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Global Review of Atlantic Salmon Aquaculture Life Cycle Assessment: A Novel Approach

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Abstract

In the past half-century, Atlantic salmon aquaculture has grown to become one of the most advanced food production systems worldwide. The rapid expansion of the industry, especially in the Global North, has warranted extensive efforts to assess the environmental impacts of salmon aquaculture, with the most popular framework being Life Cycle Assessment (LCA). This thesis presents a systematic review of the publicly available open-net pen Atlantic salmon LCA. It is the first of its kind to review a single production system and farmed species, and is also unique in its efforts to reanalyse life cycle inventory data using harmonised methodologies, emission models, and modelling assumptions. The importance of methodological consistency in salmon LCA is stressed throughout, as LCA is a comparative framework, and therefore requires standardised methodological application across studies to compare the impact assessment results of production systems that differ in space and time. The first analytical component is to characterise and assess the variation in key methodological choices made by practitioners. This is followed by the reprocessing the inventory data reported by selected LCAs, to yield harmonised life cycle impact assessment results. The findings of this review affirmed trends regarding the dominant environmental burden of feed production and animal by-product inclusion more specifically, and demonstrated a noteworthy reduction in the variation of results post-reanalysis of LCI data, which in turn highlights the value of harmonised methodology with regard to cross-study comparisons in LCA.

1. Introduction

The industrialisation of commercial fishing throughout the mid-twentieth century resulted in a sustained increase in the productivity of fisheries, before an eventual stagnation in catch numbers, as wild stocks began to decline. Catch returns have stagnated since the mid-1990s, and yet global fishing effort has doubled between 1990 and 2010 (Anticamara et al. 2011). This decrease in catch-per-unit-effort strongly suggests that fish stocks have declined as a result of chronic overfishing, which has occurred to such an extent that in 2021, only 62% of fishery stocks were defined as within biologically sustainable levels, as opposed to 90% in 1974 (Food and Agricultural Organisation of the United Nations (FAO), 2022, 2024). The demand for seafood has continued to grow regardless of the plateau in wild fishery productivity, and the economic incentive to provide this seafood by other means has driven the rapid expansion of the aquaculture industry (Garlock et al. 2020). Between 1970 and 2008, global aquaculture production increased at an average annual rate of 8.4%, which substantially exceeded the growth rate of other major food production systems (Hall et al. 2011; Troell et al. 2014). Now, aquaculture has surpassed capture fisheries in aquatic animal production, representing 51% of global output in 2022 (FAO 2024).

Outside of Asia, the Atlantic salmon (*Salmo salar*) has grown to become the dominant aquacultural species in terms of volume and export value (FAO 2022). Farmed Atlantic salmon is a global supercommodity, with its yield of 2.7 million tonnes in 2020 accounting for 32.6% of all marine finfish aquaculture production (FAO 2022). Commercial salmon fishing began in the 1970s and within only a couple of decades, unregulated high sea fisheries had resulted in substantial population declines (Dadswell et al. 2022). Therefore, after a brief surge in supply, wild-caught Atlantic salmon became a rarity as a result of diminishing catch returns, which presented the opportunity for aquaculture to provide an affordable alternative. Norway produced the first successful generation of farmed salmon in 1970, and the industry grew rapidly from there onwards, producing 4,000 tonnes in 1980, and 140,000 tonnes in 1990 (U.S. National Marine Fisheries Service 1990). Following Norway's success, Scotland, Chile, and Canada established industries of their own, and now, global farmed salmon production sits at over 2.8 million tonnes per annum, with Norway and Chile contributing 53% and 28% to this total (FAO 2024).

The sustained success of Atlantic salmon aquaculture can be attributed to increasingly efficient growth and feed conversion rates (FCRs), as well as an excellent nutritional profile, which make farmed salmon a favourable product for both farmers and consumers (Næve et al. 2022; Gillies et al. 2023). With regard to consumer perception, farmed salmon is so well received that it now has robust markets across Europe, Asia, and the Americas, and is a constitutive export commodity for Norway, Chile, and the United Kingdom (FAO 2024; Löfstedt et al. 2025). Developments in farm infrastructure, genetic technologies, feed formulations, and disease management have also been fundamental to improving production volumes, and as a consequence, salmon aquaculture is now one of the most profitable food systems worldwide (Asche et al. 2011; Opstad et al. 2022; Afewerki et al. 2023).

Cultivation of the Atlantic salmon requires farmers to recreate growing conditions that match its anadromous life history, which is displayed in Figure 1. The freshwater phase of salmon farming begins on land in hatcheries, which consist of either flow-through or recirculating aquaculture systems. The latter is now preferred as it protects freshwater ecosystems from effluent discharge, can facilitate higher stocking densities, and allows for the precise control of growth conditions (Mota et al. 2024). Regardless of which system is used, farmed salmon are provided with flowing, well-oxygenated water as they develop from newly-hatched alevin through to mature parr (Figure 2).

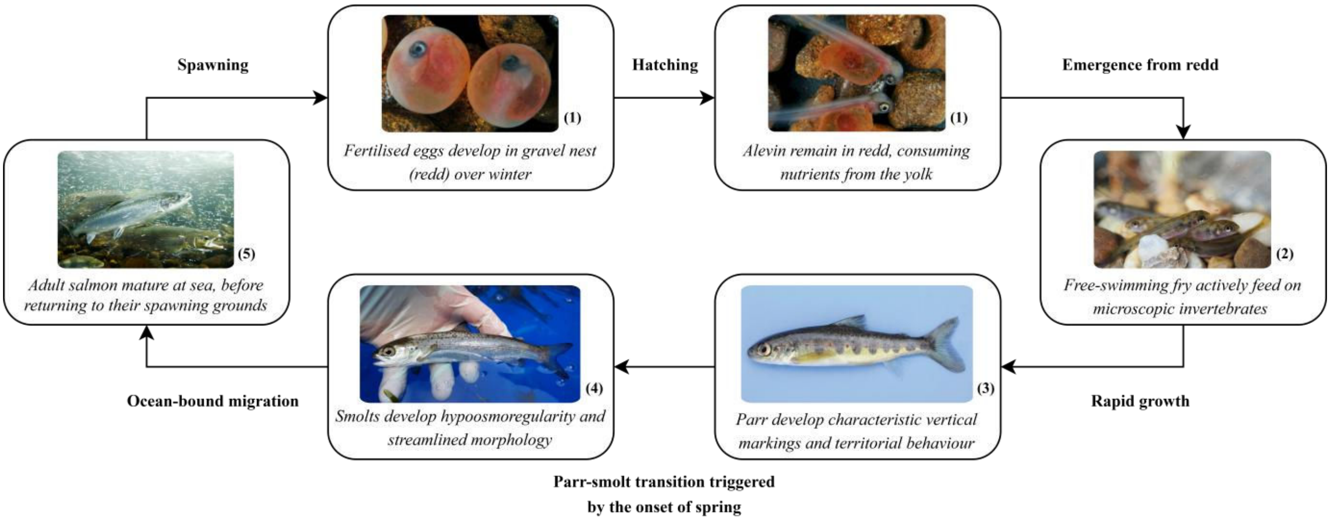

Figure 1 – Anadromous life history of wild Atlantic salmon
The parr-smolt transition is triggered in wild Atlantic salmon by spring's longer photoperiod and warmer temperatures, which stimulate the hormonal changes necessary to develop hypo-osmoregulatory capacity, a streamlined morphology, and schooling behaviour, all of which are essential for their migration to a saltwater, pelagic environment (Björnsson et al. 2011; McCormick et al. 2013).
Image credits: (1) Nick Giles, (2) Orlando 2022, (3) Connecticut Department of Energy & Environmental Protection (4) Scottish Land & Estates (5) Dilger 2023.

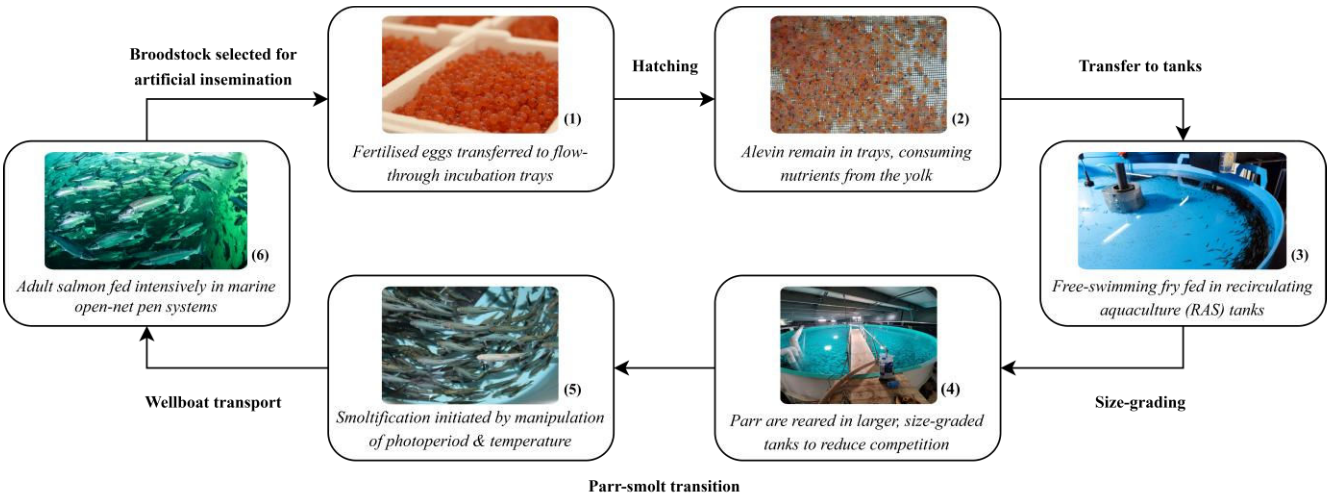

Figure 2 – Life cycle of farmed Atlantic salmon
Salmon farmers initiate smoltification by treating parr with a short-day photoperiod, before abruptly shifting to a longer photoperiod or even continuous light, in order to stimulate the necessary endocrine changes (Martinez et al. 2023). Mature smolts are then transported to marine sites in wellboats, in order to begin the grow-out phase of farming.
Image credits: (1) AquaGen 2021, (2) Randolph 2014, (3) Logan 2024, (4) SalmonBusiness 2022 (5) Sustainable Aquaculture Systems Supporting Atlantic Salmon (6) Paolantonacci 2024

Currently ~98% of global salmon production occurs in open-net pen (ONP) systems, which are reinforced mesh cages anchored in coastal waters (Fisheries and Oceans Canada 2019). It is in these marine pens where farmed salmon accumulate the vast majority of their biomass over the course of 18-24 months, to reach a harvestable weight of approximately 5.5kg (Dempsey et al. 2023). The upside to ONP systems is that ocean currents can be relied upon to maintain water quality and remove waste. However, this means that livestock and the local marine environment are exposed to one another, which presents a series of fish welfare and conservation-related challenges. With regard to fish health, salmon reared in ONP systems are threatened by infectious diseases, ectoparasites, temperature fluctuations, hypoxia, and harmful algal blooms (Sajid et al. 2024). A variety of measures have been developed to combat these issues, including smolt vaccination programs, in-feed medications, treatment baths, and cleaner fish (Boerlage et al. 2024; Mechlaoui et al. 2025). However, despite advances in medical care, mass-mortality events (MMEs) are still too frequent to ignore. For example, the Norwegian industry has invested significantly in biosafety measures, and yet in 2023 reported a record-breaking mortality rate of 16.7%, with the leading cause of death being infectious disease (Sommerset et al. 2024). A recent analysis (Singh et al. 2024) also demonstrated an increase in the frequency of MMEs at a global scale, which puts into question the efficacy of existing fish welfare management.

Environmental concerns have also grown in relation to the impacts of salmon aquaculture upon wild salmonid populations. Densely stocked ONPs provide ideal conditions for the growth of infectious pathogens, which are released into the water column. This exposes local salmonid populations to unnatural levels of disease, thus altering disease dynamics and reducing their resilience to other anthropogenic stressors (Forseth et al. 2017; Krkosek et al. 2024). Furthermore, farmed escapees exacerbate disease transmission, and can even reduce the genetic integrity of wild populations due to introgression. In Norway, escaped farmed salmon are evaluated as the greatest threat to wild salmon stocks (Forseth et al. 2017), and introgression has been identified to varying extents in two-thirds of all wild populations (Bolstad et al. 2021). Beyond introgression and disease transmission, the broader ecological impacts of salmon farming are largely a result of nutrient emissions. Uneaten feed, faeces, and liquid nitrogenous waste are emitted from net pens, and have been documented to cause eutrophication and benthic degradation in areas of poor water exchange (Buschmann et al. 2007; Taranger et al. 2015).

Another aspect of the salmon production chain that must be accounted for is the extraction of biotic resources for feed production. Traditionally, pelagic forage fish of little to no commercial value comprised a high percentage of feed ingredients (Sprague et al. 2016). However, as the industry has grown in size, it has become evident that relying upon wild fisheries entirely is ecologically unsustainable. Marine ingredients have therefore been substituted with plant-based alternatives, which now comprise the majority of salmon feed ingredients by volume (Skavang and Strand 2024). Although this has significantly improved the fish-in/fish-out (FIFO) ratio of farmed salmon (Naylor et al. 2021), the industry remains a major consumer of fishery products, including many fish species that are fit for direct human consumption (Willer et al. 2024). Plant-based substitutions beyond 50% have also been suggested to detriment the growth, health, and nutritional profile of farmed salmon (Egerton et al. 2020), and so several alternatives to marine-derived ingredients are being trialled, such as animal by-products and insect meals (Fisher et al. 2020). However, both plant and animal-derived substitutions have their own environmental implications, which can worsen the sustainability of farmed salmon from other perspectives. For example, by creating a market for animal by-products, salmon aquaculture financially sustains livestock agriculture, and is therefore in part responsible for its greenhouse gas (GHG) emissions. Furthermore, soybean is a frequently used alternative to marine proteins, but is a major driver of deforestation in South America (Song et al. 2021), and so in this case, wild fish stocks are being protected at the expense of terrestrial biodiversity elsewhere.

It is clear that salmon aquaculture consists of many facets, and therefore has a range of environmental impacts to consider. Life Cycle Assessment (LCA) has emerged as the preferred environmental impact assessment framework for food production systems, as well as aquaculture systems more specifically (Cao et al. 2013; van der Werf et al. 2020). LCA is used to evaluate environmental performance by compiling inputs and outputs within the system boundary of a production chain, in order to produce life cycle inventory (LCI) results relative to a predefined functional unit. LCIs can in turn be used to perform a life cycle impact assessment (LCIA), in which the impacts of inventory flows (e.g. methane emissions) are characterised into impact categories (e.g. global warming expressed as kg CO_2-equivalents) using characterisation factors (e.g. global warming potentials). This provides a holistic approach to environmental impact assessment (EIA), and allows practitioners to identify the environmental hotspots within a production chain, in support of better management towards the goal of sustainable food systems. Salmonids are the most studied finfish species group within the aquaculture LCA literature, likely as a result of their commercial importance and popularity in the Global North (Philis et al. 2019). Therefore, Atlantic salmon LCAs not only constitute an important part of the academic literature, but are also produced in an industrial context by salmon farming companies and their associated environmental consultancies.

Currently only one literature review of salmonid LCAs has been published (Philis et al. 2019). The study covered a range of species (Atlantic salmon, rainbow trout, Arctic char, Chinook salmon, brook trout, and brown trout), and a range of production systems, including flow-through, recirculating aquaculture, and open-net pen systems. A major conclusion of the review was that cross-study comparisons of LCIA results were largely not possible, due to methodological inconsistencies, incomplete LCIs, and confounding variables generated by multiple focal species and production technologies. These limitations undermine the relative nature of LCA, as the results for one product are most meaningful when contextualised by the results of others. Therefore, cross-study comparisons of LCAs can be used to demonstrate overarching trends within and between food production systems, however, the breadth of methodologies available to practitioners has made this impractical so far. Many reviews of aquaculture LCAs have made similar suggestions to make cross-study comparisons more feasible, which almost always revolve around improving the reporting of methodological choices and inventory data (Henriksson et al. 2012; Philis et al. 2019; Bohnes et al. 2019; Vélez-Henao et al. 2021; Hala et al. 2024).

The primary analytical component of this review includes an assessment of methodological choices and inventory completeness, together with a correlation analysis of key inventory flows (energy use, FCR, and feed compositions) and LCIA results. This is followed by the reprocessing of unit process data using HESTIA. HESTIA is an open-access, agri-environmental platform that provides the standardised LCA models necessary to recalculate a set of harmonised LCIA results. These harmonised results will then be used to perform a contribution analysis for the most consistently reported impact category in LCA (global warming in kg CO_2-eq). Finally, the variation in global warming values will be compared between the original and recalculated sets of results, in order to demonstrate the effect of methodological harmonisation upon LCA. Additionally, the intention of this work is to use the available body of literature to delimit the relative contributions of feed production and farming practices to the environmental impacts of farmed salmon at a global scale, whilst reducing the influence of methodological variations between studies.

2. Methods

2.1 Literature search

The literature search was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al. 2021). As the HESTIA-based component of this review required sufficiently complete LCIs for recalculating LCIA values, an emphasis was also placed on the quality of inventory data reported when developing exclusion criteria. It follows that exceptions were made for non-peer-reviewed studies that presented quality inventory data (Tyedmers 2000; White 2013; Hognes et al. 2014; Prescott 2017).The literature search was conducted by applying a search string to Web of Science, Scopus, and Google Scholar on the 28th of October 2024. The search string chosen was: (salmon OR "salmo salar") AND (aquaculture OR farm* OR production) AND (LCA OR "life cycle assessment*" OR “life cycle analys*”). This was developed by first identifying key studies that should be included from Philis et al. 2019, and then trialling various combinations of terms and Boolean operators, to refine search results whilst maintaining the set of previously identified key studies. This yielded 144, 58, and 100 (first ten pages) studies across WOS, Scopus, and Google Scholar respectively.

2.2 Primary Screening

Following the initial search, titles and abstracts were screened for the environmental impact assessment (EIA) of open-net pen (ONP) salmon aquaculture. The exclusion criteria were as follows:

1. Exclude studies that evidently do not contain an EIA of ONP salmon aquaculture
2. Exclude studies that focus on land-based salmon aquaculture systems

A set of 95 studies were produced across the three databases, and duplicate removal refined the total count to 61 studies (Figure 3). The reference lists of literature reviews identified by the initial search were also screened separately to ensure that no relevant studies were missed. This involved the same exclusion criteria as before, and resulted in one additional study (White 2013), to produce a final set of 62 studies for full-text review.

2.3 Full-text review

The full-text review component of study selection intended to only keep Atlantic salmon LCAs that provide HESTIA-compatible inventory data. The exclusion criteria were as follows:

1. Exclude studies that do not provide primary inventory data for at least one of the major foreground processes (feed, hatchery, or grow-out)
2. Exclude Master's theses

The rationale for excluding Master's theses was that PhD theses typically undergo external examination, ensuring greater reliability relative to master's theses. Three relevant LCAs were also excluded on the basis of undocumented inventory data (Ellingsen and Aanondsen 2006; Ellingsen et al. 2009; Sherry and Koester 2020). When a study used but did not report primary inventory data for one or more of the major processes, the author was contacted, which provided additional inventory data for Pelletier et al. 2009, and allowed for the inclusion of Newton and Little 2018. Finally, in some instances, identical inventories were presented by more than one study, and duplicates were therefore removed, such as the SINTEF report Johansen et al. 2022, which was excluded in favour of the peer-reviewed publication Ziegler et al. 2024. Another case was the exclusion of Ayer and Tyedmers 2009 in favour of Tyedmers 2000, as the latter provided primary data for all three major foreground processes.

After full-text review, 13 of the initial 62 studies remained, largely due to the exclusion of reviews and studies presenting secondary data. The final set of studies chosen for analysis are presented in Table 1, along with the number of cycles per study.

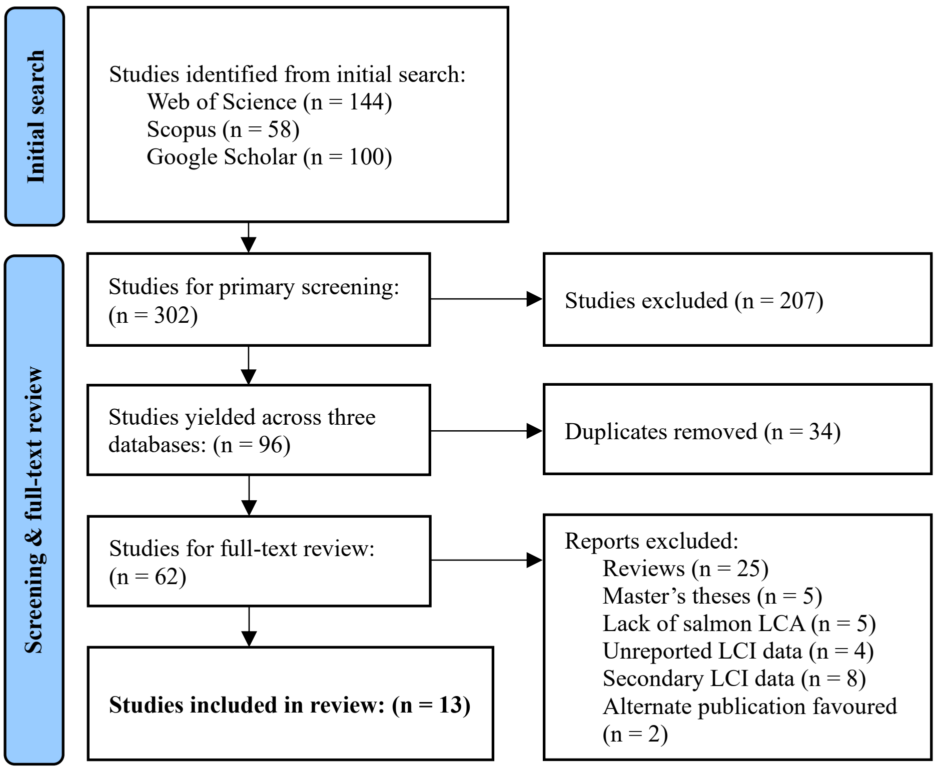

Figure 3 – PRISMA flowchart detailing the literature search stages

In this review, a cycle represents a foreground unit process (i.e. a unit process within the system boundary for which primary data should be collected). Therefore, feed production, hatchery, and grow-out cycles were categorised, with outputs being standardised to a tonne of feed, smolts, or liveweight salmon, respectively. In total, 16 feed cycles, 10 hatchery cycles, and 23 grow-out cycles were produced.

Table 1 – Selected studies and the number and type of cycles they contain

LCAs chosen for review			No. of cycles		
Study ID	**Author & Year**	**Focus**	**Feed**	**Hatchery**	**Grow-out**
1	Tyedmers, P. 2000	Comparison of salmon fisheries & salmon aquaculture in Canada	1	2	2
2	Pelletier, N et al. 2009	Assessment of salmon aquaculture in Norway, Scotland, Canada, & Chile	4	1	4
3	Boissy, J et al. 2011	Comparison of salmon fed with standard & plant-dominant diets in Scotland	2	0	2
4	Ziegler, F et al. 2013	Assessment of 22 Norwegian seafood products	1	1	1
5	White, A. 2013	Assessment of salmon aquaculture in Australia	1	1	1
6	Hognes, E et al. 2014	Assessment of salmon aquaculture in Norway	1	0	0
7	Ayer, N et al. 2016	Comparison of salmon reared in nylon and copper-alloy net pens in Chile	0	0	2
8	Prescott, S. 2017	Assessment of integrated multi-trophic salmon aquaculture in Chile	1	1	1
9	Newton & Little 2018	Assessment of salmon aquaculture in Scotland	1	0	6
10	Parker, R. 2018	Assessment of salmon aquaculture in Australia	1	1	1
11	Ziegler, F et al. 2022	Assessment of 21 Norwegian seafood products	1	1	1
12	Brown, M et al. 2022	Comparison of salmon fisheries in Alaska & salmon aquaculture in Norway	1	1	1
13	Ziegler, F et al. 2024	Assessment of salmon aquaculture in Norway	1	1	1

2.4 Analysis of methods & inventories

As variation in methodological choices is a known driver of variation in LCIA results, analysis began with the characterisation of functional units, system boundaries, co-product allocation, background data sources, and characterisation methods. Impact category selection was also quantified and linked to a comprehensive set of environmental implications related to the processes within a cradle to gate system boundary of a conventional salmon production chain (Parker 2018; Bohnes and Laurent 2019; Song et al. 2019; Sherry and Koester 2020). The intention here was to assess the extent to which current salmon LCA addresses the major environmental concerns of salmon aquaculture. Importantly, the impacts of processing and distribution post-farm gate were not considered in this review, as not all studies included these components of the production chain.

The second element of analysis focused on the completeness of reported LCIs. A process completeness checklist was designed based upon the inventories reported in the 13 studies selected, in order to encapsulate the inventory flows relevant to the feed mill, hatchery, and grow-out stages. The reporting of infrastructure inputs was only deemed necessary for the grow-out sites, as recording the infrastructure of hatcheries and feed mills in full is an unrealistic expectation for practitioners.

Table 2 – Inventory process completeness checklist

Feed Mill	Hatchery	Grow-out
Ingredient transport Energy use	Egg production Feed transport Energy use Feed use Water use Chemical use Emissions	Infrastructure use Smolt transport Feed transport Smolt use Energy use Feed use Chemical use Emissions

The process completeness checklist in Table 2 was applied to the inventories reported by the selected studies. Life cycle processes mentioned by authors but not reported in text were deemed to be incomplete, as one intention of this review is to stress the importance of data transparency in LCA.

2.5 Correlation analysis of efficiency metrics and impact assessment results

Farm-level efficiency metrics (energy use, FCR) and feed ingredient categories (fishery-derived, crop-derived, soybean, animal by-products) were statistically compared with the three most consistently reported impact categories (global warming, eutrophication, and acidification), to determine whether relationships between inventory flows and LCIA values could be observed regardless of the methodological discrepancies between studies. Spearman's rank correlation coefficient, a non-parametric test, was selected as it allows for the detection of monotonic relationships in small, heterogenous datasets. The statistical test was conducted in R, and a heatmap was produced to visualise the results.

2.6 Contribution analysis through HESTIA

The final analytical component of this review utilised HESTIA (Poore 2021, available at https://www.hestia.earth) to recalculate harmonised global warming values, by reprocessing the reported LCIs of each study. Contribution analyses were also performed to identify the relative contributions of feed ingredient production and farming practices to the recalculated global warming values. The process began with data extraction, where HESTIA-compatible templates were created in excel to store the unit process data for each cycle. Templates were designed in accordance with HESTIA's Schema and Glossary of Terms. The Schema includes seven nodes (see Table 3), which contain their own data fields with predefined data types, and characterise the overall structure of agri-environmental datasets. Nodes also contain blank nodes, which store quantitative data within their respective field. The Glossary of Terms provides terms to describe the inputs, activities, products, and environmental impacts related to food systems, and links to the Schema via blank nodes, which are described using terms from the glossary.

Table 3 – The seven nodes that compose HESTIA's Schema

HESTIA Nodes	Brief Description
Cycle	The inputs, emissions, products, and practices related to a production cycle
Site	The area on which a cycle occurred
Organisation	The organisation which manages a site
Impact Assessment	The environmental impacts created per unit of product for a cycle
Source	The source of data for a given cycle
Actor	The person or institution who produced the data
Term	An item from the Glossary of Terms

To illustrate how this all ties together, take the input of feed into the grow-out phase as an example (Table 4). Working backwards, the glossary term chosen for the input is 'Concentrate feed blend'. The feed input in kilos is the quantitative data stored within a blank node, and the blank node belongs to the 'inputs' field of the 'cycle' node.

Table 4 – A snippet of a HESTIA upload template for a grow-out cycle

cycle.inputs.0.term.name	cycle.inputs.0.value	cycle.inputs.1.term.name	cycle.inputs.1.value
Concentrate feed blend	1300	Fish fingerling (kg mass)	20

In the column headers, 'cycle' denotes the node, 'inputs' denotes the field within the node, '0' represents the first 'Input' blank node, and 'term.name' or 'value' are nested fields within the 'Input' blank node. Therefore, in this snippet of a grow-out cycle, the first input is 1300kg of feed, and the second input 20kg of smolts.

This logic is then scaled to include all the unit process data for a given cycle, such as inputs, products, emissions, and transport values. An example of a complete HESTIA upload for Parker 2018 can be found in Supplementary Material 2. Relative to the schema's nodes, the Glossary of Terms is more dynamic, and is frequently augmented as new datasets are uploaded to the HESTIA platform. Therefore, the structure provided by the schema, combined with the flexibility of the Glossary of Terms, makes upload templates adaptable to a diverse range of food systems, whilst maintaining compatibility with HESTIA. This was important in the case of salmon LCA, as the complexity of salmon aquaculture is reflected in the breadth of inventory items reported across the literature. Therefore, several additions to the Glossary of Terms were required, farm-level emission models had to be tailored for marine ONP systems, and emission data for feed ingredients had to be obtained through an ECOALIM license (ADEME 2020).

Once data extraction was completed, the templates were uploaded to HESTIA, and global warming values were recalculated using standardised methodology. More specifically, functional unit was normalised to a kilo of liveweight salmon, economic co-product allocation was applied, global warming was calculated in kg CO_2-eq, and characterisation factors were derived from the IPCC Sixth Assessment Report (Intergovernmental Panel on Climate Change (IPCC) 2021). Global warming was chosen as the sole impact category for two reasons. Most importantly, at the time of writing this thesis, the nitrogen emission models from ECOALIM were not fully integrated into HESTIA, and so the eutrophying and acidifying impacts of feed production were not yet calculable. Additionally, global warming was the only impact category reported in all the studies selected, and was therefore best suited to a comparison of variance between the sets of original and recalculated results. The first element of the contribution analysis was to compare the impacts of feed production with the combined impacts of the hatchery and grow-out stages. Then, as feed production is known to be a significant contributor of GHG emissions, a separate analysis was performed to determine the relative contributions of crop, soy, animal by-product, and fishery-derived ingredients to the global warming impact of feed production. Finally, variation within the sets of original and recalculated global warming values were compared to assess whether harmonisation through HESTIA reduced the variation among LCIA values.

3 Results

3.1 Analysis of methodological choices

To begin with, methodological variation was identified to some extent in all the variables analysed, as detailed in Table 5.

Table 5 – The key methodological choices made by LCA practitioners across the 13 studies

Study ID	Functional unit	System boundaries	Allocation method	Background process database(s)
1	1t liveweight salmon	Cradle to farm gate	mass	-
2	1t liveweight salmon	Cradle to farm gate	energy	Ecoinvent v. 2.0
3	1t liveweight salmon	Cradle to farm gate	economic	Ecoinvent v. 2.0
4	1kg edible product	Cradle to processor gate	mass	Ecoinvent v. 2.0, SIK report 793
5	1kg HOG salmon	Cradle to processor gate	mass	Ecoinvent v. 2.2, AusLCI
6	1kg edible product	Cradle to farm gate	mass	Ecoinvent v. 3.0, Agri-footprint v. 1.1
7	1t liveweight salmon	Cradle to farm gate *	energy	Ecoinvent v. 2.2
8	1kg liveweight salmon	Cradle to farm gate	economic	Ecoinvent v. 3.0, Agri-footprint v. 1.0
9	1t HOG salmon	Cradle to processor gate *	economic	Ecoinvent v. 2.2
10	1kg HOG salmon	Cradle to distribution	energy	Ecoinvent v. 3.0, Agri-footprint v. 2.0
11	1kg edible product	Cradle to distribution	mass	Ecoinvent v. 3.5, Agri-footprint v. 4.0
12	1kg liveweight salmon	Cradle to processor gate	N/A	Ecoinvent v. 3.6
13	1kg edible product	Cradle to distribution	mass	Ecoinvent v. 3.8, Agri-footprint v. 6.0, Agribalyse v. 3.0, World Food database

System boundaries spanned cradle to farm-gate at the least, with six studies going beyond the farm-gate to include processing and distribution. The choice of functional unit was determined by system boundaries, as the studies that included processing and distribution tended to adopt a functional unit of head-on gutted salmon (HOG) or edible product, rather than liveweight salmon. The preferred co-product allocation method was mass allocation (n = 6), followed by energy and economic allocation (n = 3). As for background data sources, various versions of ecoinvent were used to by every study other than (Tyedmers 2000), which was published prior to ecoinvent's release in 2003. The Agri-footprint database was also frequently used to supplement the agricultural data provided by ecoinvent.

3.2 Analysis of impact category choices

The methodological choice that exhibited the greatest variation across studies was impact category selection. As displayed in Figure 4, global warming was calculated in every study selected, and eutrophication, acidification, and cumulative energy demand were calculated by half of the studies. Studies produced by the Norwegian research organisation SINTEF (Ziegler et al. 2013, 2022, 2024; Hognes et al. 2014) often only calculated global warming impacts, as they were exclusively GHG emission assessments, which consider one impact category: global warming in kg CO_2-equivalents. Similarly, Tyedmers 2000 only quantified GHG emissions in kg CO_2-equivalents. The remaining LCAs all calculated terrestrial acidification in kg SO_2-equivalents, and eutrophication in kg PO_4^{3-}-equivalents, while Ayer et al. 2016 used ReCiPe's 'Marine eutrophication' in kg N-equivalents.

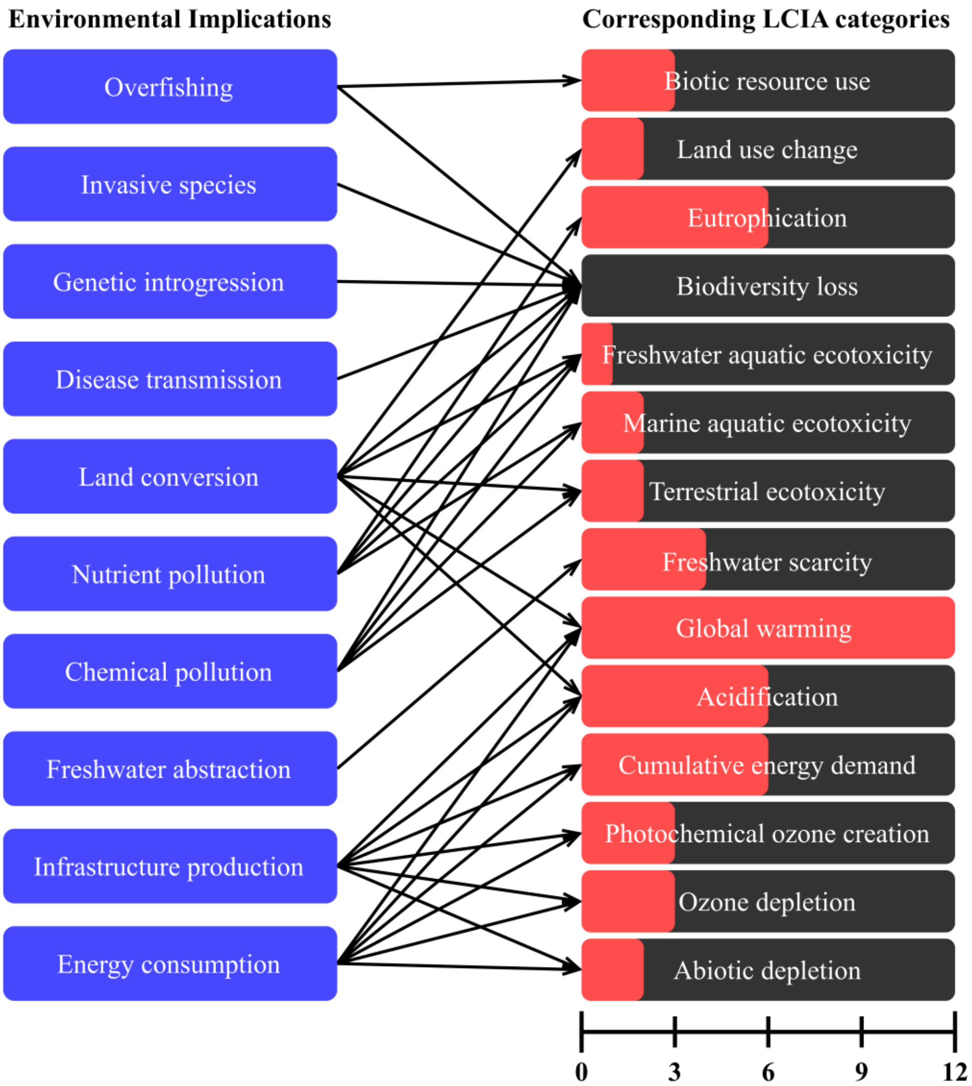

Figure 4 – The environmental implications of salmon aquaculture and their links to impact categories
Red progress bars represent the number of studies that used a given impact category. Brown et al. 2022 used their LCI to perform an emergy analysis rather than an LCIA, and was therefore not included. Visualisation adapted from Alena Goebel's unpublished doctoral work (2025).

The impact assessment methods used to produce results for each impact category were also inconsistent, largely due to the release of newer methods within the timeframe analysed (Table 6). This generates variation in LCIA results across studies, as different impact assessment methods can offer different characterisation factors for a given emission or resource use. For example, the global warming potential of methane over a 100-year time period is 25kg CO2-eq under IPCC 2007 and 28kg CO2-eq under IPCC 2013, and so identical inventory flows would yield different global warming values depending on the version of IPCC used. Therefore, despite the seemingly consistent application of impact assessment methods, differences in the versions used were likely a source of variation in LCIA results.

Table 6 – The characterisation methods used across the 13 studies

Study ID	Characterisation method(s)	Study ID	Characterisation method(s)
2	CML2 Baseline 2001, VDI 1997, Papatryphon et al. 2004	8	CML2 Baseline 2001
3	CML2 Baseline 2001, VDI 1997, Papatryphon et al. 2004	9	CML2 Baseline 2001
4	IPCC 2007, VDI 1997	10	CML2 Baseline 2001, VDI 1997
5	IPCC 2009, CML 1992, VDI 1997, Papatryphon et al. 2004	11	IPCC 2013, Blonk Consultants 2016
6	ReCiPe v. 1.07, Mekonnen & Hoekstra 2010	12	ReCiPe v. 1.13
7	ReCiPe v. 1.07, VDI 1997	13	IPCC 2021, Blonk Consultants 2016

Global warming was calculated either with IPCC characterisation factors or characterisation methods that use IPCC characterisation factors (CML-IA & ReCiPe). Eutrophication, terrestrial acidification, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, ozone depletion, photochemical ozone creation, and abiotic depletion were calculated using versions of either CML-IA or ReCiPe. Cumulative energy demand was calculated using the method outlined in VDI Guideline 4600, which was later integrated into ecoinvent. Biotic resource use was calculated using the method specified in Papatryphon et al. 2004. Land use change GHG emissions were calculated twice using the methods specified in Blonk Consultants 2016. Finally, freshwater scarcity was calculated once using the method specified in Mekonnen & Hoekstra 2010.

3.3 Analysis of inventory completeness

The completeness of inventories reported by the selected studies was again highly variable (Figure 5), mainly due to data collection constraints and the exclusion of processes deemed negligible in environmental impact.

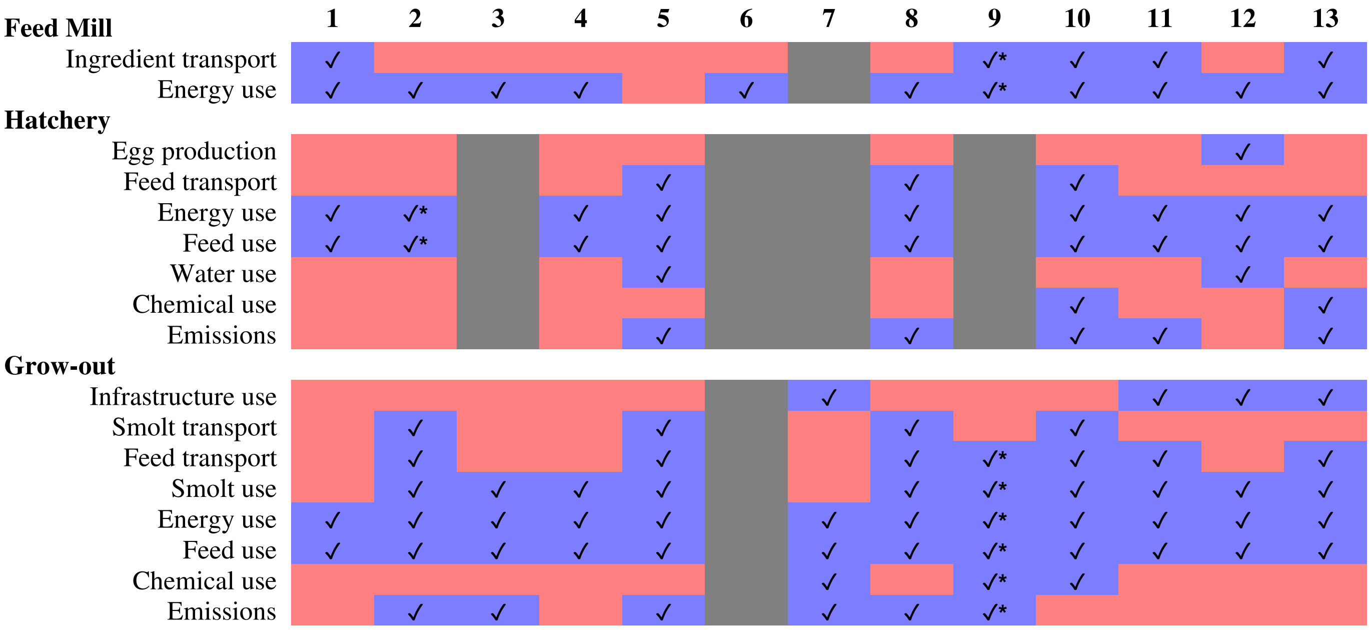

Figure 5 – Inventory completeness checks for the major foreground processes

Number represent Study IDs. Ticked cells represent completeness, which was decided based upon the presence/absence of primary data for a given unit process. Grey bars represent a lack of primary data reported for an entire foreground process. Asterix denotes inventory components that were not reported, but obtained by contacting authors. For feed production, energy use was consistently reported, however, the transport modes and distances of feed ingredients to the feed mill were reported in less than 50% of cases. For the farming stages, energy and feed use were consistently reported, however, processes relevant to the health of aquatic ecosystems (water use, chemical use, nutrient emissions) were sparsely reported. Likewise, the reporting of transport modes and distances to the hatcheries and net pens varied.

3.4 Correlation analysis

As for the farm-level efficiency metrics, energy use in the form of electricity and fossil fuels showed no significant correlation with any of the impact categories, which contradicts the presumption that fuel combustion is a primary driver of GHG emissions at the farm level. However, feed conversion ratio (FCR) positively correlated with all three, suggesting that a greater feed input per tonne of salmon harvested is a strong contributor to the environmental impacts of salmon aquaculture. Regarding feed composition, animal by-product inclusion positively correlated with eutrophication and acidification, whilst very narrowly falling below the significance threshold for global warming. Soybean inclusion was the opposite, with strong negative correlations for eutrophication and acidification, which is somewhat surprising given the known association between soybean agriculture and land use change (Song et al. 2021). Fishery-derived ingredients exhibited a weak but insignificant, negative correlation with global warming, and a neutral relationship with eutrophication and acidification. Finally, crop-derived ingredients did not correlate significantly with any of the impact categories, but did show weak positive relationships with global warming and eutrophication.

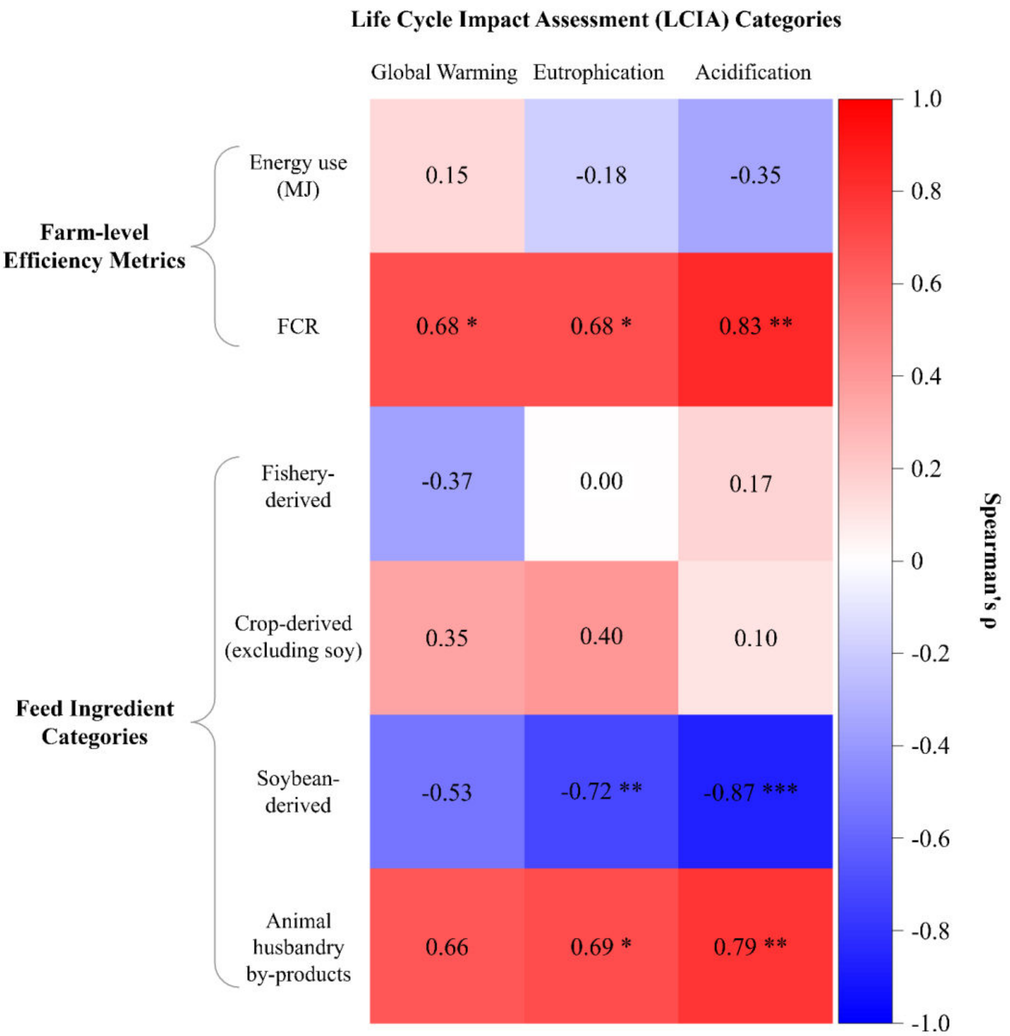

Figure 6 – Heat map to visualise the results of the Spearman's rank test

Positive correlations (in red) indicate that increasing the given metric or ingredient share is associated with higher environmental impacts, while negative correlations (in blue) indicate the opposite. Values shown are Spearman's ρ coefficients. Asterisks denote statistical significance thresholds: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). Sample sizes differed for each impact category due to variation in impact category selection. $n = 16$ for correlations with global warming, $n = 10$ for correlations with eutrophication, and $n = 11$ for correlations with acidification.

3.5 Contribution analyses

In almost all cases, global warming results recalculated through HESTIA were lower than the original values reported in text (Figure 6). This was most commonly a result of HESTIA using economic co-product allocation, which assigns a lesser impact to animal by-products in comparison to mass or energy allocation. Additionally, the reporting of inventories was imperfect, and so at times, inventory processes that were incorporated into the original impact assessments were undocumented, and were therefore unaccounted for in the recalculated values. Finally, nitrous oxide emissions were only calculable at the farm level, as the nitrogen emission models for feed ingredients were not yet integrated into HESTIA. This likely explains a relatively small but consistent proportion of the reduction between original and recalculated values. In alignment with previous findings, feed production was the dominant contributor to global warming impacts of the majority of production chains analysed. There were however a few exceptions to this, and upon inspecting the inventories of the outlier studies, it became clear that unusually high fuel consumption rates were the causal factor. In Boissy et al. 2011, high fuel consumption at the grow-out sites in particular elevated farm-level contributions, whilst also increasing the total recalculated values beyond those reported in text. The discrepancy between original and recalculated values were likely a result of incorrectly reporting, as the consumption rates of diesel and natural gas were implausible (see Supplementary Material 1 for details). Similarly, grow-out fuel consumption rates were relatively high for both Parker 2018 and Ziegler et al. 2024, which inflated the contribution of farming stages to the total global warming values.

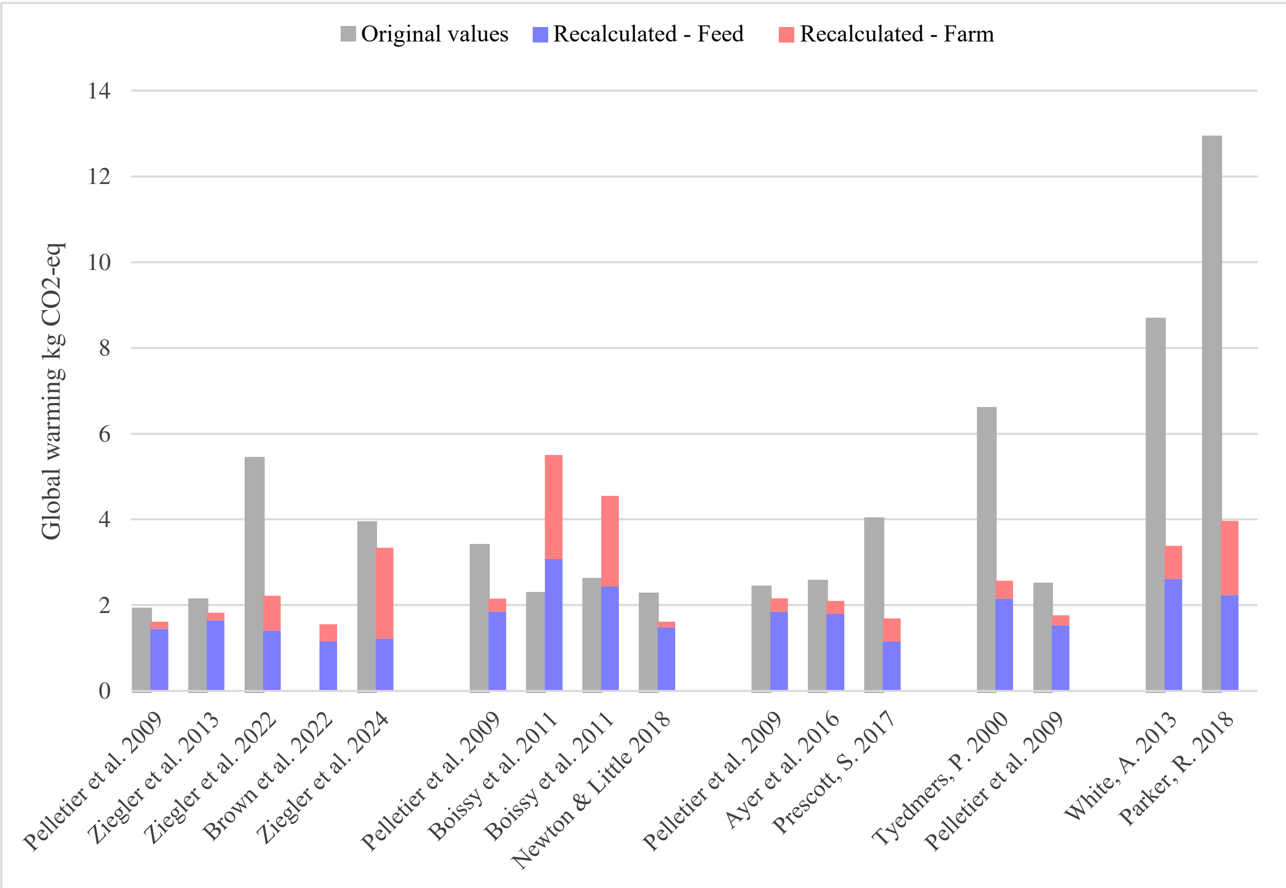

Figure 6 – Comparison of original and recalculated global warming values

Studies are clustered by location, and are ordered by publication date within the clusters, to illustrate how global warming values vary in space and time. The country of each grouping are as follows:

1st group = Norway, 2nd group = Scotland, 3rd group = Chile, 4th group = Canada, 5th group = Australia

Brown et al. 2022 did not perform an LCIA and so only recalculated values are shown.

The relative contributions of feed ingredient categories to the global warming impacts of feed production exhibited noteworthy temporal and geographical trends, in spite of the small sample sizes for each producer nation. Firstly, studies covering all nations apart from Scotland showed diminishing contributions for fishery-derived ingredients over time, and increasing contributions for crop and soy-derived ingredients collectively, which reflects the global trend towards increasingly plant-based salmon diets. Boissy et al. 2011 likely obscured this trend for the Scottish studies, as the second grow-out cycle used a low-fishery diet in experimental trials, although the Scottish industry is known for its high usage of fishery-derived feed ingredients (Shepherd et al. 2017).

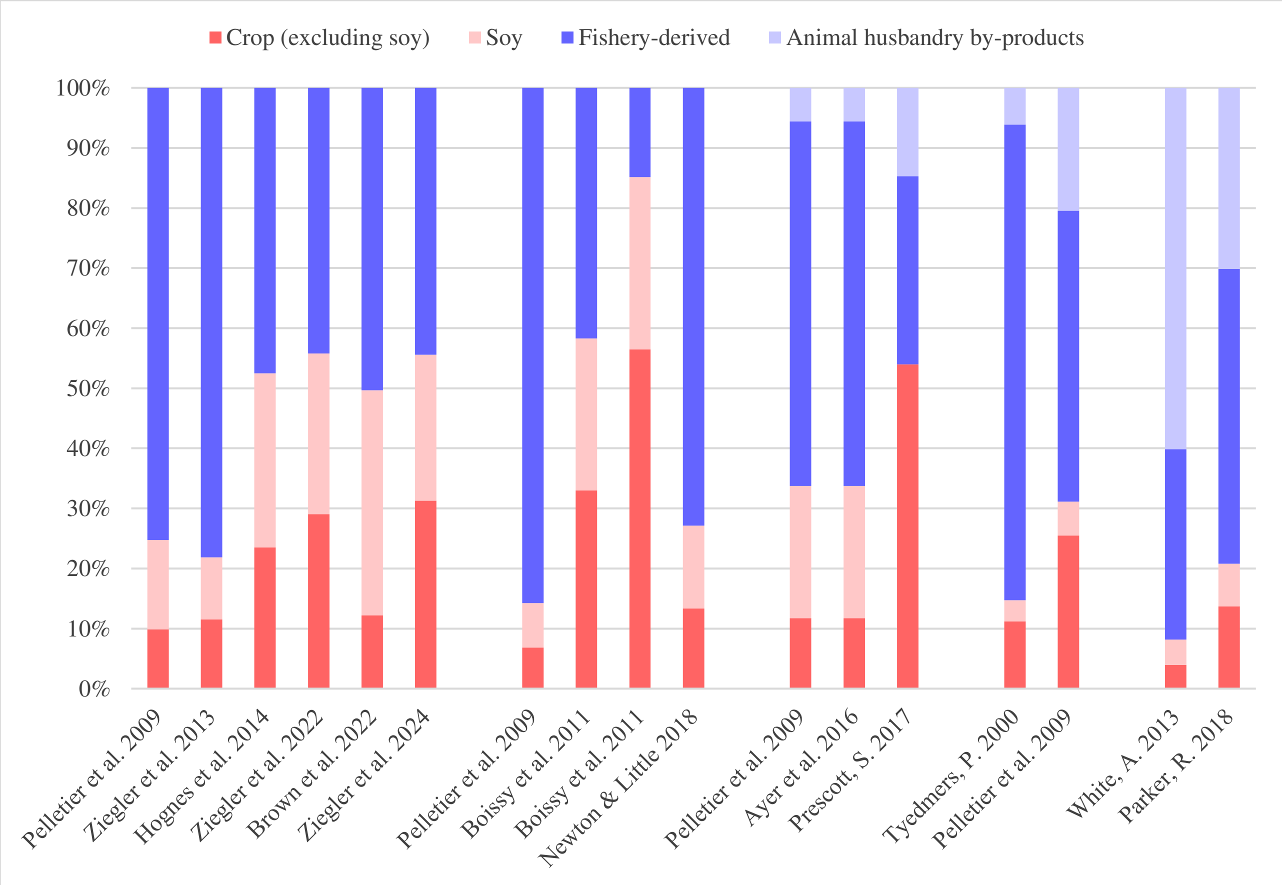

Figure 7 – Relative contributions of feed ingredient categories to the recalculated feed impacts
Relative contributions of the categories are expressed as percentages rather than absolute values to aid visual comparisons between studies. The clusters are the same as in Figure 6. Note the addition of Hognes et al. 2014, which only provided primary data for feed production.

Animal by-products contributed relatively little to the total impact for Canadian and Chilean feeds, which included only poultry by-products. The Australian industry was unique in that animal by-product and fishery-derived ingredients contributed approximately even amounts to the global warming of feed production, resulting from the use of poultry, pork, and beef by-products, which subsidise the need for fish proteins. Finally, when disregarding the potentially anomalous results of Boissy et al. 2011, the studies with the highest feed impact values, namely Tyedmers 2000, White 2013, and Parker 2018, had the smallest crop and soy-derived global warming contributions.

3.6 Variation analysis

The concluding analytical component of this review was to visually compare the distributions of the original and recalculated global warming impacts per kg salmon. The mean and median values of the recalculated results were lower than those of the original results (Figure 7). The two Australian outliers were also brought within the interquartile range of the recalculated values, narrowing the data distribution significantly. The important result is that harmonising methodologies through HESTIA notably reduced the variation and right-skewness of global warming values, and if it were not for the large and potentially anomalous recalculated results of Boissy et al. 2011, this effect would have been even more pronounced.

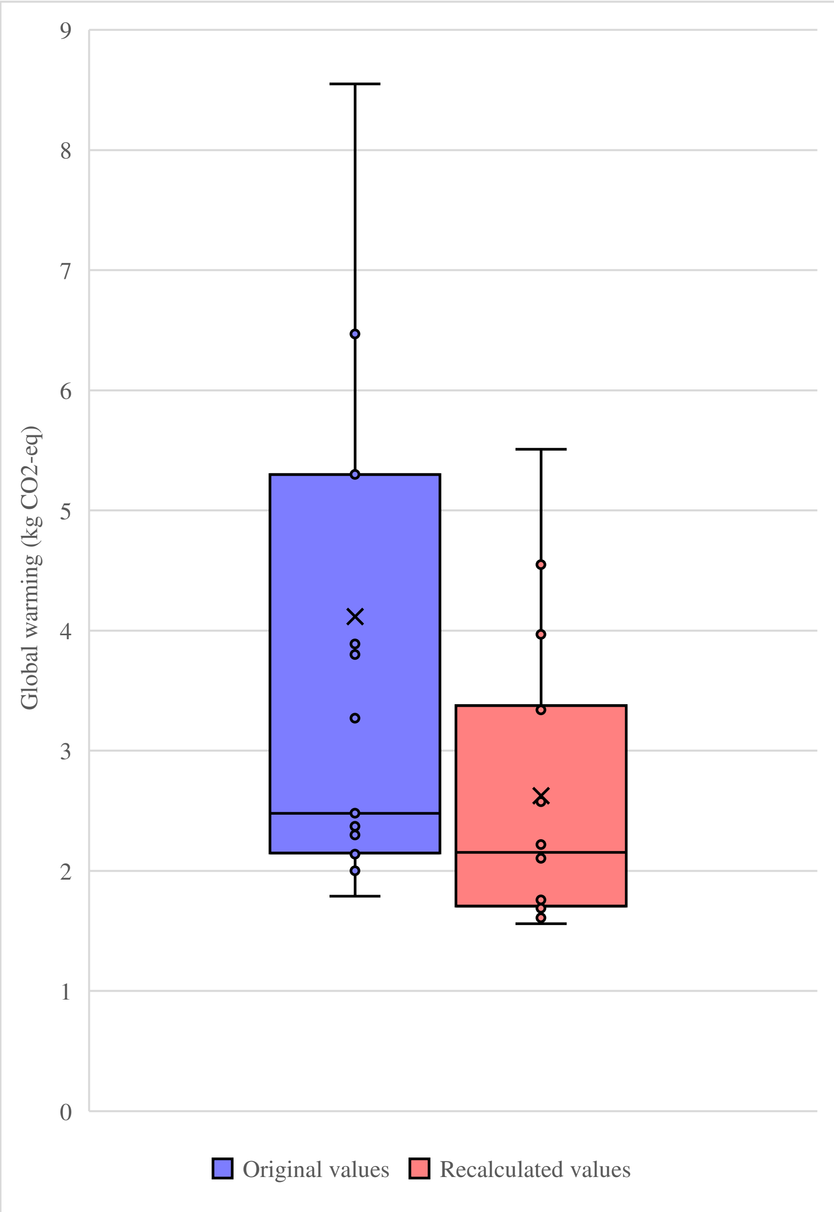

Figure 7 – Boxplots of original and recalculated global warming values

For each dataset, the box represents the interquartile range, the horizontal line denotes the median, and the × symbol denotes the mean. Dots represent the values from individual studies, and the whiskers extend to the most extreme values within 1.5 times the interquartile range from the lower and upper quartiles. For the original values boxplot, the outlier value of 12.8kg CO_2-eq from Parker 2018 is included in the calculation of the mean, median, and interquartile range, but not displayed to improve visual clarity. The largest original value displayed is therefore 8.55kg CO_2-eq from White 2013. Likewise, the two largest values of the recalculated boxplot 4.55 and 5.51kg CO_2-eq, which are both from Boissy et al. 2011.

4 Discussion

4.1 Analysis of methods

Given the expansive geographical and temporal scope of this review, some variations in methodological applications are to be expected, however, choosing to analyse a single focal species in many ways streamlined the comparison of inventory and impact assessment values. Beginning with system boundaries, the inclusion of cradle to farm-gate processes was consistent, however, practitioners often used secondary data for one or more of the major foreground processes, and at times excluded smolt production from impact assessments altogether. Operations beyond the farm-gate, such as slaughter, processing, and distribution were regularly accounted for, especially in the SINTEF-derived works, which stressed the influence of international distribution upon the carbon footprint of farmed salmon. System boundary choice was therefore determined by the goal and scope of a given study, and in the context of this review did not impede cross-study comparisons, as coverage up until the farm gate was sufficient to standardise all inventory data to a common functional unit. Likewise, despite inconsistencies in the functional unit of choice, it was almost always possible to back-calculate impact assessment values relative to a kilo of liveweight salmon. A notable exception was Ziegler et al. 2013, in which CED was expressed per kilo of edible product only, and therefore could not be accurately compared with other CED values. The selection of system boundaries and functional units therefore do not need to be identical throughout salmon LCA, but would best accommodate cross-study comparisons when impact values are reported per liveweight salmon in addition to whichever functional unit is used. More consistent system boundary expansion to include processing stages may also be beneficial, as expressing impacts per unit of edible product is more relevant to the consumer, and supports comparisons with other terrestrial animal products commonly assessed per unit of edible product, such as poultry, pork, or beef (Al-Zohairi et al. 2022; Copley and Wiedemann 2023; Putman et al. 2023).

The choice of allocation method was highly variable, and a lack of consensus on which allocation method to use is by no means unique to salmon LCA (Wilfart et al. 2021). Mass, energy, and economic allocation all have their strengths in certain contexts, and the intention of this review was not to weigh in on which is superior, but rather to demonstrate the effect that varying allocation methods are having upon LCIA outputs. The obvious examples within the selected studies were those focusing on Australian salmon aquaculture (White 2013; Parker 2018), which presented substantially higher global warming values compared to the other selected studies, as a result of high animal by-product inclusion, coupled with high feed conversion ratios. In both cases, the environmental burden allocated to animal by-products was amplified by the allocation method of choice, as Parker 2018 used energy allocation, which assigns impacts according to the gross caloric content of animal by-products, and White 2013 used mass allocation, which assigns impacts according to the weight of animal by-products. Neither option accounts for the fact that by-products incentivise animal agriculture to a lesser extent than their edible counterparts, and therefore should be allocated a smaller proportion of the environmental impact to rear a given livestock. Economic allocation does however take this into account, and as HESTIA's default allocation method is economic, the recalculated results for these two studies were significantly lower. Furthermore, standardising all studies to economic allocation through HESTIA certainly contributed to the substantial decrease in variation observed in the recalculated global warming values. Multifunctionality is therefore a significant driver of variance in LCIA values in the context of salmon LCA, and can be addressed by the inclusion of sensitivity analyses, so that practitioners present their results according to more than one allocation method.

The results of LCAs are also determined by the impact categories chosen by practitioners, as individual categories are unique in the environmental impacts that they account for. In the LCAs reviewed, the inclusion of impact categories beyond global warming was highly varied, reflecting differences in study scoping and the characterisation methods applied. For example, the SINTEF-derived studies which defined themselves as carbon footprint analyses only focused on characterising global warming, rather than providing a wholistic environmental impact assessment of salmon aquaculture. Furthermore, the two most commonly applied characterisation methods (CML Baseline 2001 and ReCiPe) differ in the range of categories they offer, and the selection of impact categories from either method was seemingly arbitrary, as none of the studies that used CML Baseline 2001 or ReCiPe presented an identical set. In summary, the representation of impact categories in salmon LCA is inconsistent, and at times limited to climate-related impacts. Although quantifying the global warming impacts of farmed salmon is of high relevance, this neglects the full environmental impacts of the salmon production chain. It is therefore advisable for practitioners to use the impact categories offered by ReCiPe, which comprehensively cover the impact categories identified as relevant to salmon aquaculture in Figure 4. With regard to the more obscure environmental impacts of salmon aquaculture, namely disease transmission and genetic introgression, more tailored impact categories are required. This was first addressed by Ford et al. 2012, in which several impact categories were proposed, such as the number of escaped salmon and the number of disease outbreaks per functional unit of farmed salmon produced. However, none of the salmon LCAs that followed put these proposed categories into practice, and therefore the context-specific impacts of ONP salmon aquaculture are largely undetected by LCA at present.

4.2 Analysis of inventories

Constructing LCIs is an inherently data intensive process, and it is therefore understandable that practitioners failed to report inventories with total process completeness. Nevertheless, energy and feed use were reported consistently across the selected literature, which almost entirely covers the greenhouse gas emission profile of farmed salmon, but does little to quantify local environmental impacts, which are better described by the inventory flows water use, chemical use, and nutrient emissions. Therefore, in order to comprehensively assess the environmental profile of salmon aquaculture, the coverage of these inventory flows should be improved, in conjunction with the use of representative impact categories, such as marine & freshwater eutrophication, marine & freshwater ecotoxicity, and freshwater scarcity. If this were to be complimented by the reporting of salmon-specific inventory flows, such as cleaner fish inputs, the number of escaped salmon, or the number of disease outbreaks, the ability of LCA to wholistically assess salmon aquaculture would be improved dramatically. However, this is all dependent upon the willingness of farming companies to share potentially sensitive information regarding medicine usage or disease outbreaks for example, which is a limitation external LCA practitioners have little control over.

4.3 Correlation analysis

The results of the correlation analysis at times deviated from expected trends. For example, while feed conversation ratio demonstrated significantly positive correlations with global warming, acidification, and eutrophication, energy use showed no such correlations, which is antagonistic to the assumption that on-farm energy consumption is a significant contributor to GHG emissions. Similarly, with regard to feed composition, animal by-product inclusion positively correlated with all three impact categories as expected, and yet counterintuitively, soybean inclusion showed a strong negative correlation with acidification. The unexpected correlations between these inventory flows and impact values were likely a result of multiple interacting factors. First, the use of differing background data sources, including varying versions of ecoinvent and Agri-footprint, might have introduced inconsistences in the emission factors or system boundaries for a given input. For example, soy-derived ingredients have very different contributions depending on whether land use change (LUC) is considered, as deforestation of the Amazon is driven by soybean agriculture and responsible for substantial GHG emissions (Castanheira and Freire 2013). Therefore, as LUC was rarely accounted for in the selected studies, the negative correlation between soy inclusion and acidification was likely a result of soy ingredients substituting the inclusion of animal by-product and fishery-derived ingredients. More broadly, the quality of inventory reporting was uneven, and may have also contributed to the unexpected relationships observed. In particular, the correlation between energy consumption and global warming was possibly obscured by partial omissions of fuel use at the hatcheries or grow-out sites. For example, the more recent SINTEF publications (Ziegler et al. 2022, 2024) were the only studies to include the consumption of marine diesel oil by support vessels in their assessment, and therefore reported comparatively high energy uses.

4.4 Contribution analyses

Recalculating global warming impacts with standardised methodology and emission models demonstrably reduced the variation in results. To begin with, global warming values decreased post-recalculations for all but one of the selected studies, thus narrowing the overall distribution of recalculated values. Although this was in part due to the limitations of incomplete inventory reporting and lacking feed-level nitrous oxide emissions, the degree to which results decreased was seemingly determined more by the application of economic allocation, which radically reduced the global warming values of feed formulations with higher proportions of animal by-products. Overall, the reduction in variance of global warming values, as well as the disappearance of extreme outliers, demonstrate the appreciable effect that variations in allocation and characterisation methods can have on impact assessments. The dominant impact of feed production was further investigated in the percentage contribution analysis for feed ingredient categories, which in combination with the preceding contribution analysis, demonstrated a difference in the environmental performance of plant and animal-based feeds. When not considering the results of Boissy et al. 2011, there appears to be a relatively clear inverse relationship between the absolute global warming value of feed production and the relative contributions of crop and soy-derived ingredients. More precisely, the studies with the lowest feed impacts (Prescott 2017; Brown et al. 2022; Ziegler et al. 2022, 2024) exhibited the highest relative contributions of plant-based ingredients, and the studies with the highest feed impacts (Tyedmers 2000; White 2013; Parker 2018) exhibited the highest relative contributions of animal-based ingredients.

5 Conclusion

This systematic review of Atlantic salmon LCA clearly identifies methodological inconsistency as a primary driver in the variation of reported environmental impacts, which has obscured trends within the literature to date. The recalculation of impact values with consistent methods and modelling choices has produced the largest comparable dataset on the environmental impacts of salmon farming currently available, whilst also demonstrably reducing the variation generated by methodological inconsistency, to suggest that the impacts of salmon farming at a global scale vary less than previously believed. This, combined with the correlation analysis of key inventory flows and reported impact values, has identified feed production, and more specifically animal by-product inclusion, to be the strongest predictor of global warming in the context of salmon aquaculture. The inverse is also true, as the feeds with the highest relative contributions of plant-based ingredients presented the lowest overall impact scores. With regard to farm-level impacts, the negligible contributions of fish emissions to global warming suggest that the Atlantic salmon itself is an efficient livestock with a relatively minor environmental burden, when not considering the impacts of feed production and fuel combustion. In the current body of Atlantic salmon LCA literature, there is a heavy focus on global warming, whilst impact categories that describe the more context-specific environmental implications of salmon aquaculture are lacking. It is therefore advisable that practitioners more regularly incorporate impact categories relevant to the health of aquatic ecosystems (freshwater & marine eutrophication, freshwater & marine ecotoxicity) and the extraction of resources for feed production (terrestrial ecotoxicity, biotic resource use, and land use change). Finally, this work evidences the improved capacity of cross-study comparisons in LCA, once large-scale data aggregation into platforms such as HESTIA is achieved. HESTIA itself is currently most specialised to crop agriculture, and is actively developing emission models tailored to the array of unit processes in Atlantic salmon LCA. Therefore, with time, it will be possible to calculate a full range of environmental impacts using the categories mentioned above, and additionally, the ease of recalculating uploaded datasets within HESTIA will allow practitioners to constantly update results with the most up-to-date emission models. To conclude, accurate environmental impact assessment is essential in directing the actions of policymakers regarding the future of open-net pen salmon farms, and these findings taken together indicate how LCA can evolve in support of better management towards the goal of sustainable salmon aquaculture.

Supplementary materials:

Link to excel file containing supplementary materials 1 & 2: Supplementary materials.xlsx

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Management report:

I encountered, but mostly overcame, a series of roadblocks whilst writing this thesis. Performing a literature review was a large task in itself, but the HESTIA component of this review required a steep learning curve that I did not anticipate the full extent of. Data extraction was expected to take maybe a month or so, but took over three months in reality, as I largely had to self-teach myself how to use HESTIA, and the sheer amount of data reported across the selected studies was a lot to handle accurately. On many occasions I had to go back and amend my uploads to accommodate the changes to HESTIA were made in order to model the feed and grow-out cycles too. Feed ingredient modelling was particularly difficult, as I only became aware that a large number of salmon feed ingredients lacked emission modelling in HESTIA once I had fully embarked upon data extraction. The HESTIA team and I were put under considerable stress to source and integrate emission models for these ingredients, which was not helped by the Global Life Cycle Feed Institute (GFLI), which offered but did not provide emission models in time, so that an ECOALIM license had to be purchased instead only a couple of weeks before the submission deadline. Joseph Poore, the lead of HESTIA but not a registered supervisor of mine, had to work very hard to get even the global warming models integrated into HESTIA in time. Unfortunately, this was not possible for the nitrogen modelling, and so my recalculations were limited to global warming, which was sufficient, however I would have liked to assess eutrophication and acidification also. The global warming HESTIA results were provided to me in full on the 18th of May, leaving only a week for me complete my results and discussion, and to respond to my supervisors' suggestions, which meant the final part of the write up was more rushed than I would have liked. Nevertheless, I am glad that I persevered and believe the results of my work are still accurate and meaningful. As to the delays with HESTIA, it was largely out of my control, and more a result of me selecting a food system that HESTIA is yet to be tailored for. Of course, I didn't know this was the case when choosing to focus on salmon farming, but the combined work of myself and the HESTIA team to accommodate this means that the salmon LCAs I uploaded now constitute some of the first animal product aggregations on the HESTIA platform, which should be foundational to HESTIA's aquaculture-related work going forward.