EUROPEAN PARTNERSHIP

Disentangling Global Supply Chains

A Systematic Map of Research on the Biodiversity and Social Impacts of European Blue Food Consumption

Co-funded by the European Union

Document Information

Grant Agreement number	101052342
Project acronym	Biodiversa+
Project full name	The European Biodiversity Partnership
Biodiversa+ duration	7 years
Biodiversa+ start date:	Start date: 1st October 2021
For more information about Biodiversa+	Website: https://www.biodiversa.eu/ Email: contact@biodiversa.eu LinkedIn: Biodiversa+

Deliverable title	D4.13: Disentangling Global Supply Chains: A Systematic Map of Research on the Biodiversity and Social Impacts of European Blue Food Consumption
Dissemination level	Public
Authors	Neal Haddaway (Freelance researcher; Harper Adams University; University of Johannesburg), Helen Sampson (Freelance researcher), Ingrid Kelling (Heriot-Watt University), Marija Sciberras (Heriot-Watt University), Hazel Cooley (Freelance researcher), Linda Errington (Freelance researcher), Sini Savilaakso (Juno Evidence Alliance; University of Helsinki, Finland)
Contributors	Steve Cook
Work package title	Work Package 4: Connecting R&I programs, results and experts to policy
Task or sub-task title	Subtask 4.1.2: Desk studies and production of knowledge syntheses
Lead partner	FRB
Date of publication	May 2026
Disclaimer	Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. This deliverable has not yet been approved by the European Commission.

Cover page illustration: Photo by Norbert Buduczki (Unsplash)

What is Biodiversa+

The European Biodiversity Partnership, Biodiversa+, supports excellent biodiversity research with impact for policy and society. Connecting science, policy and practice for transformative change, Biodiversa+ is part of the European Biodiversity Strategy for 2030, which aims to put Europe's biodiversity on a path to recovery by 2030. Co-funded by the European Commission, Biodiversa+ brings together partners from research funding, research programming and environmental policy across European and associated countries to work on five main objectives:

1. Plan and support research and innovation on biodiversity through a shared strategy, annual joint calls for research projects and capacity building activities
2. Set up a network of harmonised schemes to improve monitoring of biodiversity and ecosystem services across Europe
3. Contribute to high-end knowledge for deploying Nature-based Solutions and valuation of biodiversity in the private sector
4. Ensure efficient science-based support for policy-making and implementation in Europe
5. Strengthen the relevance and impact of pan-European research on biodiversity in a global context.

More information: https://www.biodiversa.eu/

Table of contents

Executive Summary

Background

Seafood is integral to global food systems, offering essential nutrients and livelihoods to millions. As aquaculture now supplies over half of the world's seafood, its social and biodiversity impacts are coming under increased scrutiny. Europe, a major consumer and importer of farmed seafood (blue food), is at the centre of these global supply chains. While aquaculture supports rural economies and food security, it also generates significant ecological harms—including nutrient pollution, disease spread, habitat loss, and dependence on wild-caught fish for feed. These impacts are compounded by social risks such as labour exploitation, livelihood displacement, and food insecurity in producing regions. Despite growing awareness, the scientific evidence base is uneven across species, geographies, and disciplines.

Methodology

Here we report on the results of a systematic map undertaken to explore the biodiversity and societal impacts of European blue food production-consumption chains, with a focus on cod, salmon, sea bass and sea bream farming. We developed a comprehensive search strategy across five bibliographic databases and multiple grey literature sources. The research question was structured using a modified (Population Comparator Intervention Outcome) PICO framework, considering social and ecological systems as the population, aquaculture as the exposure, and any social or biodiversity outcomes. Screening was conducted at two stages (title and abstract, and full text), followed by meta-data extraction and coding. We used a random subsampling approach to ensure a representative analysis of the evidence base, with 60% of the evidence examined in total.

Results

We identified 210 relevant studies (205 academic and 5 grey literature) from across >28,000 search results. The map uncovered a diverse but uneven evidence base regarding the biodiversity and social impacts of European blue food supply chains. Research efforts are heavily concentrated on particular species and regions, largely in line with production volumes, with Atlantic salmon (*Salmo salar*) being the most frequently studied species, particularly in Canada, Chile, and Northern Europe (Norway and the UK). A significant secondary evidence base on sea bass (*Decentrus labrax*) and gilthead sea bream (*Sparus aurata*) also exists, primarily clustered in the Mediterranean, while evidence concerning cod (*Gadus spp.*) remains very limited.

A stark thematic imbalance exists between ecological and social research. The vast majority of identified studies investigate ecological outcomes, with a significant focus on benthic community composition, wild fish mortality, and the impacts of sea lice. Meanwhile, social impacts are underrepresented as a whole, and key aspects are entirely absent, such as labour conditions and food security in producing regions. Furthermore, only one study integrated both social and ecological outcomes, indicating a critical lack of interdisciplinary research within the sector. Research methods used typically lack baselines, with a dominance of observational studies. Geographically, research focus varies; whilst Norway and Canada both emphasise wild fish effects, Canada has a focus on benthic and pathogen impacts, Norway has a minor emphasis on pathogens and benthic impacts, and Chile demonstrates a more diverse research profile that includes microbial systems and social impacts. Most studies focus almost exclusively on the rearing of adults in offshore pen systems, leaving critical supply chain stages such as feed production and processing plants largely unexamined. Only 6 studies examined the impacts of mitigation measures, demonstrating a further research gap.

Conclusions

The systematic map identifies a relatively small and uneven evidence base on the biodiversity and social impacts of European blue food production–consumption chains. Patterns of research effort largely mirror aquaculture production volumes and industry concentration, with Atlantic salmon and major producing countries such as Norway, Canada, Chile, and Mediterranean nations accounting for the bulk of the literature. However, this alignment with production does not translate into comprehensive coverage of impacts. Even within high-production systems, research is narrowly focused on a limited set of species, locations, impact pathways, and production stages, leaving substantial gaps in understanding of cumulative, indirect, and supply-chain-wide effects.

Across species and geographies, the evidence base is overwhelmingly skewed towards ecological outcomes, particularly impacts on benthic communities, wild fish interactions, pathogens, and sea lice. Social impacts are markedly underrepresented, and several key social dimensions are absent from the mapped evidence base. While some studies address attitudes or limited socio-economic effects, there is no empirical evidence engaging with labour conditions, nor with broader food security or food sovereignty implications in producing regions, which are rarely operationalised within aquaculture impact studies. Very few studies integrate social and ecological outcomes within the same analysis, limiting insight into how biodiversity impacts translate into social consequences or trade-offs along the supply chain.

The map also highlights a strong production-stage bias. Most studies focus almost exclusively on the rearing of adult fish in offshore pen systems, with minimal attention to upstream activities such as feed production and hatcheries, or downstream stages such as processing. As a result, critical components of the global supply chain that are central to cumulative environmental pressures and social risk remain poorly understood. Evidence on mitigation measures is particularly scarce, constraining the ability to assess which interventions may reduce impacts without generating new trade-offs.

Taken together, these patterns indicate that current research does not yet provide a sufficiently holistic or policy-relevant evidence base for addressing the biodiversity and social implications of European blue food consumption. Future research should prioritise filling clearly defined gaps identified by this map, including under-studied species (Pacific salmon [*Oncorhynchus tshawytscha*, *O. kisutch*, *O. nerka*, *O. keta*, *O. gorbuscha*, *O. masou*] and Atlantic cod [*G. morhua*]), impacted systems, production stages beyond grow-out, and the systematic integration of social and ecological outcomes. Strengthening evidence on mitigation strategies is essential if research is to meaningfully support the objectives of the European Biodiversity Strategy for 2030 and inform more equitable and sustainable blue food systems.

1. Introduction

1.1. Background

Seafood (here referring to marine species that are predominantly wild-caught or cultured in marine systems) plays a vital role in global food systems, providing essential micronutrients, protein, and livelihoods to hundreds of millions of people around the globe (Golden et al., 2016). Aquaculture has grown exponentially over the past few decades and now supplies approximately half of all seafood consumed globally (Food and Agriculture Organization (FAO), 2022). Europe is both a major consumer and a significant node in global seafood, i.e. blue food ("aquatic foods captured or cultivated in marine and freshwater systems", Naylor et al., 2021) supply chains, importing and producing large volumes of farmed fish, such as salmon, cod, sea bass and sea bream. These supply chains, while important for meeting dietary needs and sustaining rural economies, also carry significant ecological and social risks that are increasingly the subject of scientific and policy concern (Bostock et al., 2010; Bush et al., 2019).

The environmental impacts of aquaculture are diverse and often severe. Intensive production systems have been associated with a range of negative outcomes for marine and also freshwater ecosystems, including nutrient pollution (Islam, 2005), eutrophication (Folke et al., 1994), the spread of disease (Krkošek et al., 2011), escape of non-native species (Naylor et al., 2005), and the degradation of sensitive habitats (Primavera, 2006). For instance, studies in Norway and Chile - two of the world's leading salmon producers - have shown how nutrient loading from open-net pen systems contributes to harmful algal blooms and shifts in benthic community structure (Folke et al., 1994; Boissy et al., 2011). These changes adversely affect local biodiversity and reduce the resilience of ecosystems to other stressors, such as climate change and overfishing.

Feed production for aquaculture introduces additional complexity in terms of environmental and social impacts (Micheli et al., 2014). Fishmeal and fish oil, commonly used in diets for carnivorous species like salmon, are typically derived from wild-caught forage fish, linking farmed seafood to extraction pressures in marine ecosystems elsewhere, for example the overexploitation of artisanal fisheries in West Africa in connection with salmon feed supply chains in Northern Europe (Feedback UK, 2024). Naylor et al. (1998) characterised this dependency as "nature's subsidies" to aquaculture, highlighting the ecological costs embedded in feed inputs. More recent studies have underscored the significant ecological footprint of feed production, including habitat conversion, greenhouse gas emissions, and trophic disruptions in marine food webs (Cottrell et al., 2020).

Beyond ecological impacts, aquaculture also has far-reaching social implications. These include land and water use conflicts (Bavinck et al., 2014), displacement of traditional livelihoods (Stonich & Bailey, 2000), labour rights concerns (Vandergeest & Marschke, 2019), and food security trade-offs (Belton et al., 2018). Labour exploitation in aquaculture and seafood processing has also received growing attention, particularly in supply chains that serve European markets. Reports of human rights violations in Asian aquaculture have been demonstrated to involve forced labour and unsafe working conditions, which prompted calls for greater transparency and accountability in global seafood supply chains (Environmental Justice Foundation, 2015; Vandergeest, 2018). However, despite widespread media and reporting by non-governmental organisations, academic research into the social dimensions of aquaculture remains sparse and fragmented, especially in comparison to the ecological literature (Bush & Marschke, 2014; Béné et al., 2015).

There is also evidence of uneven distribution of research effort across species and geographies, likely reflecting the levels of commercial interest in each. For example, salmon aquaculture has received considerable scientific scrutiny, especially in Europe and North America, with numerous studies exploring issues such as fish welfare, antibiotic use, and interactions with wild salmonids (Ford & Myers, 2008; Newton & Little, 2017). In contrast, research into cod aquaculture is relatively limited, despite efforts to expand farming operations in the North Atlantic.

Moreover, many studies adopt narrow disciplinary lenses or focus on specific stages of the production chain, limiting their relevance to understanding systemic or cumulative impacts. Very few studies explicitly link biodiversity outcomes to social consequences, such as how the degradation of coastal ecosystems affects food security or employment in producer countries (Kittinger et al., 2015). Likewise, life cycle assessments often focus on carbon emissions or resource efficiency (Ziegler et al., 2016) but may overlook cultural, gendered, or distributional aspects of sustainability.

This lack of integrated, cross-cutting evidence hampers efforts to design seafood systems that are both ecologically sustainable and socially just. It also constrains the ability of policymakers to respond to biodiversity loss and social inequity in seafood supply chains with informed, evidence-based interventions.

In the European context, the strategic importance of addressing these challenges is articulated in the EU's *European Green Deal* and the *Farm to Fork Strategy*, which aim to position the food system as a global standard for sustainability. Central to this ambition are the "Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030." These guidelines explicitly task Member States and stakeholders with reducing the environmental footprint of farmed seafood while ensuring societal acceptance and economic viability. By emphasising the need for increased diversification, improved environmental performance, and enhanced transparency, the EU policy framework aims to underscore the need for a holistic understanding of the sector's impacts. However, the implementation of these guidelines relies heavily on the availability of robust, synthesised data that can bridge the gap between high-level sustainability targets and the practicalities of diverse production systems across the continent, and further afield when taking into account the impacts of European food imports.

In response, there is growing consensus on the need for transdisciplinary research that maps the full range of impacts of seafood production and trade, especially those associated with high-consumption markets like the European Union. Calls for such work are echoed in global assessments, including the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which identifies unsustainable food systems as a primary driver of biodiversity decline. The Blue Food Assessment (Nature, 2021) similarly emphasises the need for robust evidence on the trade-offs and synergies associated with different aquatic food production systems. Without a clear understanding of where evidence exists and where gaps remain, efforts to monitor, mitigate, or transform the impacts of blue foods will remain limited in scope and effectiveness.

Given the complexity, geographic spread, and uneven evidence base of seafood supply chains, there is an urgent need to systematically map the current knowledge on their impacts. Such a synthesis not only illuminates the extent and distribution of biodiversity and social consequences, but also where further research is needed to support policy and practice aimed at making blue food systems truly sustainable.

1.2. Conceptual framework

We have designed a model in Figure 1 that outlines our conceptual framework for this review. The conceptual framework illustrates how European demand for blue food (such as farmed fish and seafood) creates ripple effects both within Europe and globally, through European aquaculture production and importation from other countries. It emphasizes the complex trade-offs between economic and socio-ecological costs and benefits like employment, biodiversity impacts of pollution, loss of livelihoods, and biodiversity decline.

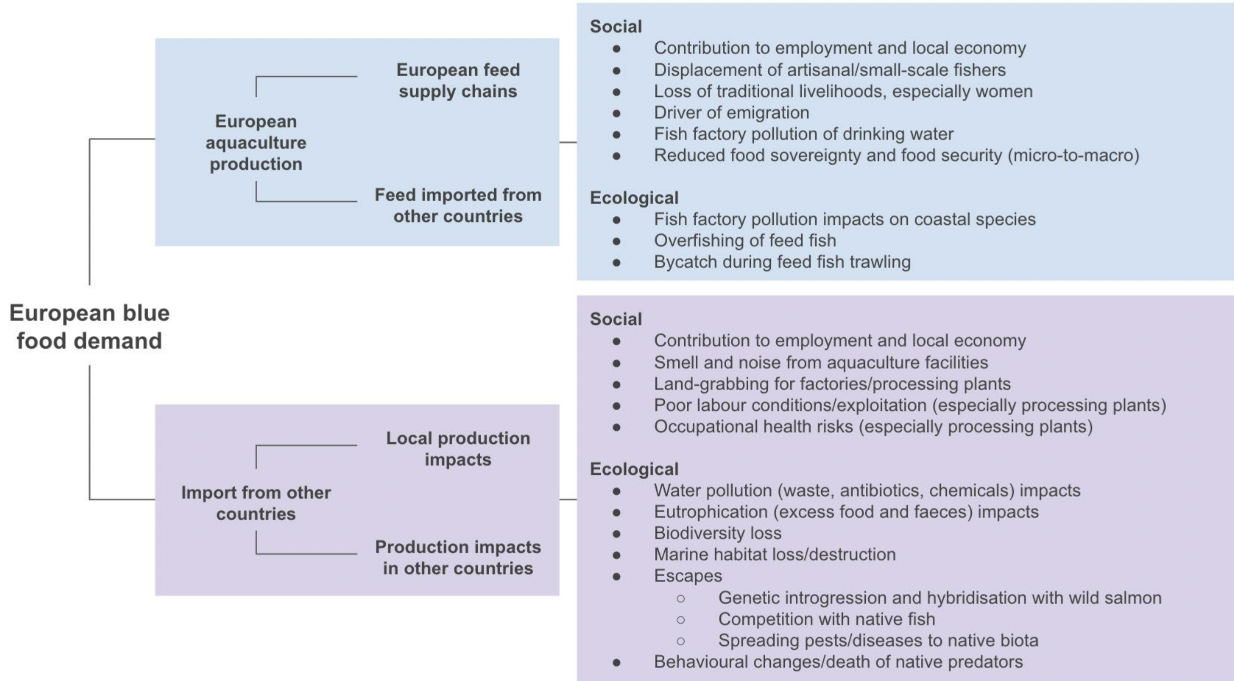

Figure 1. Conceptual framework describing the key pathways for social and ecological impacts caused by European blue food demand via aquaculture.

1.3. Review objective and research questions

Our systematic map has the following primary and secondary questions:

Primary question: What evidence exists on the impacts of European blue food production consumption chains on biodiversity and society?

We have the following secondary questions:

- What ecosystems and species are most studied?
- For which seafood production systems have biodiversity and social impacts been most frequently reported?

- What monitoring methods have been used to assess the biodiversity impacts of these blue foods?
- What research exists into minimising the biodiversity and social impacts of these blue foods, and which of these interventions are considered 'nature-based solutions'?

1.4. Components of the research question

We break down the questions above into the following key elements, based on our knowledge of the evidence base - full justification is provided in the eligibility criteria, below.

Population	Global social and ecological systems, including aquaculture and fisheries in countries that export marine-derived foods ('blue foods') to European markets.
Exposure	The farming of cod (genus Gadus), salmon (*Salmo salar*, *Oncorhynchus tshawytscha*, *Oncorhynchus kisutch*, *Oncorhynchus nerka*, *Oncorhynchus keta*, *Oncorhynchus gorbuscha*, and *Oncorhynchus masou*, but excluding *Oncorhynchus mykiss*), sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*). We will include research on the impacts of fish feed for these species. These species are chosen because of their importance in European blue food markets and their shared production methods. Shellfish, due to their different culture methods and inputs, are excluded here.
Outcome	Any social and/or biodiversity impacts reported (e.g. species diversity and abundance, employment, household income).

1.5. Stakeholders' role in the review

This systematic map has been conducted under work package 4 ("Connecting R&I programs, results and experts to policy") of Biodiversa+, the European Biodiversity Partnership. Biodiversa+ is a network of national and regional research and innovation funders and environmental policy bodies across Europe, working to support science-based policymaking and coordinate biodiversity research aligned with EU priorities.

The secondary questions are designed to align with key Biodiversa+ flagship objectives by identifying which ecosystems, species, and biodiversity metrics are most commonly studied, thereby supporting improved transnational biodiversity monitoring. They also explore research on interventions and social outcomes, directly contributing to Biodiversa+ goals of ecosystem restoration and societal transformation for sustainable biodiversity management.

2. Methods

This systematic map was conducted according to an a priori protocol (Haddaway et al., 2025), following the CEE Guidelines and Standards for Evidence Synthesis in Environmental Management (2018) and James et al. (2016), and reported in line with ROSES reporting standards for systematic maps (Haddaway et al., 2018).

2.1. Deviations from the protocol

We have not deviated from our plans in our *a priori* protocol.

2.2. Searching for articles

See Annex 2 for full details of the search strategy across sources.

2.2.1. Searching bibliographic databases and search specialism in the team

We searched the bibliographic databases listed in Table 1 using tried-and-tested search strings (see below) in English (since all major databases index in English) between the 2nd and 20th of June 2025. We also included targeted searches across specialist resources for grey literature. We searched the following databases using the string below (see Section 5d).

Table 1. Bibliographic databases used for literature searching.

Database	Comments
Scopus	1960 to present
CAB Abstracts	EBSCO CAB abstracts - 1973 to present
Web of Science Core Collection	Includes: • Science Citation Index Expanded (SCI-EXPANDED)--1970-present • Social Sciences Citation Index (SSCI)--1970-presentSocial Sciences Citation Index (SSCI)--1970-present • Arts & Humanities Citation Index (AHCI)--1975-presentArts & Humanities Citation Index (AHCI)--1975-present • Conference Proceedings Citation Index – Science (CPCI-S)--1990-present • Conference Proceedings Citation Index – Social Science & Humanities (CPCI-SSH)--1990-present • Emerging Sources Citation Index (ESCI)--2015-present

ASFA: Aquatic Sciences and Fisheries Abstracts	Via EBSCO
ProQuest Dissertations and Theses	Via Web of Science

2.2.2. Searching for grey literature

We performed searches in Google Scholar and manually screened all results using the following basic search strings (searching only title words). These terms were translated into Spanish, French and Norwegian (see Annex 2 for a record of these searches):

- cod AND (aquaculture OR farming OR cage) AND impacts

  [“allintitle: cod impacts farming OR aquaculture OR cage” in GS syntax]
- salmon AND (aquaculture OR farming OR cage) AND impacts

  [“allintitle: salmon impacts farming OR aquaculture OR cage” in GS syntax]
- sea bass AND (aquaculture OR farming OR cage) AND impacts

  [“allintitle: sea bass impacts farming OR aquaculture OR cage” in GS syntax]
- sea bream AND (aquaculture OR farming OR cage) AND impacts

  [“allintitle: sea bream impacts farming OR aquaculture OR cage” in GS syntax]

In addition, we searched the websites of a range of key organisations listed in Table 2.

Table 2. Organisational websites searched for grey literature.

Organisation	Website	Search terms
FAO (AGRIS)	https://agris.fao.org/adv-search/en	(cod OR gadus OR “atlantic salmon” OR “salmo salar” OR “farmed salmon” OR “reared salmon” OR “caged salmon” OR“sea bass” OR “sea bream”) AND (farm* OR cage* OR pens OR penned OR pen OR aquacultur* OR reared OR rearing OR cultivat* OR culture OR domesticated OR mariculture OR aquaculture) AND (impact* OR effect*)
CGSpace	https://cgspace.cgiar.org/home	cod farming “salmon farming” sea bass farming sea bream farming
Centre for Ecology and Hydrology	https://www.ceh.ac.uk	cod farming salmon farming sea bass farming sea bream farming

Centre for Environment, Fisheries and Aquaculture Science	https://www.cefas.co.uk	cod farming salmon farming sea bass farming sea bream farming
Fisheries Research Service	https://www.gov.scot	cod farming salmon farming sea bass farming sea bream farming
United Nations Environment Programme	https://www.unenvironment.org	cod farming salmon farming sea bass farming sea bream farming

2.2.3. Justification of search limits

We have not included geographical/time period or any other limitations to our searches.

2.2.4. Search string

We used the search string in Table 3 across the databases outlined in Table 1 above.

Table 3. Bibliographic database search string.

Component	String
#1 Farming	TITLE-ABS-KEY(farm* OR cage* OR pens OR penned OR pen OR aquacultur* OR reared OR rearing OR cultivat* OR culture* OR mariculture* feed OR feeds OR fishmeal OR "fish meal" OR "fish oil" OR fishoil OR pellets OR aquafeed OR "aqua feed" OR diet*)
#2 Species	TITLE-ABS-KEY(((cod AND fish) OR gadus) OR (salmon OR "salmo salar" OR "S. salar" OR "Oncorhynchus kisutch" OR "Onchorhynchus kisutch" OR "O. kisutch" OR "Oncorhynchus tshawytscha" OR "Onchorhynchus tshawytscha" OR "O. tshawytscha" OR "Oncorhynchus tshaivytscha" OR "Onchorhynchus tshaivytscha" OR "Oncorhynchus keta" OR "Onchorhynchus keta" OR "O. keta" OR "Oncorhynchus masou" OR "Onchorhynchus masou" OR "O. masou" OR "yamame trout" OR "Oncorhynchus nerka" OR "Onchorhynchus nerka" OR "O. nerka" OR "Oncorhynchus gorbuscha" OR "Onchorhynchus gorbuscha" OR "O. gorbuscha" OR "Sparus aurata" OR "S. aurata" OR seabream OR "sea bream" OR dorada OR dorade OR "gilt-head bream" OR gilthead OR "Dicentrarchus labrax" OR "D. labrax" OR seabass OR "sea bass"))
#3 Outcome	TITLE-ABS-KEY((biodiversity OR "bio-diversity" OR "biological diversity" OR ((species OR communit* OR ecosystem* OR functional OR tax* OR trait* OR flora* OR hydrophyte* OR fauna* OR meiofauna* OR macrofauna* OR microfauna* OR plankton* OR phytoplankton* OR benthic OR benthos OR alga* OR plant* OR animal* OR vertebrate* OR invertebrate* OR macroinvertebrate*) W/5 (biomass OR divers* OR abundan* OR richness OR heterogen* OR indicator* OR frequen* OR composition* OR distribution* OR migrat* OR density OR dispers* OR reproduction OR mortalit* OR focal OR keystone OR umbrella OR "red-list" OR "red-listed" OR redlist* OR threaten* OR endangered OR rare OR extinct*)) OR (risk AND extinct*)) OR (social OR societal OR socio* OR employ* OR income OR empower* OR communit* OR econom* OR "cultural heritage" OR "traditional knowledge" OR livelihood* OR poverty OR

	inclus* OR "food security" OR gender* OR participat* OR migrant* OR emigrat* OR immigrat*))
#4	#1 AND #2 AND #3

2.2.5. Comprehensiveness of search - benchmark papers

We assembled a list of 12 relevant articles that were used to test the recall of the searches above (see Annex 1). No studies were missed and the search string was considered complete prior to publication of the protocol.

2.2.6. Citation searching & reference list checking

We conducted forwards and backwards citation chasing (collating all citations of and references from a set of articles) using the benchmark list, combining the results with those of bibliographic database searches prior to deduplication and screening. This ensured that the small number of records not terminologically linked were captured.

2.2.7. Search update

Given the short timespan and limited resources for this review project we have not performed a search update.

2.3. Managing results

We managed references in EndNote 21, performing an initial deduplication using the method outlined in Bramer et al. (2016), before moving records into Rayyan.ai, where we performed a final stage of deduplication at a more sensitive level. Screening of titles and abstracts, and full texts, took place in Rayyan.

2.4. Article screening

2.4.1. Eligibility criteria for including studies

Our review used the following inclusion criteria:

- **Population** - Global social and ecological systems, including aquaculture and fisheries in countries that export marine-derived foods (‘blue foods’) to European markets.
- **Exposure** - farming of cod (genus Gadus), salmon (S. salar, O. tshawytscha, O. kisutch, O. nerka, O. keta, O. gorbuscha, and O. masou, but excluding O. mykiss, which is predominantly farmed in freshwaters), sea bass (D. labrax) and gilthead sea bream (S. aurata). We will include research on the impacts of fish feed for these species where titles or abstracts reference aquaculture of relevant

species. We include research related to both sea-based open-net pens and land-based systems for these marine finfish.

- **Outcome** - any and all impacts on social or ecological communities reported. This includes any impacts on biota, but excludes impacts on the abiotic environment, excluding, for example, research relating to prevalence of aquacultural chemicals in the environment without explicit investigation of the impacts on biota. All studied social impacts will be eligible for inclusion, including positive effects such as employment, providing the impacts are investigated empirically.
- **Study type** - any empirical research study examining impacts using an established scientific method based on some causal relationship (i.e. observational, quasi-experimental, experimental), including life cycle analysis and modelling, but excluding studies without primary data.

2.4.2. Screening process

Articles were screened at two levels: title and abstract, and full text. We screened in random blocks of 20%, screening titles and abstracts and then full texts for each block before moving on to the next. This allowed us to plan accordingly and present results at an earlier stage - such practice allows a representative picture of the evidence base to be mapped should resources not allow full screening of all search results within the resources available. In this way, despite potentially large evidence bases, patterns of clusters and gaps across the evidence are clear from a representative sample of full texts. In the end, we manually screened 8,310 records (60%) at title, abstract, and full text. This cut off was chosen pragmatically as resources limited further work on the additional two blocks of 20%. Although incomplete, we believe the randomisation and large proportion of the evidence base assessed will yield a representative picture of the evidence base and should not be a systematically biased sample. Following consistency checking (described below), the evidence base was screened by one reviewer (HS).

2.4.3. Checking consistency of screening decisions

Prior to screening, a consistency test was conducted to ensure that reviewers applied the eligibility criteria uniformly to a random set of 273 records. The records were independently screened by two reviewers (NRH and HS), who were blind to each other’s decisions. After screening, all conflicts were discussed, and the eligibility criteria were clarified where necessary. A total of 23 conflicts were found across the 273 test records, with 12 relating to relevant reviews, which were readily agreed to be includible during discussion, and 11 meaningful subject conflicts that were easily resolved, the majority of which related to erring on the side of inclusion as the correct judgement. Since this represents a very high level of agreement (92% overall, 96% excluding logistical disagreements), screening immediately proceeded in full by one reviewer (HS), with random blocks of 20% being screened as described above.

2.4.4. Reporting reasons for exclusion

The following potential reasons for exclusion were used to describe any screened full text deemed to be ineligible for the review:

- **Ineligible population** - not a social or ecological system (e.g. industrial system with no clear link to social impacts)
- **Ineligible exposure** - not aquaculture or aquaculture feed supply chains
- **Ineligible outcome** - not a social or biodiversity impact
- **Ineligible study type** - not empirical primary research (e.g. opinion piece)
- **Ineligible species** - not cod, salmon (excluding rainbow trout), sea bass or gilthead sea bream
- **Ineligible system** - not a sea pen or marine land-based facility

2.5. Data extraction and coding

2.5.1. Data extraction process

All articles included at full text were subjected to coding and meta-data extraction. We proceeded in blocks of 20%, extracting meta-data and coding studies across each block before proceeding to the subsequent block, as described for screening. This better allowed us to plan and use limited resources efficiently, and provides a representative picture of the evidence base prior to completion of data-extraction in full.

2.5.2. Consistency checking for construct validity and error checking

A small subset of articles (n=5) was subjected to meta-data extraction and coding by two reviewers independently (NRH and HS), with a full discussion of all discrepancies before a single reviewer (HS) then proceeded with the remaining random blocks of included full texts. No discrepancies were found following discussion of each study, and single-reviewer data extraction then proceeded in full.

2.5.3. Meta-data extracted

We extracted a range of meta-data from the included full text articles, and these were coded as described in Table 4. 'Impact category' was created iteratively based on the author's descriptions of social and biodiversity impacts. These themes were created during coding and in regular consultation across the review team to consolidate related themes and differentiate across related and hierarchical themes. Following an initial data extraction of a small set of studies, the review team met to confirm the themes and finalise the codes prior to completing data extraction. Additional emergent themes that fitted outside of this category were added iteratively, with further rounds of discussion to ensure agreement across the team.

Table 4. Data extraction variables.

Item	Description (predefined categories in parentheses)	Type
Study animal	The focal study animal (Cod / Salmon / Sea bass / Sea bream)	Coding
Study species	Free text description of the study species [Genus species]	Meta-data
Study country	Country in which the study took place (ISO name)	Coding
Study location	Description of the study location	Meta-data
Study latitude / longitude	Given or estimated latitude and longitude	Meta-data
Production stage	The production stage(s) studied (Feed / Roe / Fry / Smolt / Adult / Processing)	Coding
Farming system	The aquaculture system studied (Offshore pens / Freshwater hatcheries / Integrated Multi-Trophic Aquaculture (IMTA) / Semi-closed pens / Processing plants / Multi-Purpose Platforms (MPPs) / Large earthen ponds / Recirculating Aquaculture System (RAS))	Meta-data / thematic emergent clustering
Impact type	Type of impact(s) studied (Ecological / Social)	Coding
Impact details	Description of impact(s) studied	Meta-data
Impact system / category	Iterative (i.e. emergent) hierarchical categorisation of the described impacts based on an iterative clustering of codes under 'Impact details', above and in discussion across the review team authors (e.g. Ecological > Benthos > Community composition Ecological > Marine mammals > Behaviour / Ecological > Birds > Abundance Ecological > Plants > Productivity/biomass Ecological > Microbial > Abundance Social > Attitudes > Socio-economic impacts Social > Cultural practices)	Thematic clustering
Study type	Type of study (Experimental / Observational / Modelling)	Coding
Study objectives	Author-given study objectives	Meta-data
Study design	Design of the study used (BA / CI / BACI / Time series / RCT / Modelling / Qualitative)	Coding
Study length	Number of years of study	Meta-data
Funding body	Stated funding [in funding statement or acknowledgements] (Not reported / Not funded / Industry / Government / NGO / International body)	Coding
Funder	Name of funder	Meta-data

2.6. Risk of bias assessment

Because this review project is a systematic map, we have not undertaken any formal risk of bias/critical appraisal of study validity, although some of the data regarding methodology of included primary studies that were extracted pertained to study validity, and are discussed briefly in terms of its rigour and potential risk of bias across the evidence base as a whole.

2.7. Synthesis

Group bar charts, radial heat plots, heat maps, bubble plots, choropleths and evidence atlases were used to visualise potential gaps and clusters across the evidence base. Knowledge gaps (underrepresented subtopics) and clusters (with sufficient similar studies to warrant further synthesis) are identified by assessing discrepancies in the pattern of the number of studies across the categorical variables described below.

2.8. AI assistance

We have not used machine learning or artificial intelligence to assist in any component of this review.

3. Results

3.1. The systematic mapping process

We have used a ROSES flow diagram (Haddaway et al., 2018) to display the flow of records through our review (see Figure 6). The figure displays the fates of all 28,378 records within the review, including the point at which deduplicated search results were subsampled and 60% of records screened and coded for inclusion in the final map. In total, a final set of 210 studies were included in the systematic map database following subsampling and data extraction for 60% of the search results, indicative of a final potential evidence base of around 350 studies in total. The remainder of this document discusses the number of articles found within this random subsample of 60%, with percentages provided alongside absolute article counts for clarity. The fates of all articles screened at full text are provided in Annex 3.

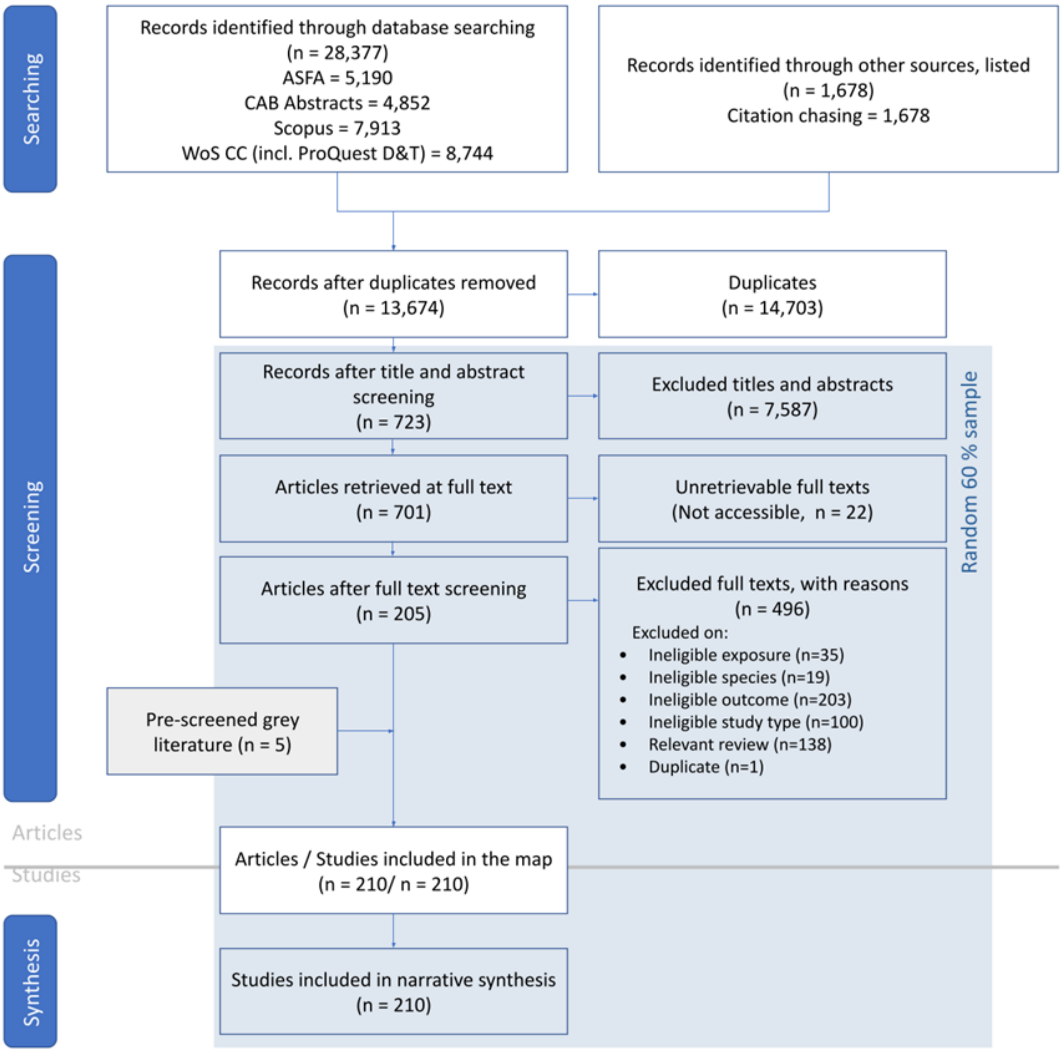

Figure 2. ROSES flow diagram showing the fates of search results through the review process.

3.2. Overview of the evidence base

The systematic map database can be found in Annex 4, and via an interactive table available here: https://thesalmonandthetomato.org/frbsystematicmap.html.

Figure 3 shows the publication trend over time for the evidence base, showing an increase commensurate with general research publication trends, although annual publication rates are variable.

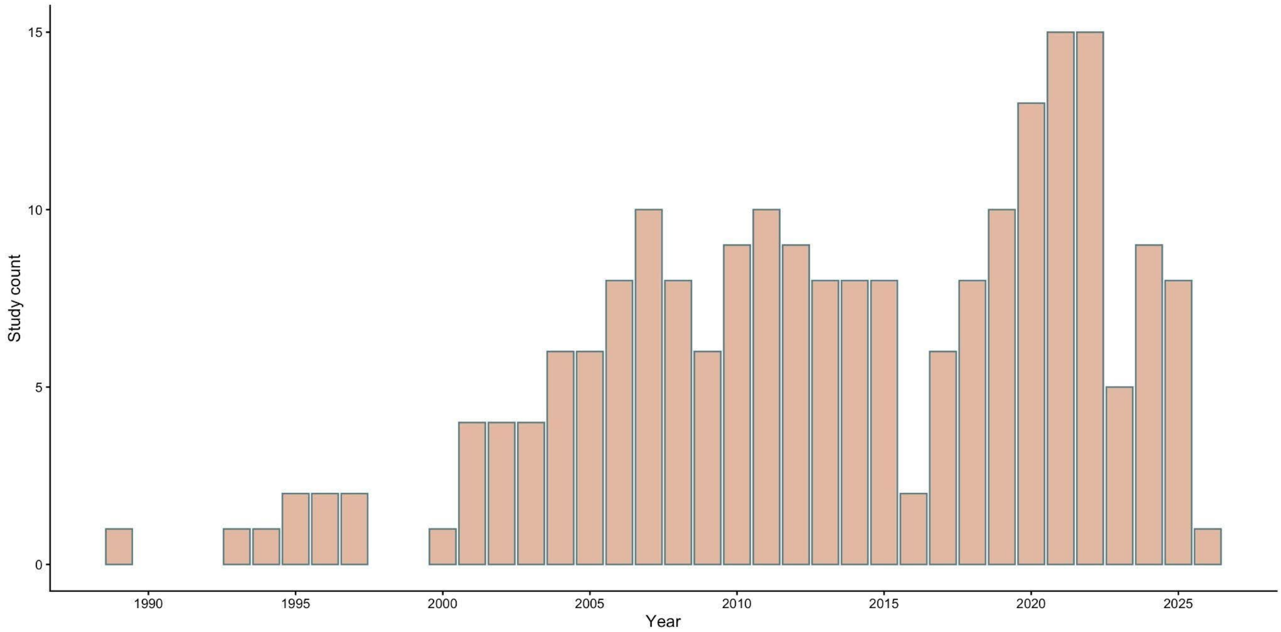

Figure 3. Publication year for the studies included in the map.

Broad patterns across the studies in the evidence base are presented in Figure 4. The most frequently studied species was Atlantic salmon (S. salar) (n=163, 78%), followed by gilthead sea bream (S. aurata) (n=32, 15%), and sea bass (D. labrax) (n=26, 23%). The vast majority of research focused on the rearing of adults (n=162, 77%), with a significant minority not stated (n=35, 17%). Studies examined offshore pens almost exclusively (n=208, 99%), with very few focusing on alternative systems, like freshwater hatcheries (n=9, 4%) and processing plants (n=8, 4%). Integrated Multi-Trophic Aquaculture (IMTA) and Recirculating Aquaculture System (RAS) were the subject of 1 study each (0.5%), as were large earthen ponds.

Most studies used observational designs (total n=175, 83%), followed by experimental (total n=34, 16%) and then modelling (total n=22, 10%) studies. Observation and modelling designs were used in the same study for 13 articles (6%), experimental and observational in 6 (4%), and experimental and modelling in 1 (0.5%). Some 8 studies used modelling designs alone (3%), collating data from other primary sources (not including evidence syntheses, which were not eligible for inclusion in this map). Study designs were relatively diverse, with time-series (n=53, 25%) and comparator-impact (CI) (n=48, 23%) the most common single designs, and frequent use of multiple designs (n=64, 30%). Baselines (in Before-After, Before-After-Comparator-Impacts, and Randomised Control Trials) were used across only 22 studies (10%).

The vast majority of studies investigated ecological impacts (n=174, 83%), with a relatively small number examining social impacts (n=34, 16%), and only two focusing on both (n=2, 1%, see Section 3.3.5, below). Mitigation evaluation was only investigated in a very small minority of studies (n=6, 3%).

Funding was reported for most studies (n=167, 80%), with government being the most commonly reported source of funds (n=115, 55%), followed by research institutes (n=61, 29%), NGOs (n=36, 17%), and industry (n=30, 14%).

The remainder of our results focus on patterns across cross-tabulations and finer resolution data.

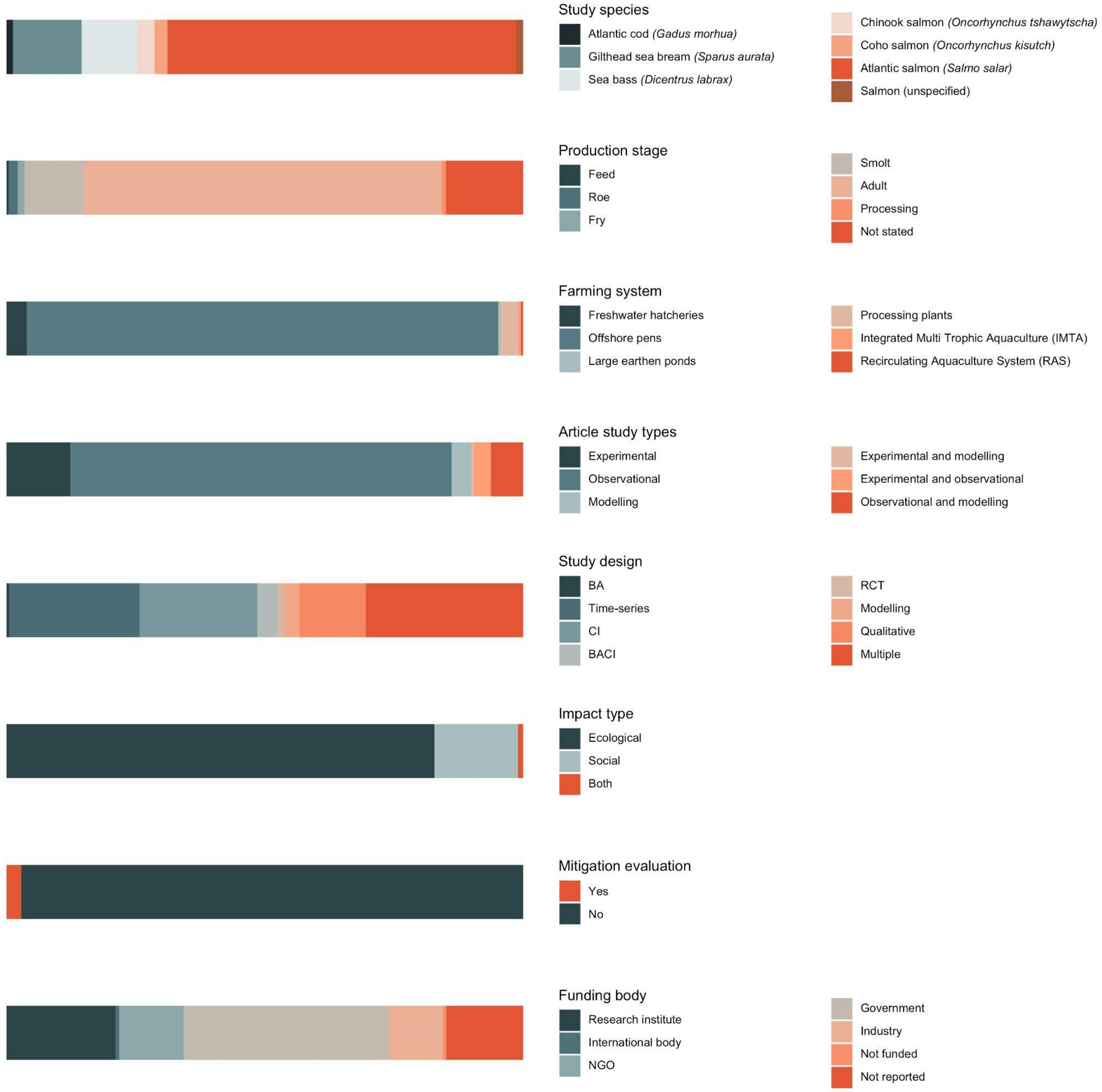

Figure 4. Summary plots showing the proportion of articles in the map according to extracted meta-data.

3.3. Analysis of the evidence base

3.3.1. Study species and locations

Figure 5 displays the spread of evidence across countries by species, showing the historic prevalence of Atlantic salmon (S. salar) research in producing countries (Canada, Chile, Norway, the UK, and Australia). Interestingly, this attention is not correlated with historic fish production levels (Pandey et al., 2023), for which Norway has overwhelmingly predominated for several decades. Other species of salmon have been investigated in isolation in some countries, for example chinook salmon (O. tshawytscha) in Argentina and New Zealand.

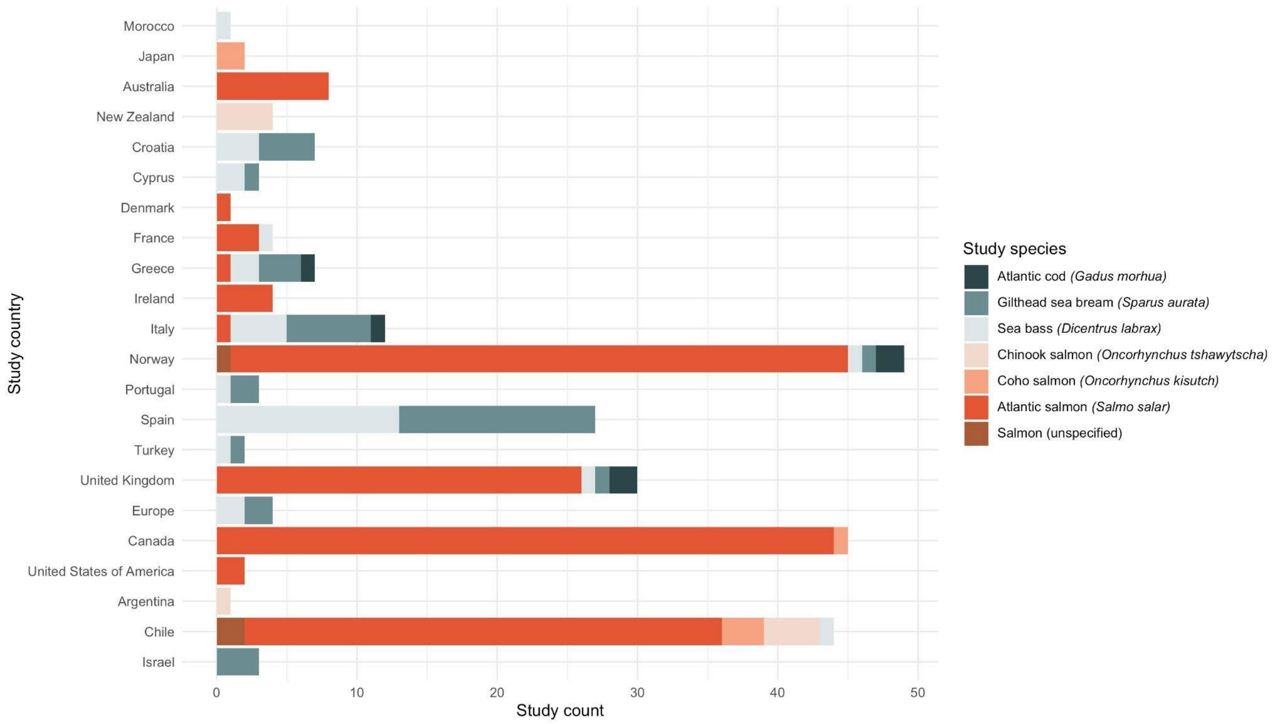

Figure 5. Species studied across countries in articles within the map.

Table 5 shows the number of studies in which species were investigated together, demonstrating that sea bass and sea bream were commonly investigated together, unsurprising since the species are often cultivated (separately) within the same facilities (e.g. by companies such as Cooke, https://www.cookeespana.com/). It is unusual that one study combined Atlantic salmon and sea bass, given their limited geographical overlap.

Table 5. Species investigated in combination in the same studies.

Species	**Number of studies**
Sea bass (*D. labrax*), Gilthead sea bream (*S. aurata*)	20
Atlantic salmon (*S. salar*), Coho salmon (*O. kisutch*), Chinook salmon (*O. tshawytscha*)	2
Atlantic salmon (*S. salar*), Sea bass (*D. labrax*)	1
Atlantic salmon (*S. salar*), Coho salmon (*O. kisutch*)	1
Atlantic salmon (*S. salar*), Chinook salmon (*O. tshawytscha*)	1
Atlantic cod (*G. morhua*), Atlantic salmon (*S. salar*), Sea bass (*D. labrax*), Gilthead sea bream (*S. aurata*)	1
Salmon (unspecified), Atlantic salmon (*S. salar*)	1

For other non-salmonids, Mediterranean countries demonstrate a large collective body of evidence on both sea bream (S. aurata) and sea bass (D. labrax), driven primarily by Spain, Italy and Croatia. Cod has only been studied in a very small number of studies from Norway (n=2, 1%) and the UK (n=1, 0.5%).

The maps in Figure 6 show the distribution of studies across the world, demonstrating the emphasis in Canada, Northern Europe and Chile for Atlantic salmon and sea bream and sea bass in the Mediterranean. Only 6 studies involved data from multiple countries (3%), examining impacts on wildfish (n=3, 1.5%), benthos (n=1, 0.5%), plants (n=1, 0.5%), and plankton (n=1, 0.5%).

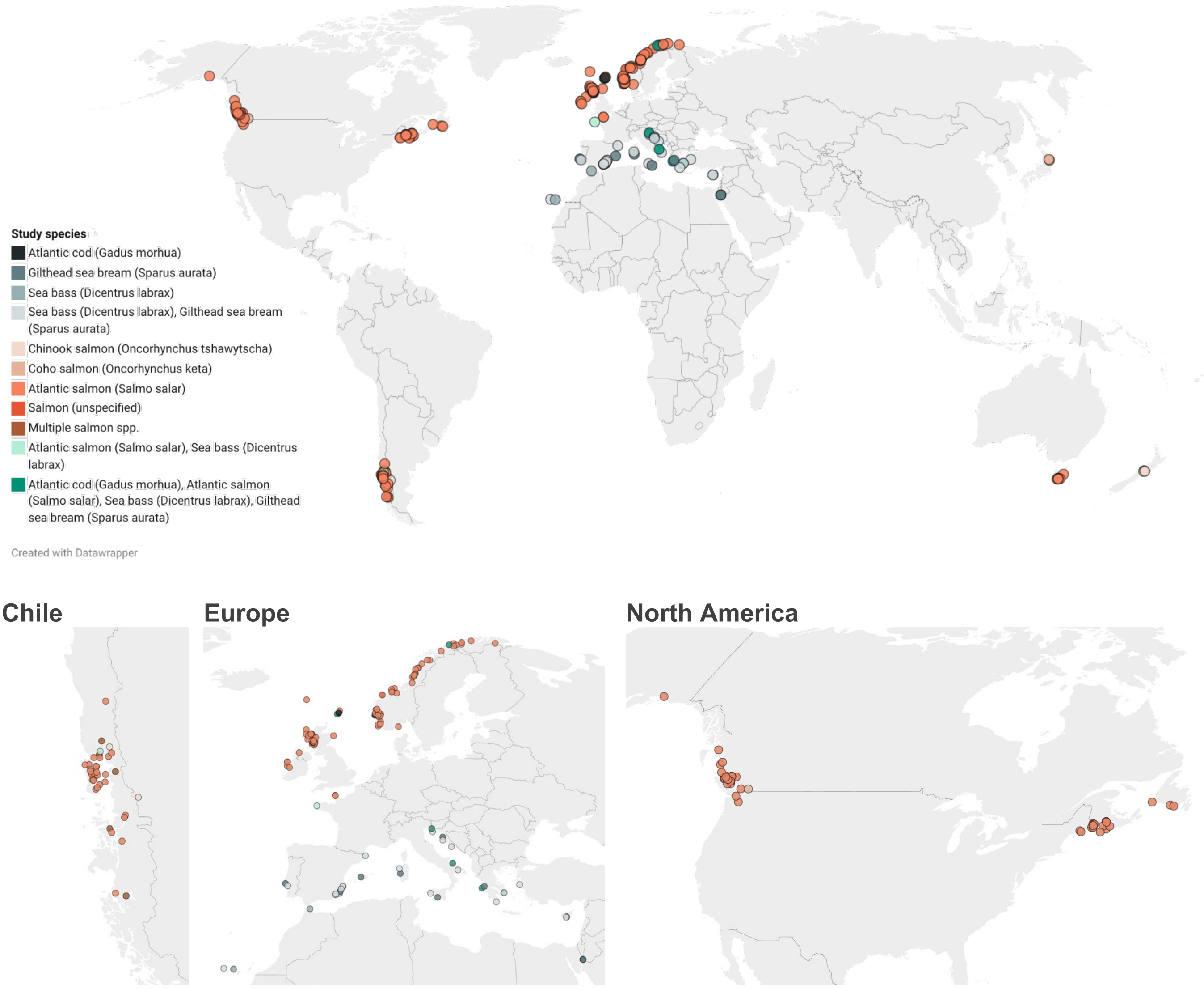

Figure 6. Evidence atlas showing study location by species. Insets show hotspots in Chile, Europe, and North America. Studies plotted for all major locations provided in the article. Two multinational studies without coordinates not plotted. One study with no discernible coordinates/location not plotted. Interactive version available online (https://thesalmonandthetomato.org/frbsystematicmap.html).

3.3.2. Production stage and species

Figure 7 displays the production stages (from feed to processing) against study species for the included studies. The emphasis on Atlantic salmon is evident, but also apparent is the lack of studies on earlier stages, particularly feed. This may reflect a lack of species-specificity of research on feed supply chain impacts.

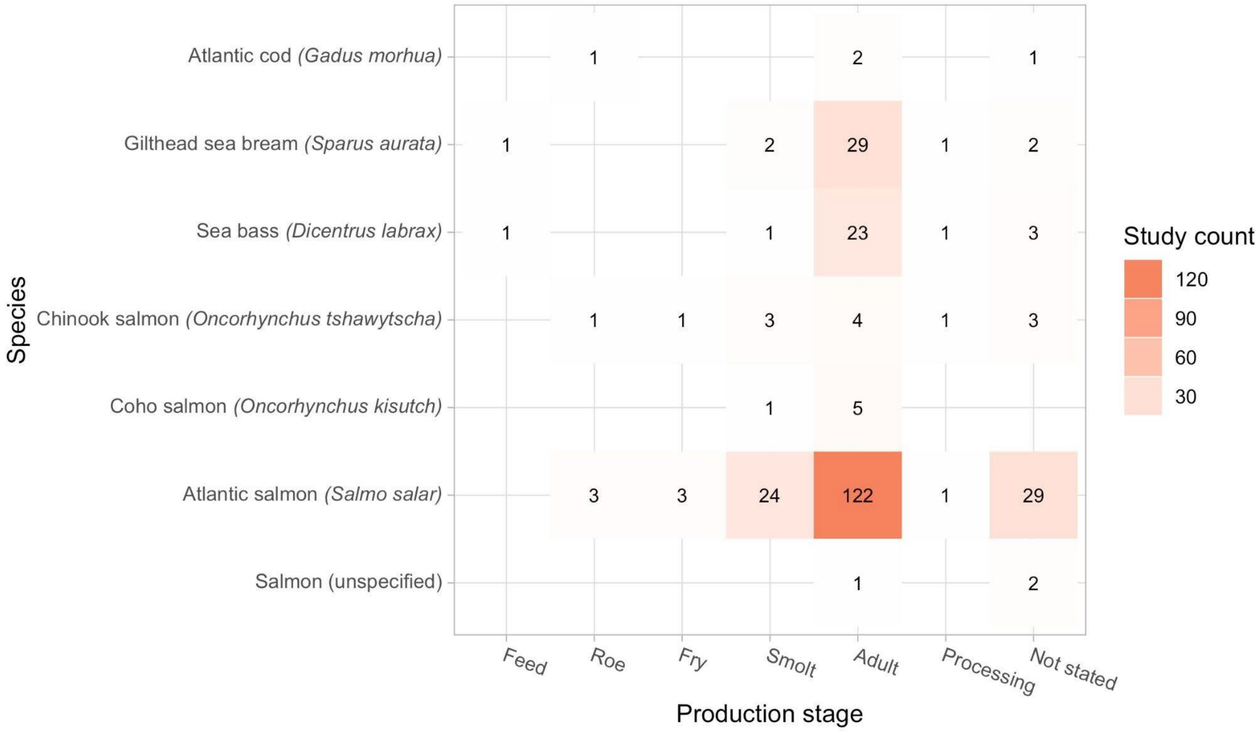

Figure 7. Study species against production stage in included articles.

3.3.3. Measured impacts

Figure 8 shows the impacts measured across the included studies, separated into social and ecological, impacted systems, and measured outcomes. Outcomes are reported at the finest scale identifiable within articles, and are therefore to some degree clustered (i.e. crustacea and gastropods within benthos).

There is an evident emphasis on ecological outcome measures (n=176, 84% of studies), with far fewer social outcomes reported (n=36, 17%).

Within social impacts, studies on attitudes (n=40, 11% of measured outcomes) were relatively evenly spread across perceptions of socio-economic, environmental, and general impacts. Across ecological outcomes, the most frequently studied were impacts on benthos (total n=100, 27%) and wild fish (n=100, 27%), with significant focus on specific final outcomes of benthic community composition (n=41, 11%), benthic abundance (n=35, 10%), wild fish interference with escaped fish (n=25, 7%), wild fish health (n=25, 7%), and impacts on sea lice (n=24, 7%).

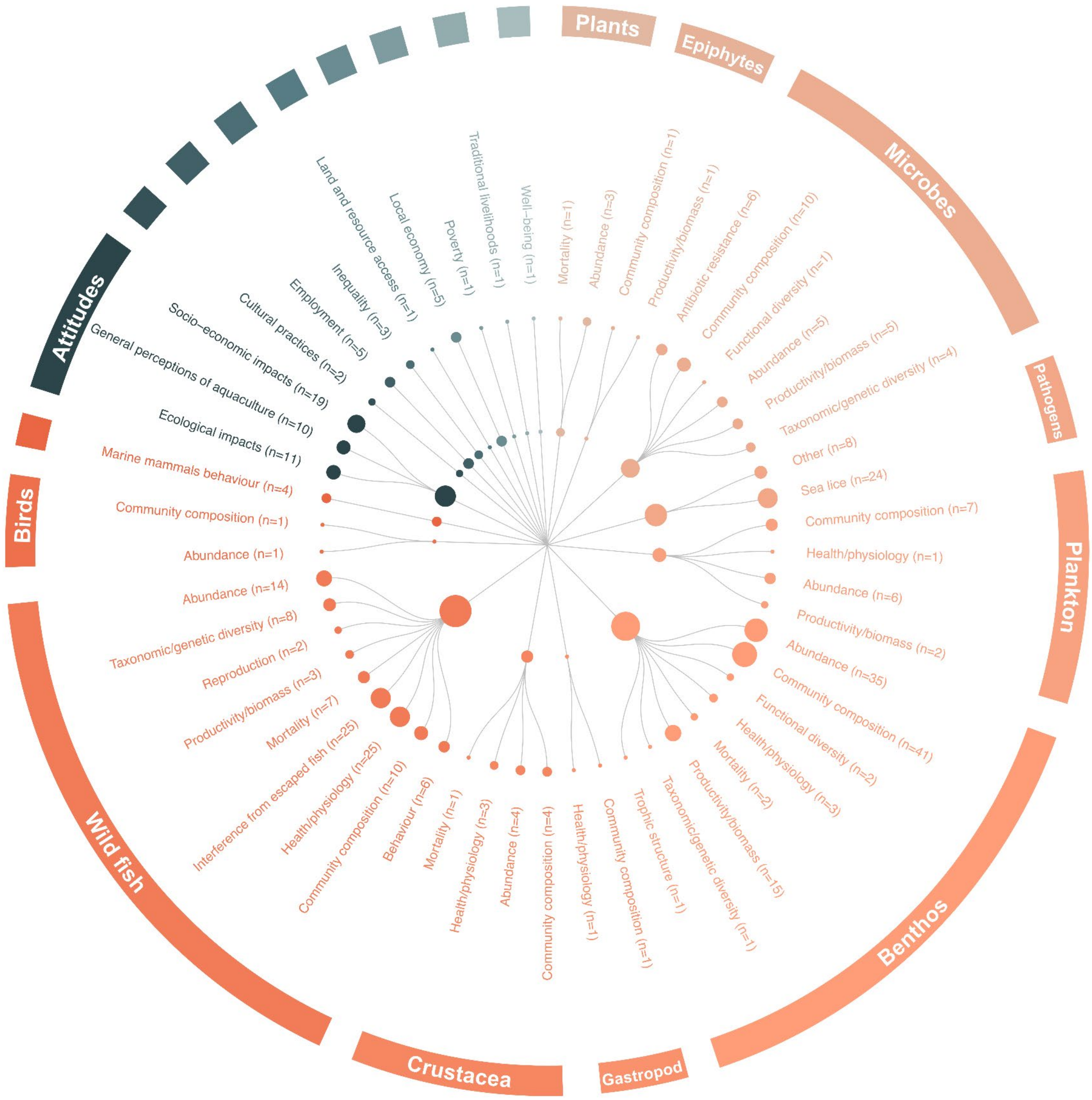

Figure 8. Radial heat plot showing the distribution of evidence across impacted systems: social (blue-grey) and ecological (salmon pinks) are separated across impacted systems (legend) and measured outcome (outer text). Counts are the number of measured outcomes across all studies.

Impacted systems and measured outcomes are presented across study species in Figures 9. Atlantic salmon research dominates across almost all outcomes, with the exception of a small number of uncommon outcomes, including plant mortality and gastropod community composition and health/physiology.

Atlantic salmon research is noticeably more common than for other species in research relating to sea lice and wild fish health/physiology in particular. Sea bream and sea bass research focuses primarily on benthic abundance and community composition, with notable attention on socio-economic attitudes, wild fish abundance, and escaped fish interference with wild fish. The limited cod research was limited to benthic abundance (n=1, <0.5%), community composition (n=1, <0.5%), productivity/biomass (n=2, 0.5%), and escaped fish interference with wild fish (n=1, <0.5%). Research on chinook and coho salmon was mostly distributed across better represented outcomes.

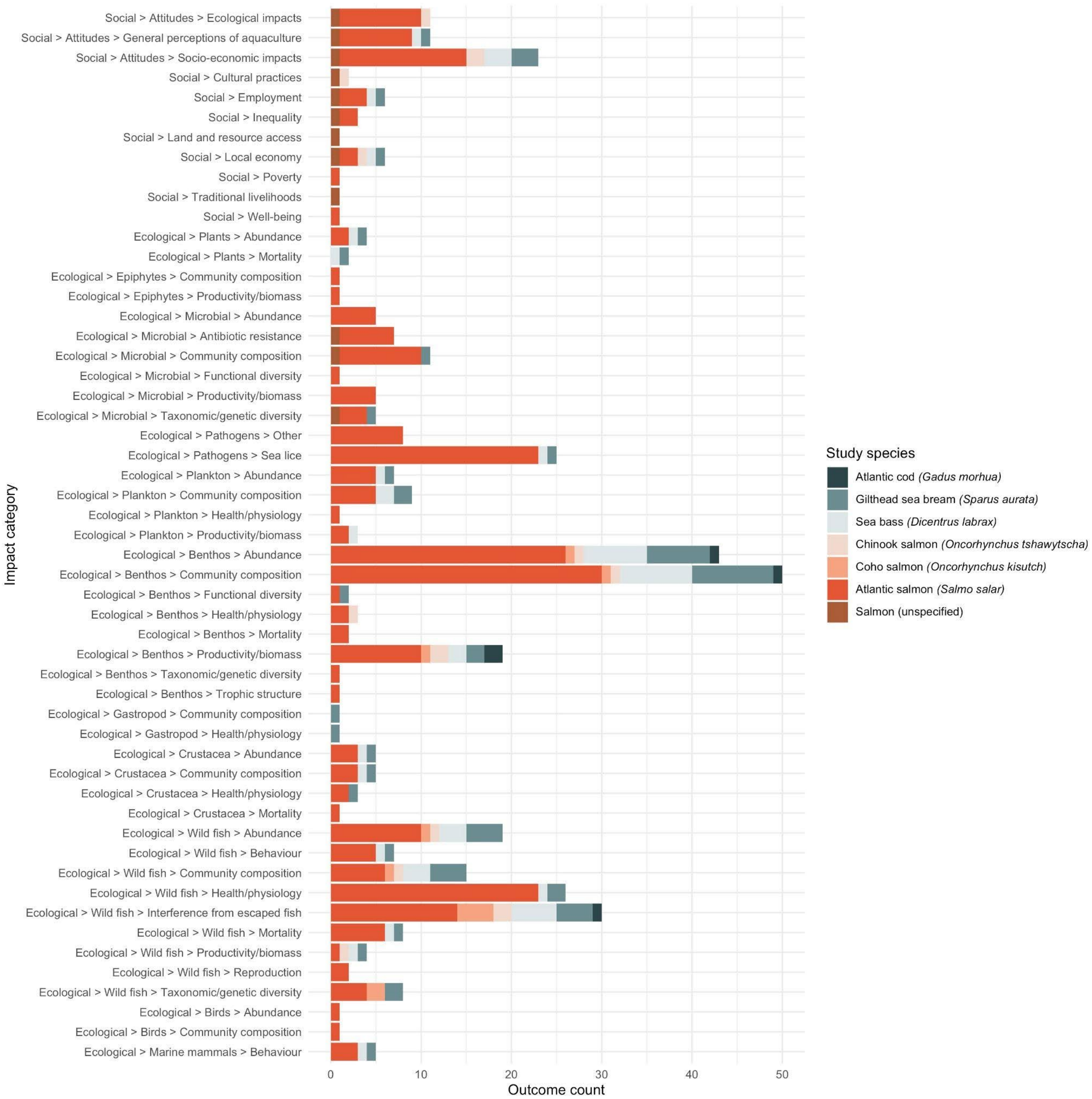

Figure 9. Impact categories measured across study species amongst included articles. Counts are the number of measured outcomes across all studies.

Figure 10 shows the spread of measured systems by study country, demonstrating a stark difference in research attention between Norway and Canada, which both have strong focuses on wild fish (n=31, 9% of measured outcomes and n=30, 8%, respectively) and benthic impacts (n=20, 5% and n=24, 7%, respectively), compared to Chile, which has a key focus on microbes (n=15, 4%) and attitudes (n=10, 3%) as well as a small number of studies across a diverse range of other systems, including social impacts. The United Kingdom has a less prominent focus on any one system, with an even spread across benthos (n=14, 4%), wild fish (n=7, 2%), and pathogens (n=7, 2%), amongst others. Spain has a relatively strong focus on wild fish impacts (n=14, 4%).

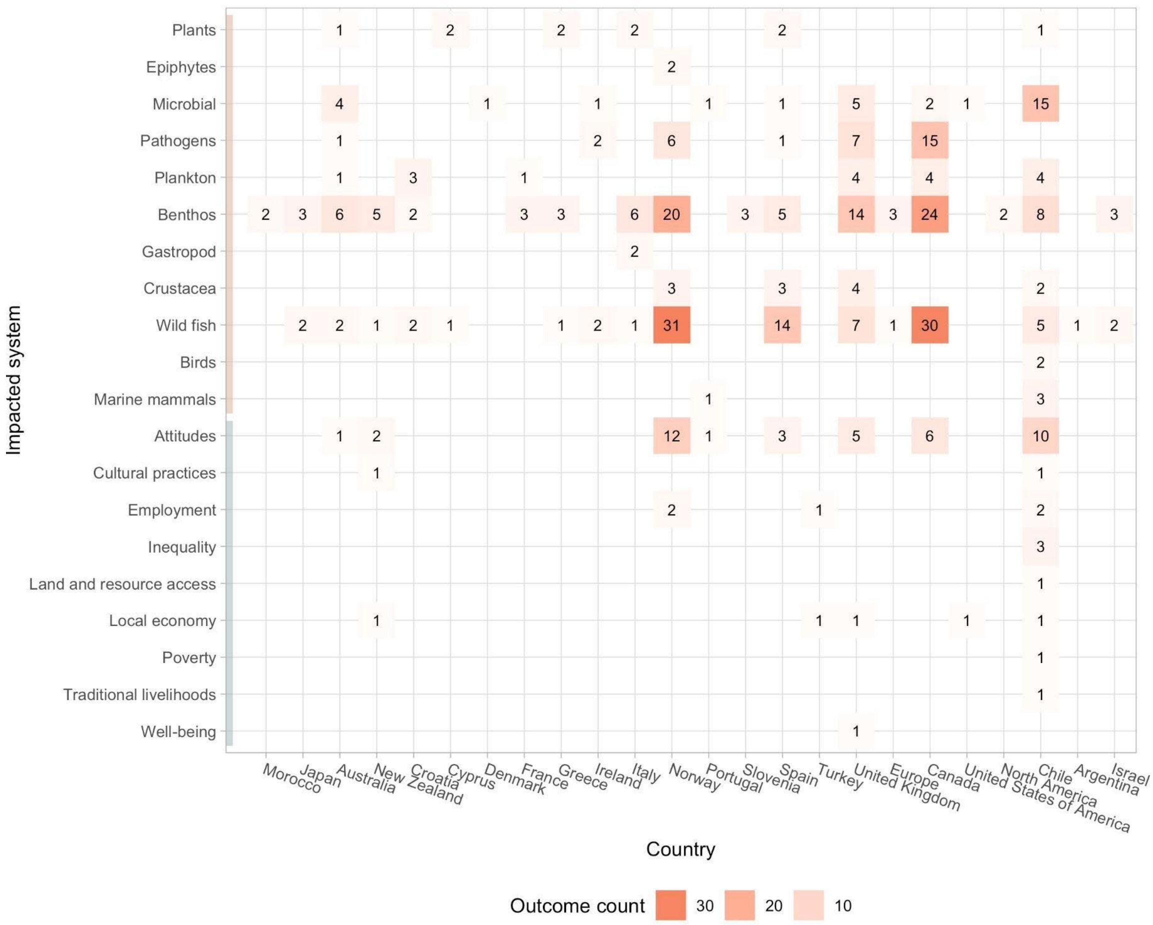

Figure 10. Impacted systems measured across countries within included studies. Counts are the number of measured outcomes across all studies.

3.3.4. Exposure pathways

Exposure pathways are visualised across species in Figure 11. Sea bream and sea bass show a similar pattern to Atlantic salmon in their emphasis on fish escapes and organic pollution, although Atlantic salmon also has a sizeable volume of research on sea lice (n=25, 12%), chemical pollution (n=13, 6%), and pathogens (n=11, 5%) - both of the latter are almost completely unrepresented in other species. A substantial volume of studies referred only to ‘aquacultural activities’ across species (n=60, 29%).

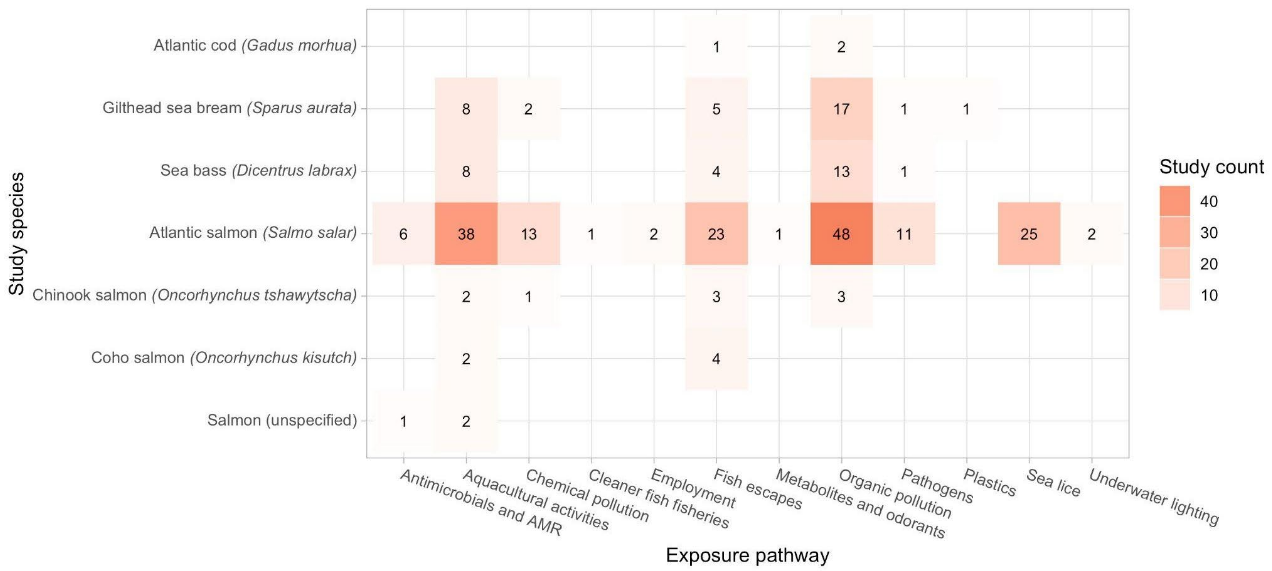

Figure 11. Exposure pathways by study species investigated within included articles.

Exposure pathways are combined with impacted systems in Figure 12. In addition to demonstrating obvious and perhaps less informative linkages (e.g. the impacts of sea lice on pathogen populations), other more interesting patterns are evident. For example, the general lack of chemical pollution pathway studies is clear, but also that the small number of studies on this pathway have focused on the benthos, microbes, and plankton, with other systems unstudied. It also highlights the lack of studies on particular pathway attribution for some systems, where aquacultural activities are dealt with collectively; for example, in public attitudes, perhaps as expected, but also benthos (presumably an unstated reference to organic enrichment and pollution) and wild fish (through a combination of farmed fish and physical structures). Wild fish populations are the most diversely investigated system, with almost all pathways covered except, notably, chemical pollution.

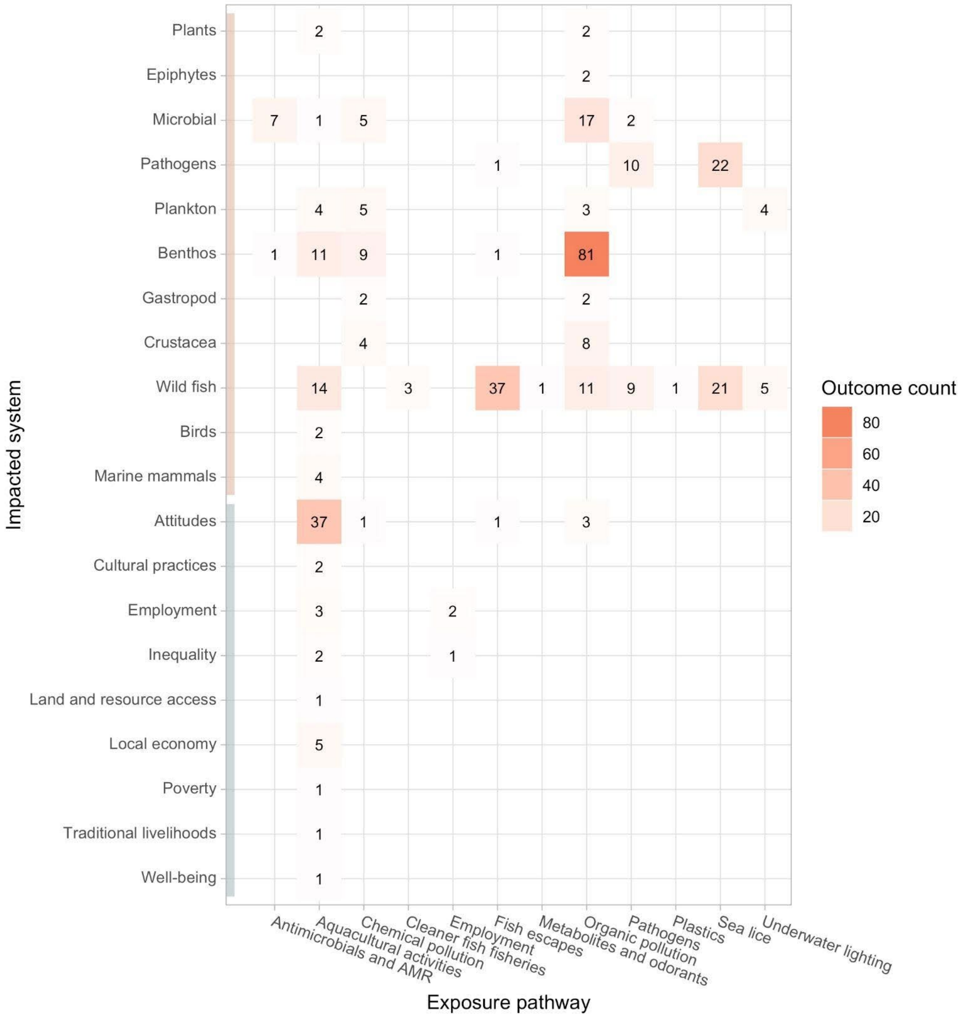

Figure 12. Impacted systems by exposure pathways for included studies. Counts are the number of measured outcomes across all studies.

3.3.5. Interdisciplinarity

Only one study (0.5%) investigated both social and ecological outcomes (Table 6; see also the systematic map database in Annex 4). The study examined both attitudes towards otter predation of sea bream and sea bass farms, and the impacts on otter behaviour. This demonstrates the almost complete lack of interdisciplinarity in the evidence base.

Table 6. Studies combining measurement of social and ecological outcomes.

Article / Country	Species / Production stage	Impact categories	Article study type
Freitas 2007 / Portugal	Sea bass, Sea bream / Adult	Ecological > Marine mammals > Behaviour Social > Attitudes > Socio-economic impacts	Observational

3.3.6. Study methods

Study methods are shown across impacted systems in Figure 13, showing key differences in methodological approaches across subtopics. As well as obvious correlations (e.g. qualitative designs for social outcomes), other interesting patterns emerge. CI designs are more common for benthic system studies than other well-investigated systems, for example wild fish and pathogens, where time series and multiple designs are prevalent. The smaller number of modelling study designs are used most commonly for wild fish outcomes, with very few for pathogen, microbial and benthic outcomes. Most modelling studies were used in combination with other study designs because of our requirement for empirical data. There is a noticeable lack of baseline studies (BA, BACI and RCT designs), which is surprising given the nature of the exposure; long-term, predictable and seasonal farming activities. In addition, randomised control designs (RCTs) were used in only 3 (14%) studies in isolation of other methods.

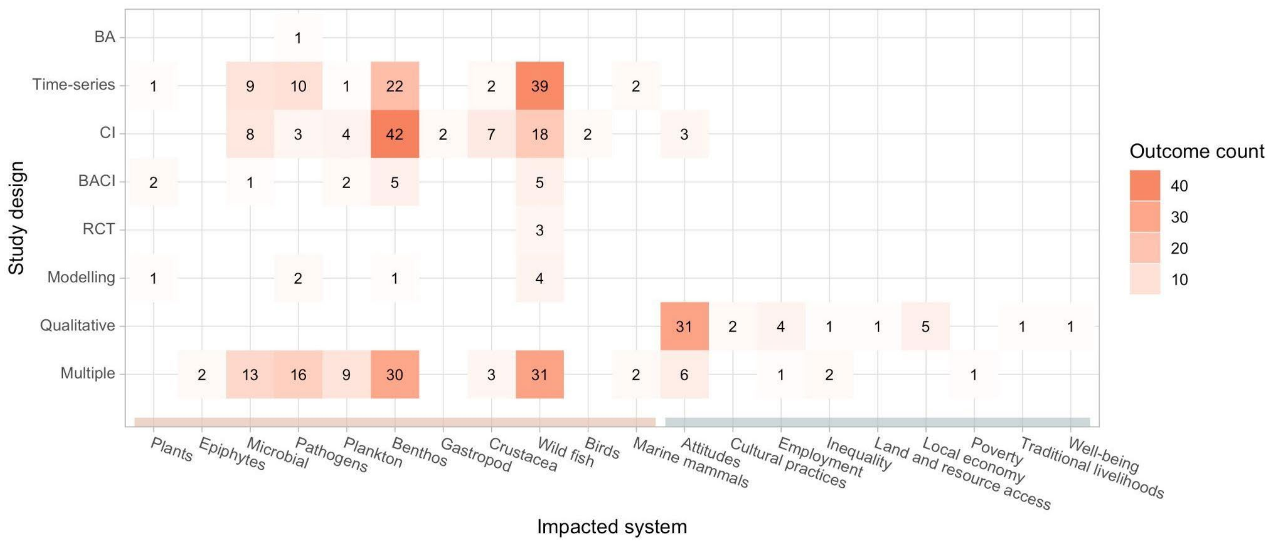

Figure 13. Study designs used across impacted systems in included articles. Counts the are number of measured outcomes across all studies.

Focusing on multiple study designs, the majority of these were combining time-series with CI (n=36), modelling (6) or BACI (5) study designs (Table 7). RCTs were only used in combination with modelling and time series designs in 1 study each.

Table 7. Number of articles employing multiple study designs.

Study designs	Number of articles
CI, Time-series	36
Modelling, Time-series	6
BACI, Time-series	5
Modelling, Qualitative	4

CI, Modelling	2
CI, Modelling, Time-series	2
Qualitative, Time-series	2
BACI, Modelling	1
BACI, CI, Modelling	1
BA, Qualitative	1
Modelling, RCT	1
RCT, Time-series	1
CI, Time-series, Qualitative	1
CI, Modelling, Time-series	1

Studies were predominantly undertaken over 12 months or less, with a median length of 2 months (Figure 14). A spike of studies at exactly 12 months in length likely demonstrates an arbitrary preference of a full year. Although this permits full seasonality for ecological studies, it does not reflect production timescales for the species involved, which requires cage rearing for c. 2 years. Few studies involved very long time periods, with these being dominated by modelling studies.

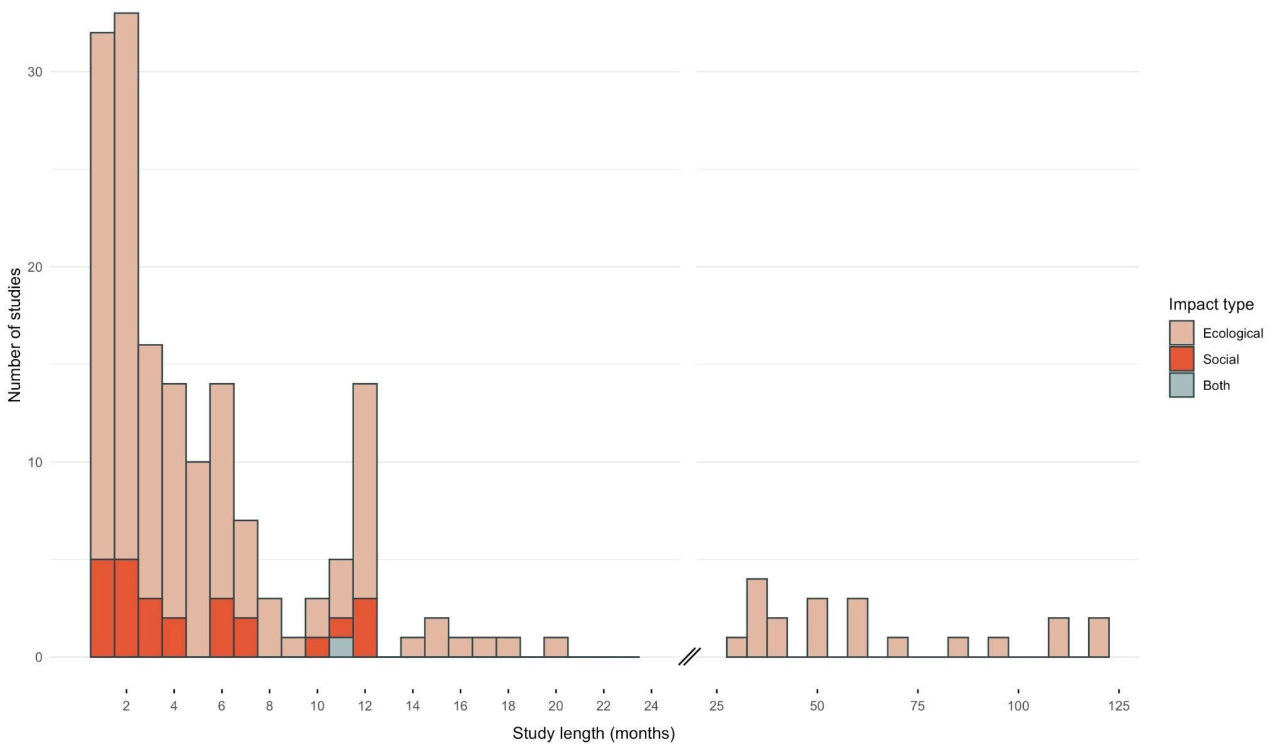

Figure 14. Study length by measured impact type across studies in the map.

3.3.7. Funders

Figures 15-18 display study funder separated by country, study species, affected system, and exposure pathway. Examining funders across different countries (Figure 15), it is apparent that Chile has received greater research institute funding relative to government funding than other countries. Meanwhile, Norway has received very little funding from NGOs. Conversely, Canada has received substantial funding from NGOs. Funding for British research is relatively diverse in its sourcing with a focus on government sources, whilst Spanish research has been less funded by NGOs and industry. A lack of reporting of funding was most prevalent in Canada.

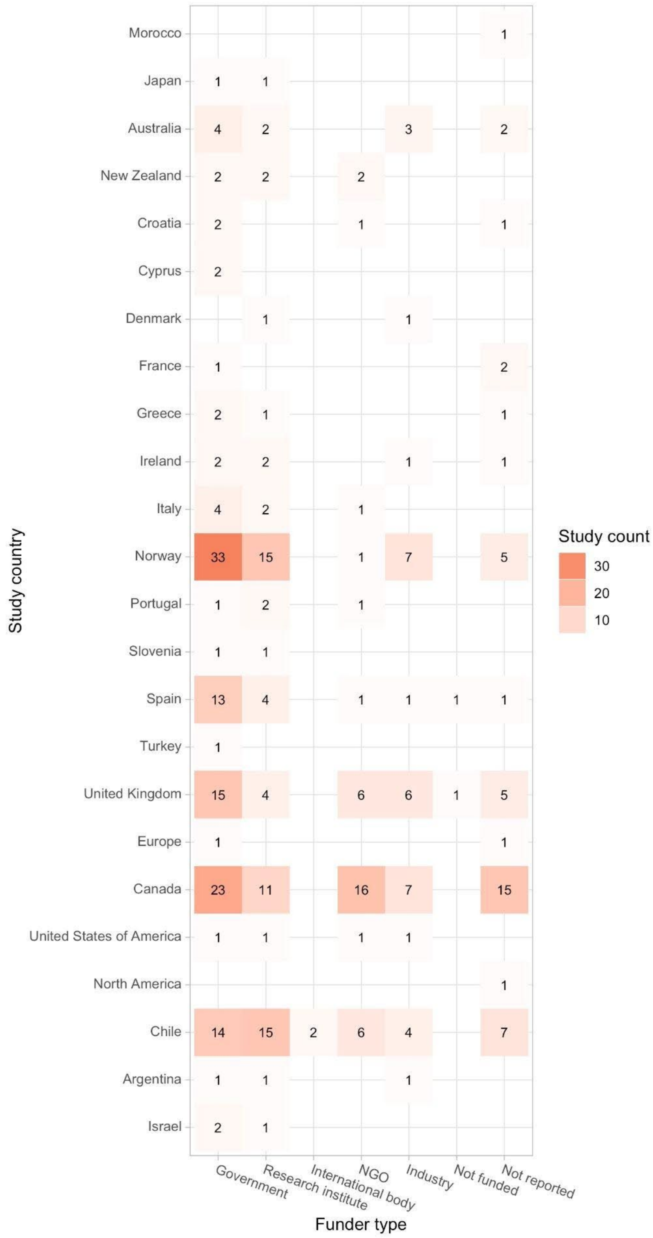

Figure 15. Funder type by country for included studies.

Across species (Figure 16), NGO and industry funding was more common for Atlantic salmon than either sea bream or sea bass, reflecting the greater scrutiny of impacts for salmon farming in recent years. A concerning proportion of Atlantic salmon research (n=36, 17%) did not declare its funding.

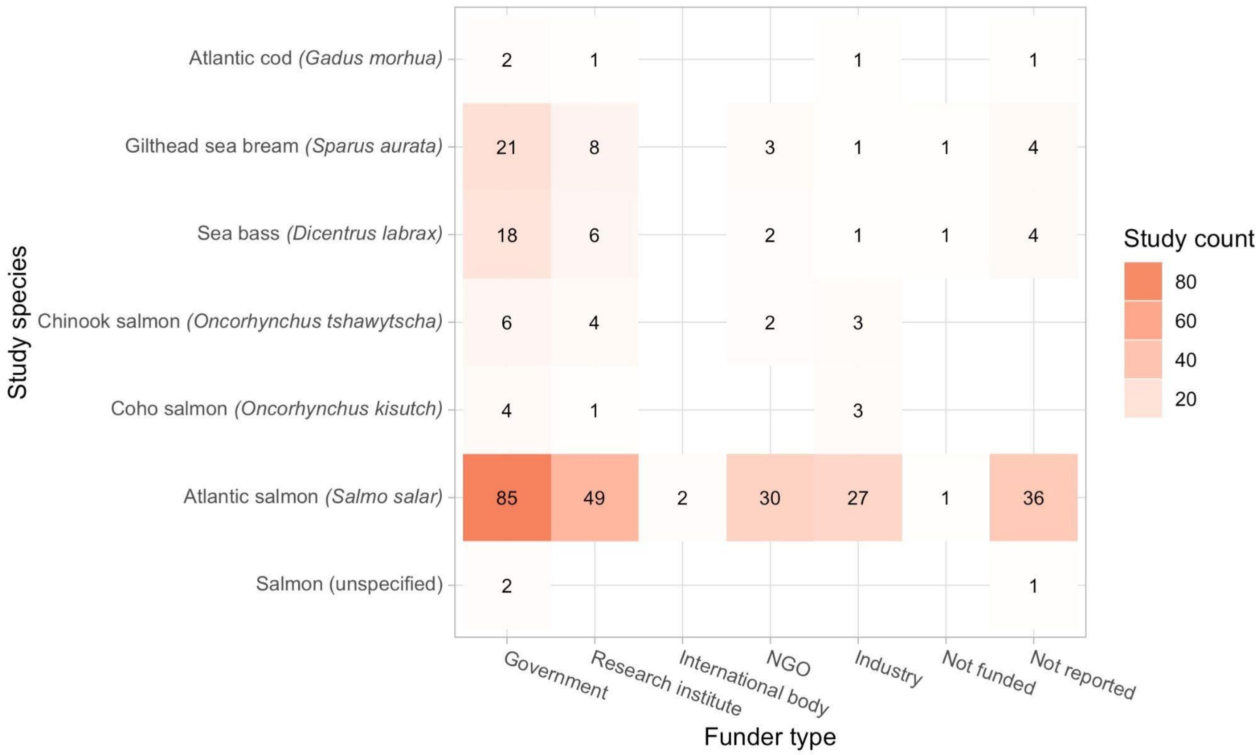

Figure 16. Funding type by species for included articles.

Examining funders across impacted systems (Figure 17), there appears to be an underrepresentation of studies on attitudes by NGOs and industry, where government and research institutes have provided financial support. Industry and NGOs have not funded any research on plankton, where other funders have. Interestingly, a lack of reporting of funding is most concentrated in studies of benthos and wild fish.

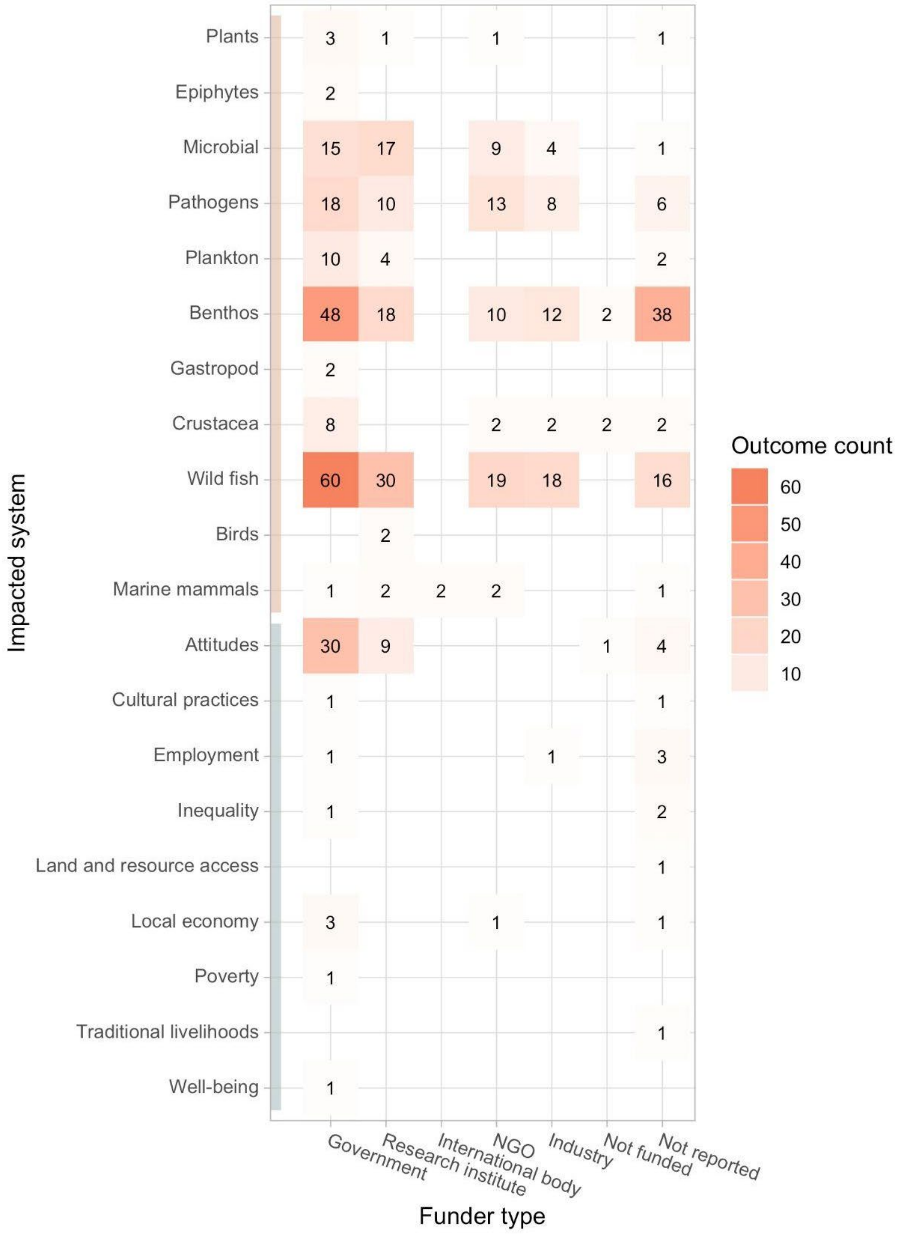

Figure 17. Funding body by impacted systems across included articles. Counts are the number of measured outcomes across all studies.

Turning to exposure pathways (Figure 18), government funding for organic pollution is particularly prevalent (n=38, 18%), whilst they appear to have underfunded research into the effects of sea lice (n=12, 6%) and chemical pollution (n=5, 2%) relative to other pathways and funders. Given their current use by the salmon farming industry as an alternative treatment for sea lice, the lack of studies across funders on the impacts of cleaner fish is surprising. Plastics and antibiotic resistance are other pathways that are emerging or understudied across funders, although some initial financial support is apparent.

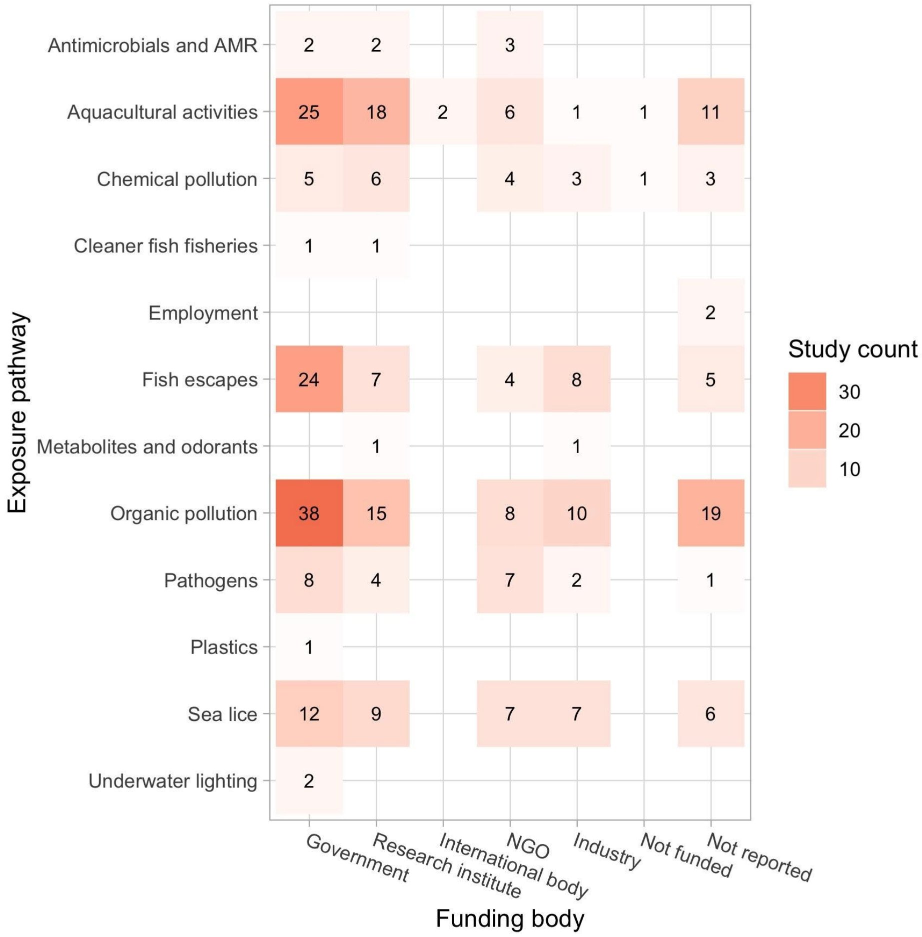

Figure 18. Funder type by exposure pathway across included studies.

3.3.8. Mitigation measures

Only six studies investigated mitigation measures for social and ecological impacts of aquaculture (Table 8). Four studies examined the impacts of sea lice management on wild fish populations, one of which evaluated protected areas for sea lice infection risk management, whilst others examined on-farm sea lice control measures. One study examined the recovery of benthic communities following the closure of salmon farms after the 2011 earthquake and tsunami in Japan. Although technically not a practical mitigation measure, this study is useful in understanding the recovery following salmon farm closure. A final study examined the impacts on benthic organisms of conversion to Integrated Multi-Trophic Aquaculture (IMTA), the addition of a second species within fish farms in order to manage waste. Of these six studies, only this final study could be considered a nature-based solution (Trani 2025).

Table 8. Studies investigating mitigation measures.

Article / Country	Species / Production stage	Mitigation measure studied
Butler 2002 / United Kingdom	Atlantic salmon (*S. salar*) / Smolt	Model of sea lice infection dynamics in wild salmon as a result of sea lice farm management practices
Heuch 2009 / Norway	Atlantic salmon (*S. salar*) / Adult	Monitoring of sea lice control procedures in farms
Fujii 2019 / Japan	Coho salmon (*O. kisutch*) / Adult	Rehabilitation of benthic ecosystems following the 2011 Tohoku earthquake and tsunami that resulted in the closure of salmon farms
Peacock 2013 / Canada	Atlantic salmon (*S. salar*) / Adult	The impacts of sea lice management in salmon farms on wild salmon population dynamics
Serra-Llinares 2014 / Norway	Atlantic salmon (*S. salar*) / Adult	Evaluation of National Salmon Fjords protection on sea lice infection risk in wild salmon
Trani 2025 / Italy	Sea bass (*D. labrax*), Gilthead sea bream (*S. aurata*) / Adult	Recovery of macro-zoobenthic organisms following conversion to Integrated Multi-Trophic Aquaculture (IMTA)

4. Discussion and conclusions

4.1. Assessment of the evidence base

Small evidence base

This map has identified a relatively small evidence base that explicitly links blue food production of cod, sea bass, gilthead sea bream and salmon to biodiversity and/or social outcomes. However, this evidence is fragmented both across disciplines (e.g. ecology, fisheries science, social science), and across systems, with clusters of evidence on a small number of well-studied topics, and a large number of under- and un- represented systems more broadly. An ongoing parallel scoping review (Haddaway et al. 2024) has identified over 12,000 research articles relating to all aspects of salmon farming, which suggests the evidence base identified herein on social and ecological impacts constitutes an overall knowledge gap. Although abiotic environmental impacts are outside the scope of this review, it is unlikely that this additional evidence base would contribute vastly more evidence on the broader environmental impacts that were considered here.

Thematic imbalance (ecological vs social impacts)

There is also a thematic imbalance across the core content of this evidence base, with a strong dominance of ecological impact studies relative to social ones. There is a cluster of social impact studies relating to attitudes, but all other outcome measures are either poorly represented or seemingly entirely missing. This is likely to be a result of a number of historical factors relating to the aquaculture industry, including: a historical regulatory focus on environmental compliance and biosecurity (Aly and Fathi, 2024); the negative feedback pathways for ecological impacts on farmed fish productivity (Banderol, 2024); stronger funding pipelines for ecological monitoring (Overland and Sovacool, 2020); and, the fragmentation of social impact research into development, labour, and human rights literatures (Alomoto et al., 2022).

Taxonomic bias

Atlantic salmon overwhelmingly dominates the evidence base, whilst sea bass and sea bream are relatively under-studied, and cod and other Pacific salmon (Oncorhynchus spp.) species are almost absent. This is in-line with production levels for these species (Figure 19), which are predominated by Atlantic salmon, and with the contemporary treatment of Atlantic salmon as a model species for the industry (Houston and Macqueen, 2018). However, the lack of research on Coho salmon is surprising given the aquacultural activity - although indeed the majority of Pacific salmon research comes from Chile, where this minor production is concentrated.

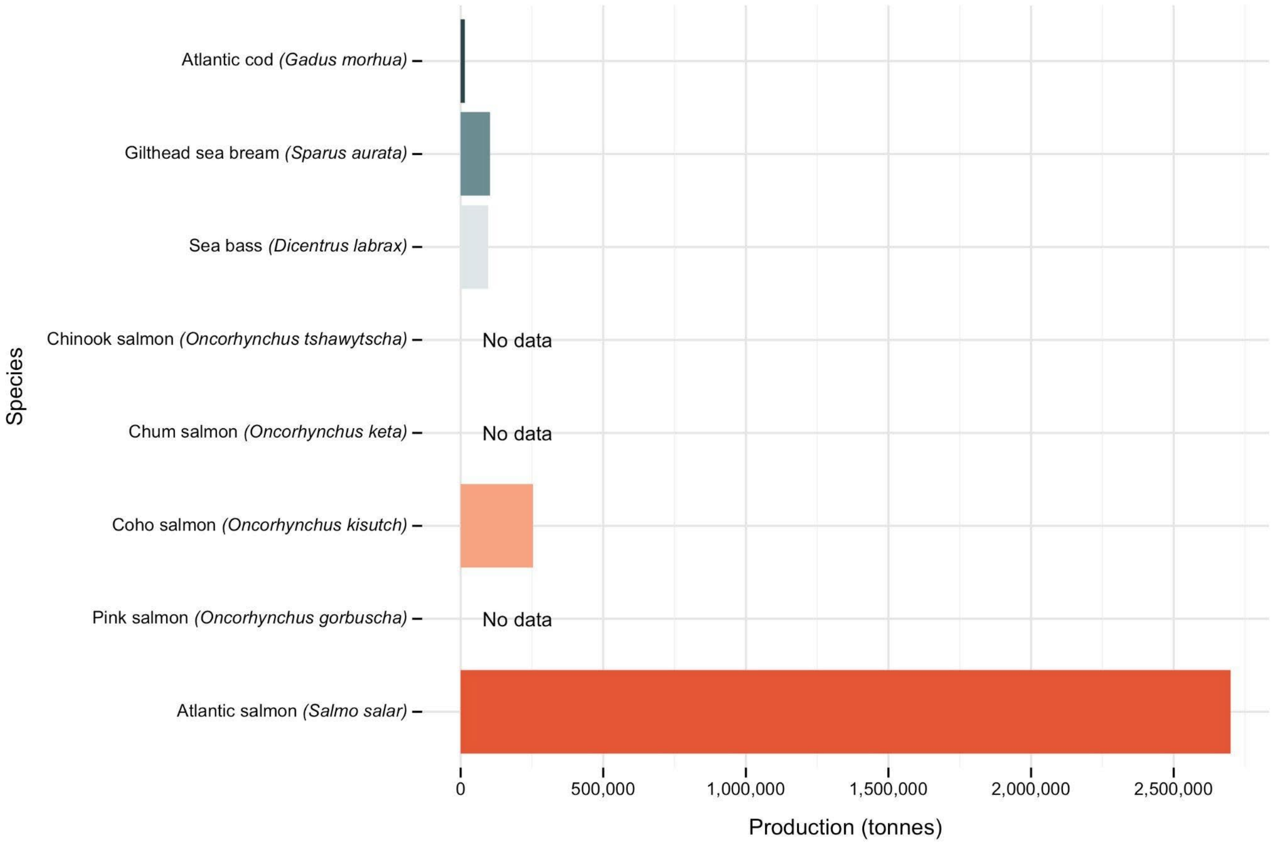

Figure 19. Annual global aquacultural production of the species considered within this review. Data for Atlantic cod only from Norwegian exports. Data for Gilthead sea bream and sea bass only from the Mediterranean. 'No public data' indicate a likely negligible industry with no FAO data reported at the species level for Pacific salmon (Oncorhynchus spp.). Data for Gilthead sea bream and sea bass from Pistrin (2024), Coho salmon from FAO (2024), and Atlantic salmon from OECD (2025).

Geographic hotspots

As expected, evidence is clustered in major fish producing regions (i.e. Norway, Canada, Chile, and the Mediterranean). However, despite its historic significance as the leading global producer of salmon, Norway has a comparatively small evidence base on social and ecological impacts relative to Canada and Chile. This potentially reflects differences in research funding structures, regulatory monitoring practices, and academic publication incentives, but perhaps also relate to more visible negative impacts because of the looser regulations in Chile (Outeir et al., 2022), and strong protest movements in both countries.

Geographic differences in subject focus

Across the countries where substantial evidence exists, there are significant differences in the subjects investigated. Studies from Norway and Canada have focused on interactions with wild fish through disease transmission and genetic impacts from escapees, as well as impacts on benthic organisms from nutrient enrichment. Research from Chile focuses more on ecological impacts of low water quality and affected sediments through microbial systems, consistent with past disease outbreaks (ISA, 2007–2009), harmful algal blooms (2016), and the absence of native salmon species. Chile also has the largest social evidence base by far, more than three times greater than any other country, in keeping with the strong counter-movement, including Indigenous populations, against the salmon farming industry.

Production stage gaps

Most studies focus on adult grow-out stages in marine pens, with limited evidence on feed supply chains, hatcheries and early life stages, or processing and post-harvest activities. A small evidence base referring specifically to smolt exists for Atlantic salmon. This likely reflects the accessibility of grow-out sites for monitoring and the visible and obvious nature of environmental impacts from open pen fish farming. The lack of feed supply chain research is in part because feed as a conceptual discipline is not species specific, despite the feed supply chains for salmon, at least, being largely dominated by a small number of species-specific corporations, such as MOWI, which possesses a fully integrated feed supply chain for its global Atlantic salmon operations (FishFarmingExpert 2025).

Lack of evidence on mitigation

Very few studies explicitly evaluate mitigation measures or interventions, indicating a predominantly diagnostic evidence base. This may perhaps be explained by the multi-step impact pathways for ecological impacts for many impacted systems: pathways like organic enrichment, disease transmission and sea lice could have mitigation literatures that do not explicitly mention their ecological impacts, and therefore be outside the scope of this review. Given the considerable industry interest in minimising negative feedback loops, for example from sea lice induced yield losses, this mitigation literature may also not be public.

Lack of integration between social and biodiversity outcomes

There exists only a small minority of studies that jointly assess social and ecological outcomes. A closer examination of these few studies reveals truly mixed methods research, combining social perception interviews with marine mammal observations and benthic surveys, for example. The general lack of mixed methods studies is perhaps not surprising, however, given the siloed nature of academic research more generally. It also likely reflects differing methodological traditions across disciplines that would make mixed methods studies unlikely to receive funding and research attention, as well as independent publication venues. These constraints of the academic research and publishing sector are not limited to aquaculture, and efforts to ameliorate the challenges that result in resistance to interdisciplinarity require substantial, coordinated systems-level change. The result is a limit in the insights available into trade-offs, cascading impacts, and integrated policy responses.

4.2. Recommendations for future research

4.2.1. Gaps

Future research on the impacts of blue food in the context of the species examined herein should prioritise social dimensions, such as land and resource access, traditional livelihoods, labour rights, and food security. Key aspects of potential social impacts of salmon farming are entirely absent and should be examined, including the impacts of noise, smell and other pollution impacts on local communities, labour conditions for employees, and the impacts of feed supply chains, such as food security and enforced migration in source locations such as West Africa (Feedback 2024).

There is also an urgent need for studies that bridge the gap between ecological and social sciences to capture cumulative, cascading, and systemic impacts.

Research should expand beyond the "farm gate" to investigate the global knock-on ecological and social effects of fish farming, particularly in feed-producing regions like West Africa. Evidence exists in the media from investigative journalism for ecological damage caused by fishmeal factories that supply European aquaculture (Earth Journalism Network 2021), and a connection between Spanish imports of fishmeal and occupation of Western Sahara (Veguilla 2022). Academic research should investigate these indirect effects.

There is a slight underrepresentation of research on chemical pollutant pathways and impacts on ecological (and social) systems that would benefit from further investigation. Despite the apparent move away from the use of chemical sea lice treatments in favour of lump fish, these treatments have been in place for decades and their long-term impacts should be better understood.

Finally, there were very few longer term (>18 month) studies, with most represented by modelling designs. There is therefore a need for research into the long-term effects of both ecological and social impacts of aquaculture.

4.2.2. Clusters

A number of clusters of evidence exist that would warrant further investigation via full evidence synthesis (either quantitative or qualitative). These include:

- **Country-specific syntheses across all impacts:** e.g. for Norway, Chile, the UK, or Spain, inherently restricted by species
- **Benthic and microbial impacts across countries:** either restricted to Atlantic salmon or all salmon species
- **Social impacts (particularly attitudes):** across all species and countries, but with an inherent focus on salmon farming in Chile
- **Impacts on wild fish:** either across all species, or just for Atlantic salmon or sea bream
- **Organic pollution exposure pathway:** inherently on microbial, benthic and crustacean systems
- **Chemical and antimicrobial pollution** exposure pathway across all impacts and species
- **Fish escapes** exposure pathway across all impacts and species
- **Sea lice** exposure pathway across all impacts for all salmon species

Due to the subsampling approach used in this map, these syntheses would require screening and data extraction on the additional 40% of search results prior to initiating synthesis. Alternatively, subsearching the search results using a newly developed targeted search string could reduce screening effort for any one conceptually distinct topic.

4.2.3. Methodological Rigour

While various designs (time-series, comparator-impact) are used, the lack of widespread "Before-After-Control-Impact" (BACI) studies suggests a need for more rigorous experimental designs in assessing the impacts of aquaculture for these species. Whilst it is unsurprising that so few randomised control trials exist, the lack of BACI studies is a key methodological research gap.

4.3. Implications for research, policy and practice

Implications for research arising from this systematic map relate to the limited and uneven coverage of the existing evidence base. The mapped literature is concentrated on a narrow set of species, geographies, impact pathways, and production stages, with a strong emphasis on ecological outcomes associated with adult grow-out in offshore pen systems. Social impacts are sparsely represented, and very few studies integrate social and ecological outcomes within the same analysis. As a result, current research provides only a partial picture of the impacts associated with European blue food production–consumption chains. The map also identifies several clusters of evidence that appear sufficiently developed to warrant full synthesis, including research on benthic and microbial impacts of salmon farming, interactions with wild fish, and attitudinal social impacts in specific producing regions. These clusters provide an opportunity for more focused quantitative or qualitative synthesis, alongside targeted primary research to address the substantial gaps identified elsewhere.

For policy and practice, the findings highlight clear constraints on the evidence available to inform decision-making. While ecological impacts in major producing regions are relatively well studied, the lack of evidence on social outcomes, mitigation measures, and non-grow-out stages limits the ability to assess sustainability across entire supply chains. This uneven evidence base risks policy discussions being informed by a narrow subset of impacts and contexts. Expanding and synthesising the evidence in the priority areas identified by this map would improve the alignment between research, policy needs, and practical decision-making related to European blue food systems.

4.4. Limitations

4.4.1. Of the evidence base

The evidence base synthesised herein is limited in its volume, and in terms of its thematic scope, being primarily focused on ecological impacts rather than social. In addition, there is a significant lack of integrated, mixed methods and interdisciplinary designs, resulting in a dearth of systematic analyses across social and ecological and across full supply chains and production systems. Without full critical appraisal of study methods it is hard to point to concrete deficiencies in methods, but study lengths are also relatively short, particularly given the low median study period and a mismatch with typical aquacultural production timescales (2-3 years). Furthermore, the lack of study designs that employ baselines (BA, BACI, RCT) demonstrates a methodological deficiency that should be strengthened in future research.

4.4.2. Limitations of this review

Our review is not without its limitations. Firstly, we used a random subsampling approach to screen and extract data from the search results. The resulting synthesis is, however, based on a large proportion of the potential evidence base (60%) and the randomisation ensures representativeness.

Although not a limitation, the narrow focus on biodiversity outcomes (excluding intermediate abiotic environmental outcomes, e.g. eutrophication) means that this is not an assessment of all environmental impacts. Further research could expand this scope to cover abiotic impacts as well.

Finally, the nature of our search strategy required research to make explicit reference to an included species. As such, some evidence, particularly on feed supply chains, may exist outside of our evidence base, since it may not specify the farmed animal, instead referring to “aquaculture fishmeal”, for example. However, the link to these species is then unlikely to be explicit and the connection far more challenging to evidence, since the majority of fishmeal is consumed by aquaculture in China (undercurrentnews 2025).

5. Declarations

5.1. Demonstrating procedural independence

Authors will not make judgements on any articles which they have authored.

5.2. Competing interests

The authors declare they have no competing interests.

5.3. Funding information

This work was funded by Biodiversa+, the European Biodiversity Partnership, under the European Union's Horizon Europe research and innovation programme (GA No. 101052342). Funded by the European Union. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the granting authority, the Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

5.4. Author's contributions

NRH; conceptualisation, methodology, investigation, formal analysis, validation, data curation, visualisation, supervision, project administration, funding acquisition, writing - original draft, writing - review & editing

HS; investigation, data curation, writing - review & editing

IK; writing - review & editing

MS; writing - review & editing

HC; visualisation, writing - review & editing

LE; writing - review & editing

SS; writing - review & editing

5.5. Acknowledgements

We thank Joseph Langridge and the Biodiversa+ active partners for their insightful and constructive comments during the planning of the protocol, and for feedback on the manuscript during drafting.

6. References

Alomoto, W., Niñerola, A., & Pié, L. (2021). Social impact assessment: a systematic review of literature. Social Indicators Research, 161(1), 225–250. https://doi.org/10.1007/s11205-021-02809-1

Aly, S. M., & Fathi, M. (2024). Advancing aquaculture biosecurity: A scientometric analysis and future outlook for disease prevention and environmental sustainability. Aquaculture International, 32(7), 8763–8789. https://doi.org/10.1007/s10499-024-01589-y

Banderol, M. (2024). Eutrophication effects on water quality and fish farm productivity. Journal of Fisheries & Livestock Production, 12(11), 1–2. https://doi.org/10.4172/2332-2608.1000591

Bavinck, M., Pelligrini, L., & Mostert, E. (Eds.). (2014). Conflicts over natural resources in the global south. CRC Press. https://doi.org/10.1201/b16498

Belton, B., Bush, S. R., & Little, D. C. (2018). Not just for the wealthy: Rethinking farmed fish consumption in the Global South. Global Food Security, 16, 85–92. https://doi.org/10.1016/j.gfs.2017.10.005

Béné, C., Barange, M., Subasinghe, R., Pinstrup-Andersen, P., Merino, G., Hemre, G.-I., & Williams, M. (2015). Feeding 9 billion by 2050 – Putting fish back on the menu. Food Security, 7(2), 261–274. https://doi.org/10.1007/s12571-015-0427-z

Boissy, J., Aubin, J., Drissi, A., van der Werf, H. M. G., Bell, G. J., & Kaushik, S. J. (2011). Environmental impacts of plant-based salmonid diets at feed and farm scales. Aquaculture, 321(1–2), 61–70. https://doi.org/10.1016/j.aquaculture.2011.08.033

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I., & Corner, R. (2010). Aquaculture: Global status and trends. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1554), 2897–2912. https://doi.org/10.1098/rstb.2010.0170

Bramer, W. M., Giustini, D., de Jonge, G. B., Holland, L., & Bekhuis, T. (2016). De-duplication of database search results for systematic reviews in EndNote. Journal of the Medical Library Association : JMLA, 104(3), 240–243. https://doi.org/10.3163/1536-5050.104.3.014

Bush, S. R., Belton, B., Little, D. C., & Islam, M. S. (2019). Emerging trends in aquaculture value chain research. Aquaculture, 498, 428–434. https://doi.org/10.1016/j.aquaculture.2018.08.077

Bush, S. R., & Marschke, M. J. (2014). Making social sense of aquaculture transitions. Ecology and Society, 19(3). https://doi.org/10.5751/es-06677-190350

Collaboration for Environmental Evidence. (2022). Guidelines and Standards for Evidence Synthesis in Environmental Management VERSION 5.1. Collaboration for Environmental Evidence. https://environmentalevidence.org/information-for-authors/

Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M., & Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. Nature Food, 1(5), 301–308. https://doi.org/10.1038/s43016-020-0078-x

Earth Journalism Network. (2021, November 19). A Foreign-owned Fishmeal Factory Causes a Stink in Senegal. Earth Journalism Network. https://earthjournalism.net/stories/a-foreign-owned-fishmeal-factory-causes-a-stink-in-senegal

Environmental Justice Foundation. (2015). Thailand's seafood slaves. Human trafficking, slavery and murder in Kantang's fishing industry. Environmental Justice Foundation. https://ejfoundation.org/reports/thailands-seafood-slaves-human-trafficking-slavery-and-murder-in-kantangs-fishing-industry

FAO. (2024). GLOBEFISH | Quarterly Salmon Analysis - June 2024. https://openknowledge.fao.org/server/api/core/bitstreams/028a57e4-fc3a-4153-a55f-59bd51db6b29/content

Feedback. (2024, January 31). Blue Empire: How the Norwegian salmon industry extracts nutrition and undermines livelihoods in West Africa. Foodrise EU. https://foodrise.eu/research/blue-empire-how-the-norwegian-salmon-industry-extracts-nutrition-and-undermines-livelihoods-in-west-africa/

FishFarmingExpert. (2025, December 22). Mowi enters partnership with Skretting. Fishfarmingexpert. https://www.fishfarmingexpert.com/mowi-skretting/mowi-enters-partnership-with-skretting/2043512

Folke, C., Kautsky, N., & Troell, M. (1994). The costs of eutrophication from salmon farming: implications for policy. Journal of Environmental Management, 40(2), 173–182. https://doi.org/10.1006/jema.1994.1013

Food and Agriculture Organization (FAO). (2022). The state of world fisheries and aquaculture 2022. https://doi.org/10.4060/cc0461en

Ford, J. S., & Myers, R. A. (2008). A global assessment of salmon aquaculture impacts on wild salmonids. PLoS Biology, 6(2), e33. https://doi.org/10.1371/journal.pbio.0060033

Golden, C. D., Allison, E. H., Cheung, W. W. L., Dey, M. M., Halpern, B. S., McCauley, D. J., Smith, M., Vaitla, B., Zeller, D., & Myers, S. S. (2016). Nutrition: Fall in fish catch threatens human health. Nature, 534(7607), 317–320. https://doi.org/10.1038/534317a

Haddaway, N. R., Cooke, S. J., Kelling, I., Sampson, H., Sciberras, M., Errington, L., & Savilaakso, S. (2025). Disentangling Global Supply Chains To Map Impacts Of European Blue Food Consumption Demands On Biodiversity And Society: A systematic map protocol. CABI Publishing. https://doi.org/10.1079/protocolrxiv.2025.00009

Haddaway, N. R., Macura, B., Whaley, P., & Pullin, A. S. (2018). ROSES RepOrting standards for Systematic Evidence Syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environmental Evidence, 7(1). https://doi.org/10.1186/s13750-018-0121-7

Houston, R. D., & Macqueen, D. J. (2019). Atlantic salmon (*Salmo salar L.*) genetics in the 21st century: Taking leaps forward in aquaculture and biological understanding. Animal Genetics, 50(1), 3–14. https://doi.org/10.1111/age.12748

Islam, Md. S. (2005). Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: Review and analysis towards model development. Marine Pollution Bulletin, 50(1), 48–61. https://doi.org/10.1016/j.marpolbul.2004.08.008

James, K. L., Randall, N. P., & Haddaway, N. R. (2016). A methodology for systematic mapping in environmental sciences. Environmental Evidence, 5(1), 7-. https://doi.org/10.1186/s13750-016-0059-6

Kittinger, J. N., Teneva, L. T., Koike, H., Stamoulis, K. A., Kittinger, D. S., Oleson, K. L. L., Conklin, E., Gomes, M., Wilcox, B., & Friedlander, A. M. (2015). From reef to table: Social and ecological factors affecting coral reef fisheries, artisanal seafood supply chains, and seafood security. PLOS ONE, 10(8), e0123856. https://doi.org/10.1371/journal.pone.0123856

Krkošek, M., Connors, B. M., Ford, H., Peacock, S., Mages, P., Ford, J. S., Morton, A., Volpe, J. P., Hilborn, R., Dill, L. M., & Lewis, M. A. (2011). Fish farms, parasites, and predators: Implications for salmon population dynamics. Ecological Applications, 21(3), 897–914. https://doi.org/10.1890/09-1861.1

Micheli, F., De Leo, G., Shester, G. G., Martone, R. G., Lluch-Cota, S. E., Butner, C., Crowder, L. B., Fujita, R., Gelcich, S., Jain, M., Lester, S. E., McCay, B., Pelc, R., & Sáenz-Arroyo, A. (2014). A system-wide approach to supporting improvements in seafood production practices and outcomes. Frontiers in Ecology and the Environment, 12(5), 297–305. https://doi.org/10.1890/110257

Nature. (2021). Harness the world's aquatic 'blue' food systems to help end hunger. Nature, 597(7876), 303–303. https://doi.org/10.1038/d41586-021-02476-9

Naylor, R., Hindar, K., Fleming, I. A., Goldburg, R., Williams, S., Volpe, J., Whoriskey, F., Eagle, J., Kelso, D., & Mangel, M. (2005). Fugitive salmon: assessing the risks of escaped fish from net-pen aquaculture. BioScience, 55(5), 427. https://doi.org/10.1641/0006-3568(2005)055[0427:fsatro]2.0.co;2

Naylor, R. L., Goldburg, R. J., Mooney, H., Beveridge, M., Clay, J., Folke, C., Kautsky, N., Lubchenco, J., Primavera, J., & Williams, M. (1998). Nature's subsidies to shrimp and salmon farming. Science, 282(5390), 883–884. https://doi.org/10.1126/science.282.5390.883

Newton, R. W., & Little, D. C. (2017). Mapping the impacts of farmed Scottish salmon from a life cycle perspective. The International Journal of Life Cycle Assessment, 23(5), 1018–1029. https://doi.org/10.1007/s11367-017-1386-8

OECD. (2025). OECD Review of Fisheries 2025, OECD Publishing, Paris, https://doi.org/10.1787/560cd8fc-en

Outeir, L., Rau, J. R., & Ojeda, J. (2022). Historical - geographical colonization of salmon farming in Patagonia. Interciencia, 47(4), 133–139.

Overland, I., & Sovacool, B. K. (2020). The misallocation of climate research funding. Energy Research & Social Science, 62, 101349. https://doi.org/10.1016/j.erss.2019.101349

Pandey, R., Asche, F., Misund, B., Nygaard, R., Adewumi, O. M., Straume, H.-M., & Zhang, D. (2023). Production growth, company size, and concentration: The case of salmon. Aquaculture, 577, 739972. https://doi.org/10.1016/j.aquaculture.2023.739972

Pistrin, M. G. (2024). Spotlight on Spanish Aquaculture: Growth, Trends, and Future Outlook. International Aquafeed. https://www.aquafeed.co.uk/spotlight-on-spanish-aquaculture-growth-trends-and-future-outlook/?utm_source=chatgpt.com

Primavera, J. H. (2006). Overcoming the impacts of aquaculture on the coastal zone. Ocean & Coastal Management, 49(9–10), 531–545. https://doi.org/10.1016/j.ocecoaman.2006.06.018

Stonich, S., & Bailey, C. (2000). Resisting the blue revolution: Contending coalitions surrounding industrial shrimp farming. Human Organization, 59(1), 23–36. https://doi.org/10.17730/humo.59.1.86281132l884231k

Undercurrent News. (2025, October 22). IFFO 2025 day 2 recap: China devours half of world’s aquaculture fishmeal. Undercurrent News. https://www.undercurrentnews.com/2025/10/22/iffo-2025-day-2-recap-china-devours-half-of-worlds-aquaculture-fishmeal/

Vandergeest, P. (2018). Law and lawlessness in industrial fishing: Frontiers in regulating labour relations in Asia. International Social Science Journal, 68(229–230), 325–341. https://doi.org/10.1111/issj.12195

Vandergeest, P., & Marschke, M. (2019). Modern slavery and freedom: Exploring contradictions through labour scandals in the Thai fisheries. Antipode, 52(1), 291–315. https://doi.org/10.1111/anti.12575

Veguilla, V. (2022, May 11). How the fishing industry strengthened Morocco’s occupation of Western Sahara - MERIP. Middle East Research and Information Project. https://www.merip.org/2022/05/how-the-fishing-industry-strengthened-moroccos-occupation-of-western-sahara/

Ziegler, F., Hornborg, S., Green, B. S., Eigaard, O. R., Farmery, A. K., Hammar, L., Hartmann, K., Molander, S., Parker, R. W. R., Skontorp Hognes, E., Vázquez-Rowe, I., & Smith, A. D. M. (2016). Expanding the concept of sustainable seafood using Life Cycle Assessment. Fish and Fisheries, 17(4), 1073–1093. https://doi.org/10.1111/faf.12159

Annexes

Annex 1. Benchmark List

Annex 2. Search record

Annex 3. Full text screening decisions

Annex 4. Systematic map database

Annex 5. ROSES checklist

Annex 6. Included articles RIS file