not necessary for evidence maps). For these reviews, the majority (82%, n=23) included here failed to assess any aspect of risk of bias or aspects of study validity. In only 2 cases were any methods employed to minimise subjectivity during critical appraisal.

Data extraction

Reviews performed relatively poorly for formalised data extraction. Some 45% of reviews (n=16) failed to describe the methods of data extraction in any way, with a further 30% (n=11) providing minor details that precluded replicability. Slightly fewer studies reported the extracted data, with 50% (n=18) reporting no data at all, and 42% (n=15) providing only selected or limited data. One study notably described data extraction methods and presented the extracted data in full detail. In three reviews, data were reported to have been extracted by more than one reviewer, but the majority of studies failed to describe this cross-checking (presumably because it did not occur).

Synthesis

Some of these questions only applied to quantitative syntheses (7.2) and narrative syntheses (7.3), and not evidence maps. In general, narrative syntheses and evidence maps scored relatively well, although no reviews had chosen and justified their synthesis methods in advance (in an *a priori* protocol). Some 12 reviews scored badly due, in part, to the reliance on vote-counting methods or other inappropriate quantitative synthesis practices. Of the quantitative syntheses, around 50% (n=10) of the reviews scored poorly for good statistical practices (i.e. providing pooled estimates of effects along with a measure of variance and heterogeneity). Similarly, a third (n=13) of the quantitative and narrative syntheses failed to discuss or investigate variability in the findings extracted from primary studies.

Limitations

Few reviews discussed their limitations, with less than 10% of reviews (n=3) explicitly referencing any limitations of the review or the evidence base. No reviews had an explicit section dedicated to the limitations of both that discussed all major potential limitations to their methods or the evidence base (corresponding to a "Gold" judgement).

The review findings

We here summarise only the findings of the four reviews judged to be of moderate rigour during study validity assessment (i.e. Cantillo & Deshpande, 2025; Philis et al. 2019; Morris et al. 2008; Cerbule 2018). We do not discuss the findings of the reviews of low or exceptionally low rigour, since we deem these to be unreliable and suffer from a high risk of bias due to their deficient methodologies.

Moderately rigorous review findings

Several key themes emerge from these reviews, including the environmental performance of alternative feed proteins, the comparative sustainability of different production technologies, the risks associated with escaped farmed salmon, and the effectiveness and sustainability of salmon lice control methods.

Cantillo & Deshpande (2025) synthesise 91 primary studies, highlighting that while research on insect and single-cell proteins is growing, findings on their carbon footprints are highly variable (ranging from 0.1 to 132 kg CO_2/kg protein), largely due to inconsistent assumptions, system boundaries, and LCA methodologies. This limits the comparability of results and hinders robust conclusions on climate benefits, though energy and substrate production are consistently cited as key hotspots. Philis et al. (2019) similarly report that methodological inconsistencies across 24 LCA studies prevent definitive comparisons of production systems. Open-net pens show lower energy demands but higher eutrophication potential, while RAS systems exhibit higher carbon footprints. Feed Conversion Ratios (FCR) are commonly referenced as key performance indicators, but confounding factors such as feed composition and system conditions limit their utility across contexts.

Morris et al. (2008) provide strong observational evidence of the widespread presence of escaped farmed salmon—recorded in 87% of rivers surveyed within proximity to aquaculture sites between 1984 and 2006—but note a lack of standardised monitoring and insufficient genetic or population-level impact assessments. While negative effects such as genetic introgression and disease transmission are well documented in individual studies, broader conclusions are hampered by fragmented and short-term datasets. Cerbule (2018) identifies similar weaknesses in the evidence on lice control, with most data focusing on increasingly ineffective chemical treatments, while cleaner fish show promise but lack long-term, regionally generalisable studies. Warm water treatments are underrepresented in the literature, and little is known about their welfare implications or environmental trade-offs. Across all reviews, the evidence base is constrained by uneven research coverage, methodological heterogeneity, and poor integration of environmental externalities. There is a strong consensus on the need for harmonised frameworks, uncertainty analysis, and more robust comparative research to inform policy and improve the sustainability of salmon aquaculture.

Conclusions

Our review has identified a small evidence base of systematic reviews in the field of salmonid aquaculture, with just 37 reviews included. We found a larger volume of literature reviews that were not systematic, consisting of 113 full texts excluded for not being systematic. This demonstrates an interest in synthesis, but a surprising lack of intent to synthesise evidence methodologically. Considering the large volume of literature on salmon farming, it is particularly surprising that few quantitative syntheses/meta-analyses exist that summarise the evidence, particularly on well-researched topics like sea lice and other pathologies and treatments.

Our review also highlights that in the evidence syntheses identified, the majority focused on aspects of productivity, as might be expected from a highly profitable industry affected by externalities, such as disease. We identify few studies on the impacts of salmon farming on environmental systems, and no review on the social impacts, which have been widely reported through salmon feed supply chains in West Africa (e.g. in a 2024 report by the NGO Feedback: https://foodrise.org.uk/wp-content/uploads/2024/02/Feedback-BlueEmpire-Jan24.pdf). It is also important to note that although there were studies on feed supply chains, these focused on the chains themselves and not their social or environmental impact.

Our analysis identified industry funding and co-authorship as a common practice across the included reviews. This helps to explain the focus on productivity in the included reviews, but does not explain the lack of evidence relating to impacts. One can only speculate as to why evidence on impacts has not been appropriately synthesised to date.

We also show that reviews in this field are methodologically poor, with risk of bias high across most reviews and most methodological procedures, and no single review meeting even basic systematic review methods standards considered by organisations such as the Collaboration for Environmental Evidence or the Campbell Collaboration. The key problems with the methods used by these reviews include: the lack of any *a priori* protocol; unsystematic screening practices; the lack of any critical appraisal of internal validity of included studies; data extraction methods were not described; low quality of synthesis methods, including cases of vote-counting; a lack of self-reflection on their methodological limitations.

Our review is not without its limitations. We have not searched for grey literature beyond theses and dissertations, although we argue that our scope is restricted to academic publications. We have used a relatively inclusive definition of “systematic reviews”, including anything that either self-identifies as such, or includes some aspect of explicit methodology. We did this purposefully to avoid including primers or overviews that did not set out to be systematic, but our included set may overlap with excluded articles that do not refer to themselves as systematic. However, we believe our searches and screening were comprehensive enough that the risk of missing relevant reviews is very low. We will also not have included reviews focused on topics relevant to but not explicitly referencing salmon aquaculture - for example, reviews of sea lice treatment effectiveness. However, we believe it unlikely that these reviews will have neglected to include a reference to their core subject, salmon.

We also searched only English language databases. We acknowledge that evidence syntheses may exist in non-English language resources and journals, and further work should be undertaken to identify and appraise these, should they exist. However, our analysis is a methodologically robust assessment of the published English-language secondary research literature pertaining to salmon aquaculture, and our results paint a bleak picture of the state of the evidence identified.

We also note an important experience in peer-reviews obtained from first attempts at publishing this review in a leading journal dedicated to 'reviews' in the field - robust evidence synthesis methods were unfamiliar to the editor and peer-reviewer, stating that such rigorous standards for quality in evidence synthesis were 'ridiculous'. This highlights a vital need for the field to follow in the footsteps of healthcare, public policy, conservation and environmental science, ecotoxicology, and several others in embracing robust evidence synthesis, building capacity for more reliable evidence-informed policy, practice and research.

We call, therefore, for concerted and unbiased secondary research interest and funding in the field of salmon aquaculture, particularly on social and ecological impacts of the industry and its supply chains. We strongly advocate for review authors to use the highest methodological rigour in all cases, following internationally recognised best practices in evidence synthesis, such as the Guidelines and Standards for Evidence Synthesis in Environmental Management (CEE 2022). We request editors and peer-reviewers uphold a high standard in the syntheses they consider and publish.

Declarations

Competing interests

The authors declare they have no competing financial interests.

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Author's contributions

Conceptualisation - NRH;

Methodology - NRH;

Validation - NRH;

Investigation - NRH, HC;

Visualisation - HC, NRH;

Writing, Original Draft - NRH;

Writing, Review & Editing - NRH, HC, MDLR;

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Additional Files

Additional File 1 - search record.
Additional File 2 - fates of all full text screened articles.
Additional File 3 - extracted data.

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Appendix 1. Benchmark list

1. Bjarnason, A. and Magnusdottir, K.S., 2021. The Salmon Sea Fish Farming Industry in Iceland. *A review. Fish Aqua J*, *10*(2).

Iceland has for a long time been renowned for its rich fishing grounds and prolific fisheries sector. Salmon sea fish farming in Iceland, as we know it today, is however a relatively young industry which goes back only few years. It has however, already experienced strong growth in investment, production, exports revenue and is a provider of employment in rural areas in Iceland. Operating licences issued for salmon farming in sea cages in Iceland, amount in total to less than 60 thousand tons. The four biggest companies in the industry which control nearly all of the operating licences issued in Iceland, are majority owned or fully owned by Norwegian investors and existing companies in the Norwegian salmon industry. With one or two exceptions, for some reason, companies in the Icelandic fisheries and fish processing sector, do not participate as investors and shareholders in the build-up of the salmon sea fish farming industry in Iceland, and therefore, have not added salmon into their fish production.

2. Bravo, S. and Treasurer, J., 2023. The management of the sea lice in Chile: A review. *Reviews in Aquaculture*, *15*(4), pp.1749-1764.

Sea lice infestations have the largest economic and biological impact on salmon farming in Chile, similar to that seen in salmon-producing countries in the northern hemisphere. Caligus teres infesting coho salmon (Oncorhynchus kisutch) was first recorded in 1981, but Caligus rogercresseyi has been the predominant species infesting Atlantic salmon (Salmo salar) and rainbow trout (Oncorhynchus mykiss) from 1997. In contrast, coho salmon has been shown to be resistant to this sea louse species. Regulations to establish integrated pest management of sea lice were implemented by the Chilean authority in 2007. However, to date, pharmacological medicines have been the main tool used by the salmon farming industry in Chile to manage sea lice, although non-pharmacological treatments have been available since 2016. Production of farmed salmon reached 978.274 tons in 2021 and 7.72 g of medicines was prescribed per ton of harvested salmon. The highest volumes used in that year were Azamethiphos (47%) and hexaflumuron (45.5%), in addition to 5532 tons of hydrogen peroxide. This review updates the current management of sea lice in Chile and also summarizes the biological knowledge of this important parasite.

3. Duman, M., Altun, S., Saticioglu, I.B. and Romalde, J.L., 2023. A review of bacterial disease outbreaks in rainbow trout (Oncorhynchus mykiss) reported from 2010 to 2022. *Journal of Fish Diseases*.

Outbreaks of bacterial infections in aquaculture have emerged as significant threats to the sustainable production of rainbow trout (Oncorhynchus mykiss) worldwide. Understanding the dynamics of these outbreaks and the bacteria involved is crucial for implementing effective management strategies. This comprehensive review presents an update on outbreaks of bacteria isolated from rainbow trout reported between 2010 and 2022. A systematic literature survey was conducted to identify relevant studies reporting bacterial outbreaks in rainbow trout during the specified time frame. More than 150 published studies in PubMed, Web of Science, Scopus, Google Scholar and relevant databases met the inclusion criteria, encompassing diverse geographical regions and aquaculture systems. The main bacterial pathogens implicated in the outbreaks belong to both gram-negative, namely Chryseobacterium, Citrobacter, Deefgea Flavobacterium, Janthinobacterium, Plesiomonas, Pseudomonas, Shewanella, and gram-positive genera, including Lactococcus and Weissella, and comprise 36 new emerging species that are presented by means of pathogenicity and disturbance worldwide. We highlight the main characteristics of species to shed light on potential challenges in treatment strategies. Moreover, we investigate the role of various risk factors in the outbreaks, such as environmental conditions, fish density, water quality, and stressors that potentially cause outbreaks of these species. Insights into the temporal and spatial patterns of bacterial outbreaks in rainbow trout aquaculture are provided. Furthermore, the implications of these findings for developing sustainable

and targeted disease prevention and control measures are discussed. The presented study serves as a comprehensive update on the state of bacterial outbreaks in rainbow trout aquaculture, emphasizing the importance of continued surveillance and research to sustain the health and productivity of this economically valuable species.

4. Gowen, RJ, 1987. The ecological impact of salmonid farming in coastal waters: a review. *Oceanogr. Mar. Biol. Ann. Rev.*, *25*, pp.563-575.

The composition and quantity of wastes (uneaten food, faecal and excretory material) generated by cage culture of Atlantic salmon and rainbow trout, and the potential impact of this waste on both the marine environment and on production of the fish farm itself are reviewed. A number of compounds are found in fish-farm waste, but organic C, resulting in sediment enrichment, and dissolved N, resulting in hypernutrification of surrounding waters, are the most important. Sediment anoxia, reduction of benthic macrofauna, and eutrophication tend to be localized. Potential negative impacts on salmonid culture include outgassing of H2S and induction of toxic blooms. Careful preselection of sites with good water exchange, reduction of food wastage, and periodic cage redeployment are suggested to minimize environmental damage and negative feedback. Dept. of Biol. Sci., The Univ., Stirling, Scotland. (gsb)

5. Hines, I.S., Marshall, M.A., Smith, S.A., Kuhn, D.D. and Stevens, A.M., 2023. Systematic literature review identifying bacterial constituents in the core intestinal microbiome of rainbow trout (Oncorhynchus mykiss). *Aquaculture, Fish and Fisheries*, *3*(5), pp.393-406.

Fish aquaculture has become the fastest growing sector in global food production. Thus, ensuring the sustainability of aquaculture practices is of the utmost importance. Studies in higher vertebrates (i.e. mammals) have demonstrated the role of the host microbiome in physiological processes from nutrient acquisition to pathogen protection. Therefore, analysis of fish microbiomes is an important factor to consider with regard to overall animal health and welfare. Rainbow trout (Oncorhynchus mykiss) are an economically valued fish cultured worldwide. Several studies have identified microbial constituents inhabiting the intestinal tract of rainbow trout. To better elucidate some of the core constituents of the rainbow trout intestinal microbiome, this systematic literature review analysed the relative abundance results from 25 articles published on the rainbow trout intestinal microbiome from 2017 to 2021. Bacteria classified within the phyla Firmicutes and Proteobacteria were observed in every study. At the family level, Lactobacillaceae was consistently observed. Additionally, bacteria in the Actinobacteria, Bacteroides, and Tenericutes phyla were identified in at least 50% of the studies. Interestingly, Mycoplasma spp. were occasionally the most dominant organisms present in the microbiome. Overall, the results here identify bacteria that are commonly found members of the rainbow trout intestinal microbiome.

6. Tuševljak, N., Rajić, A., Waddell, L., Dutil, L., Cernicchiaro, N., Greig, J., Wilhelm, B.J., Wilkins, W., Totton, S., Uhland, F.C. and Avery, B., 2012. Prevalence of zoonotic bacteria in wild and farmed aquatic species and seafood: a scoping study, systematic review, and meta-analysis of published research. *Foodborne Pathogens and Disease*, *9*(6), pp.487-497.

Increased reliance on seafood has brought to light concerns regarding food safety, but the information to inform risk assessment or surveillance needs is lacking. A scoping study (ScS) was conducted to characterize published research investigating selected zoonotic bacteria and public health topics in various wild and farmed aquatic species and seafood. This was followed by a systematic review (SR) on selected bacteria (Aeromonas spp., generic Escherichia coli, Salmonella spp., and Vibrio spp.) and aquatic species (clams, mussels, oysters, salmon, and shrimp [including prawn]); a meta-analysis (MA) was conducted only at the retail level due to considerable variability among various pathogen/seafood combinations. The ScS revealed the most frequently investigated themes were farm-level prevalence and intervention research for Vibrio spp. and Aeromonas spp. Antimicrobial use (AMU) and the association between AMU and antimicrobial resistance were rarely investigated. The SR indicated a consistent lack of reporting regarding study methodology and results, precluding the

use of many studies in and full benefits of MA. MA of Aeromonas, E. coli, and Salmonella prevalence in retail salmon resulted in pooled estimates of 13% (6–-27%), 2% (0.1–-11%), and 1% (0–5%), respectively. When MA of pathogen/seafood combination resulted in statistically significant heterogeneity ($p<0.1$), median/range were reported at the region level. The results from our ScS, SR, and MA could be used for better design of future bacteriological surveys of seafood and as inputs for risk assessments or surveillance initiatives in this field.