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Quantifying the environmental support to wild catch Alaskan sockeye salmon and farmed Norwegian Atlantic Salmon: An emergy approach

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ABSTRACT

Understanding the relative contributions of the environment to commercial fisheries and aquaculture systems is an area of intense importance as it quantifies the dependence these human dominated systems have on healthy and productive ecosystems. Measures of sustainability are required that include environmental support, use of nonrenewable resources, and labor & services. This work draws on primary and secondary data used in an emergy analysis approach to assess environmental support and sustainability of a wild catch sockeye salmon fishery in Bristol Bay, Alaska and Atlantic salmon aquaculture in Norway. The analyses ended at the processing gate for both production systems. Environmental support of the sockeye fishery amounted to 69% of total inputs for landed fish and 37% for processed fish, while the environmental support for farm raised Atlantic salmon was 60% and 42% for landed and processed fish respectively. Labor and services contributed 53% of total inputs for processed sockeye and 44% for Atlantic salmon. The emergy indices for the wild caught sockeye and farmed Atlantic salmon systems were relatively high having emergy yield ratios for landed fish of 3.2 (wild caught sockeye) and 2.3 (farmed Atlantic salmon). After processing emergy yields of both systems were 1.6 (sockeye) and 1.7 (Atlantic salmon). Environmental loading ratios for the sockeye fishery were 0.45 and 1.69 for landed salmon and processed fish respectively, while for Atlantic salmon they were 0.76 and 1.40 for harvested and processed fish respectively. Emergy sustainability indexes (ESI) for both production systems were much higher than other aquaculture systems. Landed sockeye salmon had an ESI of 7.2, while that of farmed raised Atlantic salmon was 3.0, somewhat lower, but still a relatively sustainable source of high-quality protein.

1. Introduction

We perform a comparative emergy evaluation of the Alaskan sockeye salmon fishery and farmed Norway Atlantic salmon. These studies were part of a larger study investigating energy and water consumption in the USA seafood supply chain funded by the United States Department of Agriculture under the National Science Foundation's Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) program. The overall study is designed to identify strategies for increasing efficiencies and reducing wastes. We evaluate the energy, material, information (labor) and services inputs required to produce wild catch and farmed salmon using a combined Life Cycle Assessment (LCA) and emergy approach and include the *environmental* support[1] necessary for rearing and maturing both the wild sockeye and the farmed Atlantic salmon.

1.1. Study motivation

Global wild catch fisheries depend on the productivity of the world's

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[1] We define environmental support as the ability to provide a basis for the existence or subsistence of a process, without which the process would be much reduced or nonexistent. Sometimes referred to as ecosystem services.

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oceans for their continued success (Chassot et al., 2010; Friedland et al., 2012; Kildow and McIlgorm, 2010; Pauly & Christensen, 1995; Ryther, 1969; Stock et al., 2017; Watson et al., 2014). Estimates of primary productivity required (PPR) to support fisheries compared to estimates of actual net primary productivity (NPP) suggest that many global fisheries are being harvested at unsustainable rates (Coll et al., 2008; Ryther, 1969; Link and Marshak, 2019). Recently Marshak and Link (2021) quantified the links between primary production and fisheries economic performance showing that landings, revenue, and employment, among other indicators, were dependent on the underlying primary production of fisheries.

Less well known, is the dependance of aquaculture on support from the environment. In a series of papers beginning in 1988, Carl Folke and others (Folke, 1988; Folke, 1989; Folke and Kautsky, 1989; Folke and Kautsky, 1992; Folke et al., 1998) investigated the environmental support requirements of Atlantic salmon farming and wild caught salmon as well as other species using energy analysis (EA), ecological footprint analysis (EFA), and energy return of investment (EROI). They concluded that similar quantities of living biomass were required to produce equivalent amounts of salmon biomass whether the salmon were feeding in the sea or were cage farmed. The caged fish were fed pelletized feed, of which, important components were “nature's subsidies” primarily from fish meal and fish oil ingredients (Naylor et al., 1998) as well as land, water, and other natural resources (Salin and Arome Atagub, 2018).

Other than the studies by Folke and colleagues, there is a dearth of quantitative information regarding environmental support of fisheries and aquaculture. While there are numerous studies quantifying environmental (ecological) footprint of wild catch fisheries (Ding et al., 2020; Kaiser, 2019; Kroodsma et al., 2018; Parker et al., 2018; Solarin et al., 2021; Willer et al., 2022) there are fewer for aquaculture (Chang, 2017; Zhao et al., 2013).

We are aware of the large number of studies using LCA to quantify the environmental impacts of aquaculture (Bohnes et al., 2019 provide a comprehensive review of studies to date) and to a lesser degree, wild catch fisheries (Avadí et al., 2020). The vast majority of LCA environmental impact studies focus on Green House Gas (GHG) emissions, fuel use efficiencies, and fossil fuel depletion. A few studies have focused on water depletion (Ahmed and Thompson, 2019). However, LCA does not explicitly include environmental support, but rather, implies environmental impact.

To the best of our knowledge, there are few methodologies that explicitly and quantitatively include the environmental support and human labor inputs to production processes. Using emergy, it is possible to compare the inputs of labor alongside of environmental support and inputs of non-renewable resources on an equivalent basis for comparison and to judge relative importance.

While there have been a few emergy studies of aquacultural systems, to our knowledge there have been no emergy evaluations of wild catch fisheries. David et al. (2021) conducted a critical review of emergy evaluations of aquaculture, finding 16 published studies between 2000 and 2020. Of these studies one was an evaluation of farmed salmon in Oregon, USA (Odum, 2000), where estuarine support was computed based on the volume of water necessary to reduce nutrient concentrations resulting from feed inputs. Vassallo et al., (2007) evaluated an inshore marine fish farm near the Ligurian Gulf in Italy growing Gilthead seabream (*Sparus aurata*), and later (Vassallo et al., 2009) developed a dynamic emergy analysis of the same system. Wilfart et al. (2013) used emergy and LCA to evaluate a recirculating water system near Veys Bay (Normandy, France) growing Atlantic salmon among several other aquacultural systems. Studying wetland fish farming systems in the Nansi Lake area of China, Zhang et al. (2011) computed emergy indices and transformities for carp species. David et al. (2018) used emergy evaluation to study cage farming of tilapia in Brazil. Most of these studies computed emergy sustainability indices, providing some indicators of percent renewable, which can be assumed to be a close approximation of environmental support. The reviewed papers showed that intensive aquaculture production systems had high productivity but relatively low sustainability, while the reverse was true of traditional low intensity systems, which had low productivity but high sustainability.

Labor inputs to most production processes are important contributions often accounting for 50% of economic costs (Kamp et al., 2016) and as much as 30% of emergy inputs (Brown and Ulgiati, 2014). LCA studies do not explicitly include labor inputs; although recently Di Maria et al. (2019) evaluated the contribution of human labor to emissions from waste collection in central Italy. A relatively new branch of LCA called Social Life Cycle Assessment (SLCA), assess the social and sociological impacts along the life cycle of products and services. Huarachi et al. (2020) provide an excellent review of the extensive literature on the development of SLCA. Similar to traditional LCA, SLCA does not explicitly include the importance of labor to production processes, instead, it estimates impacts of processes on social and sociological systems.

In all, these factors have precipitated the following questions that have motivated this study:

1. What is the emergy of environmental support required to produce wild caught Alaska sockeye salmon compared to farmed Norwegian Atlantic salmon?
2. What proportion of total emergy in wild caught compared to farmed salmon is contributed by the environment and by labor and services?
3. What is the relative emergy sustainability of farmed Atlantic salmon compared to wild caught sockeye salmon?

1.2. Background

1.2.1. Sockeye salmon life history

Sockeye salmon (*Oncorhynchus nerka*) are anadromous fish; starting life in freshwater streams and lakes as fertilized eggs in the fall of the year, they emerge as fry from spawning sites the next spring and spend 1 or 2 years in lakes before exiting to the ocean as smolts during spring (Quinn et al., 2009). The majority of smolts from any brood year spend two winters in the ocean before returning to freshwater as mature adults in late June and early July to spawn, while a small proportion may spend one or three winters at sea (Martin & Loyd, 1996). At sea, sockeye salmon feed on invertebrates, small fish, and squid (Burgner, 1991) and are estimated to average a trophic level of 3.0 (Qin and Kaeriyama, 2016). After spawning the adult salmon die, providing a valuable source of energy and nutrients to the river and lake ecosystems (Gende et al., 2002).

1.2.2. The Bristol Bay, Alaska sockeye salmon fishery

Bristol Bay, Alaska (Fig. 1) is located between 57° and 59° north 157°–162° west in southwest Alaska and is the eastern extension of the Bering Sea. The Bay and its watershed are the most productive salmon ecosystem in North America, supporting all five species of Pacific salmon - sockeye, Chinook, coho, chum, and pink; with sockeye being the most abundant species in the ecosystem (Salomone et al., 2011). The Bristol Bay fishery is one of the only remaining “wild fisheries” supporting all five salmon species with no hatcheries (McKinley Research, 2021).

Shown in Fig. 2 is the cyclic migration of sockeye salmon, the fishing stage, and processing and packaging stage. Starting in late June or early July, and lasting from 4 to 6 weeks, sockeye salmon return to spawn in the rivers that flow into Bristol Bay (ADFG, 2020a). In 2021, the Bristol Bay sockeye run was the largest on record; 63.2 million fish returned to spawn (Alaska Public Media, 2022). Normally, the average run size is 39 million fish (ADFG, 2020a). Sockeye are harvested in the bay by about 1500 driftnet vessels and about 900 “setnetters” (using gill nets) from shore-based riverside locations (Wang, 2018). The sockeye fishery is one of the most highly managed fisheries in the world with the Alaska

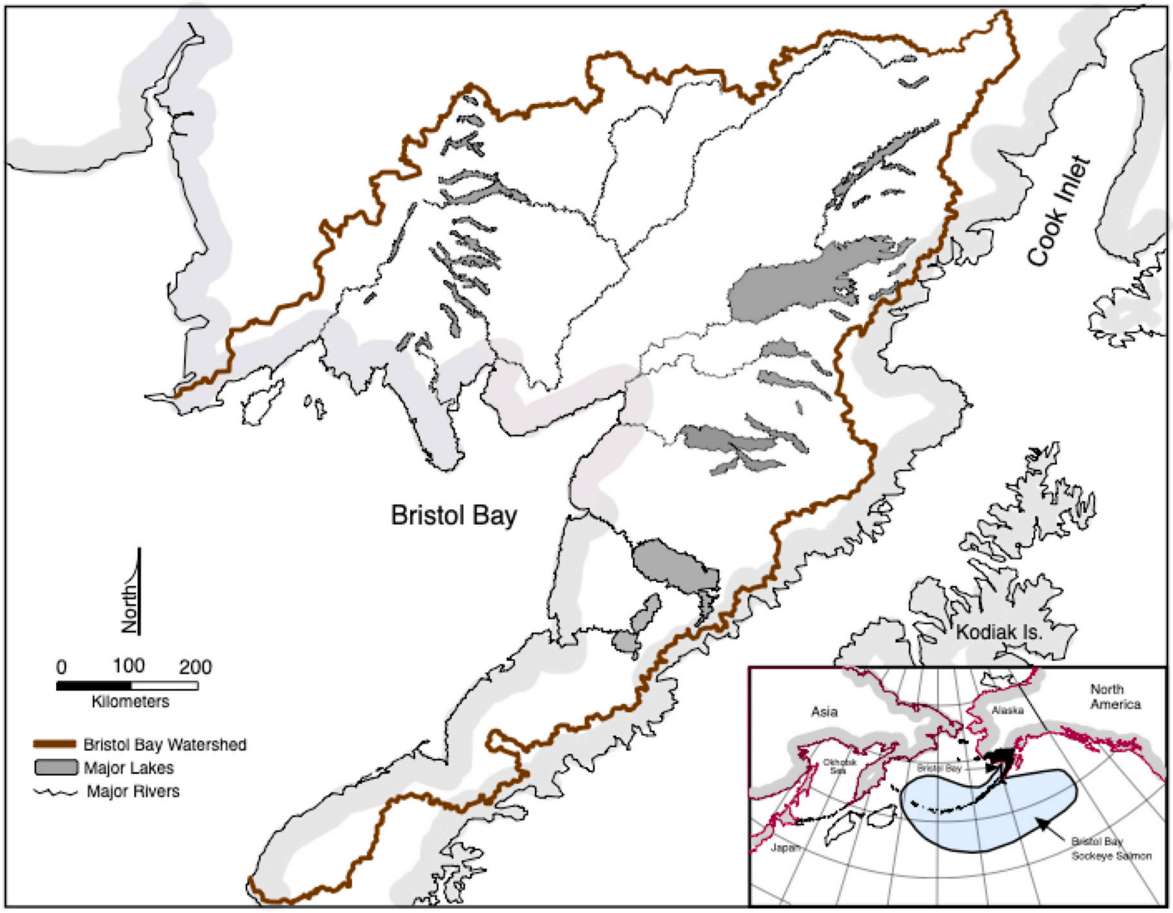

Fig. 1. Map of the Bristol Bay watershed showing the many lakes and streams that support the sockeye salmon fishery. The inset shows the Bering Sea and the estimated location of the ocean area supporting the maturing sockeye while at sea. Watershed redrawn from United States Environmental Protection Agency (2014)

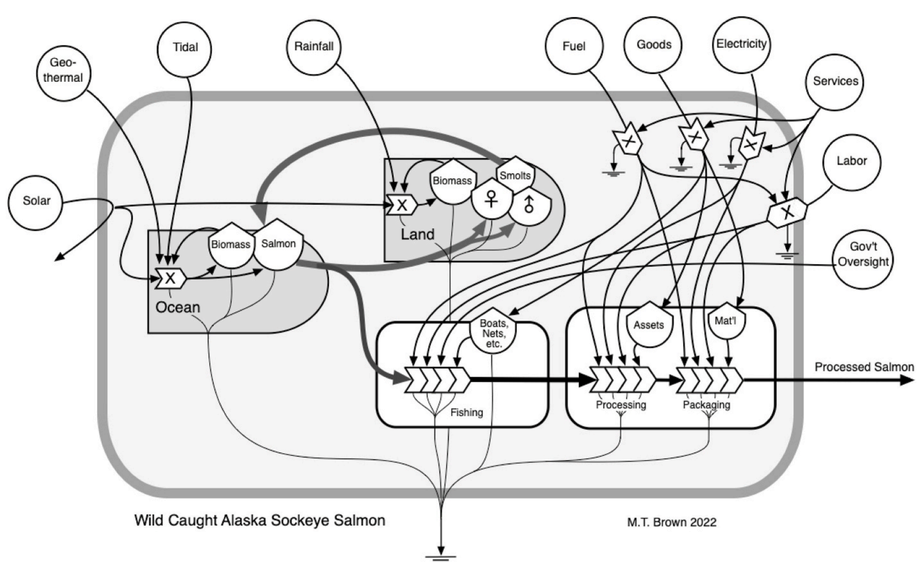

Fig. 2. System diagram of the sockeye salmon cyclic migration. Mature salmon migrate from ocean to land for spawning and after 1–3 years young smolts return to the ocean to mature for 1–3 years. During the landward migration the salmon are caught, processed, and packaged.

Department of Fish and Game (ADFG) using sophisticated methods of estimating daily runs sizes and communicating to fishers who are heavily monitored and penalized if they break regulations. The size of fishing vessels and gear, time fishing and area fished are controlled by ADFG (Boenish et al., 2020; Cunningham et al., 2019).

Because of the remoteness of Bristol Bay, (there are no roads connecting the Bay with other parts of Alaska), all material, energy and labor required by the fishery are transported in by either ocean-going barges or air transport. Harvested sockeye are processed locally in both floating and shore based processing facilities. During the period

2015–2019, an average of 71 million kg of sockeye were processed into four products: fresh & frozen headed and gutted (H & G) (67%), fresh and frozen fillets (16%), canned (13%), and salmon roe (4%). In this analysis we have concentrated on H & G as it represents the majority of the products produced and allows for direct comparison with the farmed Atlantic salmon.

1.2.3. Atlantic Salmon

Like the sockeye, the Atlantic salmon (*Salmo salar*) are anadromous, but distinct in that most do not die after spawning but return to the sea to spawn again (Fleming, 1996). Atlantic salmon are native to watersheds of Europe and Northeastern North America that drain to the temperate and subarctic regions of the North Atlantic Ocean (Webb et al., 2007). Wild populations have been in decline due, in part, to overfishing and habitat destruction and is a "listed species" in most countries (Horreo et al., 2011). In the U.S. the only Atlantic salmon sold in seafood markets are farm-raised since commercial fishing for Atlantic salmon in the U.S. has been prohibited since 1948 (NOAA, 2022).

1.2.4. Farmed Atlantic salmon

Global production of farmed Atlantic salmon in 2021 was 2.74 million metric tons representing about 3.2% of global aquaculture production. Norway, the largest producer, produces about 55% of global Atlantic salmon, followed by Chile (33%) (Statista, 2022). Fig. 3 is a map

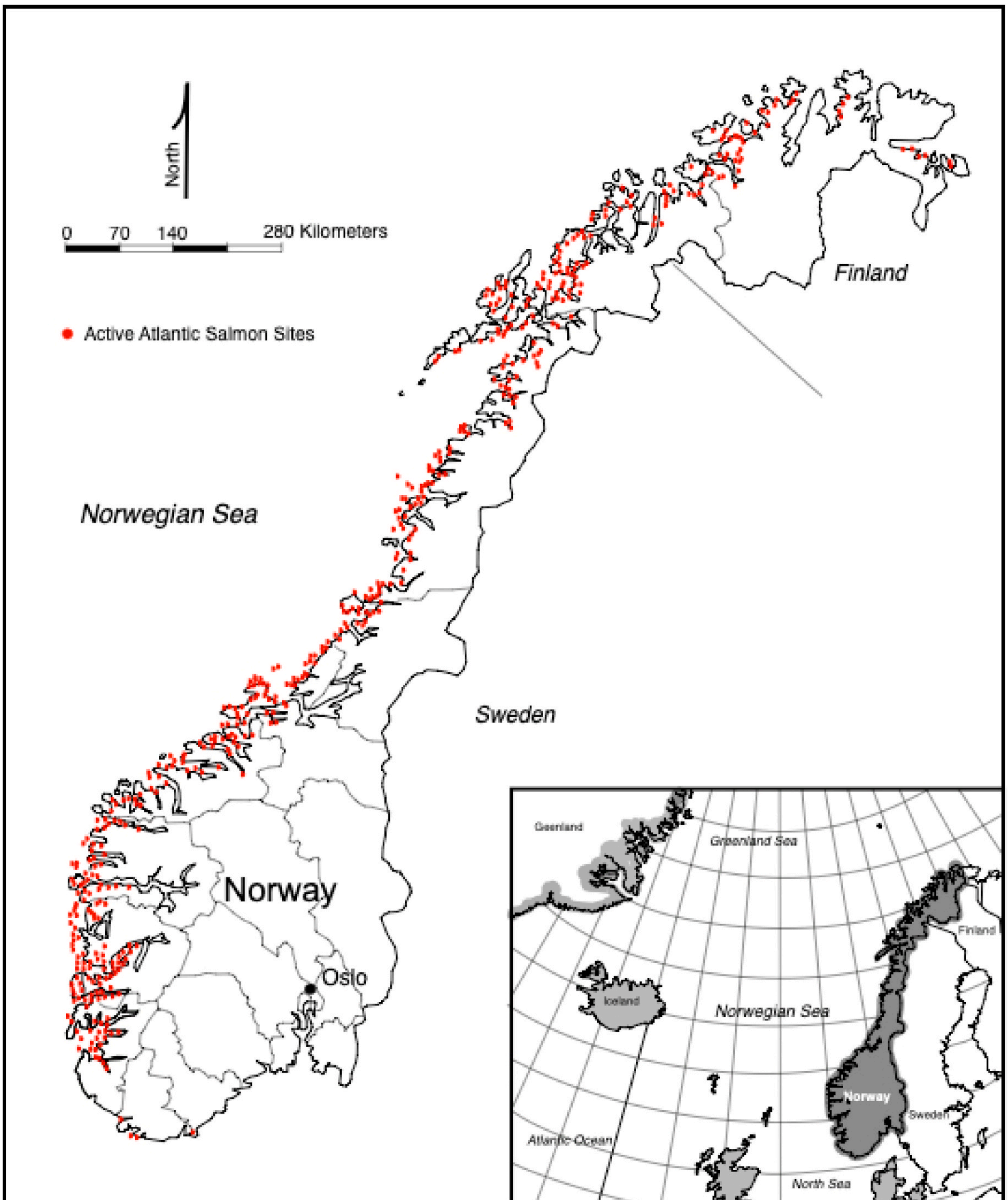

Fig. 3. Map of locations of active Norwegian Atlantic salmon sites. Redrawn from Lyngstad et al. (2016).

of Norway showing the location of active salmon sites. In 2019 there were about 1000 active grow-out licenses for Atlantic salmon in Norway (Mowi and Mowi, 2020).

While the production process for farmed salmon on the surface is relatively simple, in actual practice it has become complex, expensive, and increasingly energy intensive. Fig. 4 is a system diagram of the stages in farmed Atlantic salmon. Production begins at a hatchery, where salmon eggs are hatched and raised in freshwater tanks on land for the first 16–22 months of life (this phase is called *freshwater rearing*) (Sandvold, 2016). During the next phase, called saltwater grow out, the juvenile salmon, or *smolts*, are transferred to net pens anchored in coastal salt water and fed pelleted feed until they are harvested 12–24 months later at a harvest weight of 4–6 kg (Asche et al., 2013). Because of the length of time spent in uncontrolled coastal waters, the maturing fish are subjected to not only environmental impacts (storms, algae blooms) but also contagious viral diseases and parasitic infestation, primarily salmon lice (*Lepeophtheirus salmonis*) that result in high mortality rates; an industry average in Norway of 15% in 2020 (EY - Ernst & Young Global Limited, 2022).

The Norwegian aquaculture industry continues to evolve under both stricter governmental controls and increased environmental uncertainty. Government sets limits on the number of licenses issued, density of farms within coastal waters, and the number of observed salmon lice (Mowi and Mowi, 2020). Pen technology and materials have changed over time as has the size of pens, from about 5 m in diameter to over 50 m (Asche et al., 2013). As the number of salmon farms has risen, density dependent disease and particularly salmon lice have prompted biological and technology improvements. There has been a significant evolution in salmon lice control technologies shifting away from chemical controls to physical removal and the introduction of cleaner fish (Overton et al., 2019). The newest trend to decrease environmental uncertainty involves production of larger smolts (250–500g), referred to as post-smolts, prior to release in ocean pens reducing the time in the sea and minimizing their exposure to uncontrollable risk factors such as sea lice, diseases, and storms (EY - Ernst & Young Global Limited, 2022).

2. Materials & methods

The system boundaries for the two production systems are given in Figs. 2 and 4. The sockeye salmon system (Fig. 2) includes terrestrial environmental support for the rearing of smolts, marine environmental support for grow out to mature fish, catching, and processing and packaging. While the system boundary for farmed Atlantic salmon (Fig. 4) includes feed production, egg production and hatching, freshwater rearing, saltwater grow out, and processing & packaging.

The emergy analysis uses a Geobiosphere Emergy Baseline (GEB) of 12.0 E24 sej yr^{-1}. Primary and secondary transformities and unit emergy values (UEVs) used in this study are taken from the Emergy Characterization database (EmCFdb) (De Vilbiss and Brown, 2015). All other transformities and UEVs were computed from life cycle inventory data obtained from EcoInvent database version 3.6 (Wernet et al., 2016).

2.1. Emergy life cycle approach

This analysis uses an emergy approach to assess the environmental, material, energy, information (labor), and service inputs to wild catch and farmed salmon production systems, starting with environmental support and raw material acquisition and ending at the gate of the processing facility with headed and gutted (H & G) salmon product. Along the production chains we have considered several functional units according to the stages of each production system as follows:

Wild caught sockeye salmon.

1) 1 kg (live weight) of returning sockeye salmon
2) 1 kg (live weight) of landed sockeye salmon,
3) 1 kg of processed & packaged H & G sockeye salmon,

Farmed Atlantic salmon.

1) 1 salmon egg,
2) 1 kg (live weight) of Atlantic salmon smolt,
3) 1 kg (live weight) Atlantic salmon after grow out.
4) 1 kg of processed & packaged H & G Atlantic salmon.

The focus of this study was to quantify the environmental support of the two production chains. We considered as renewable environmental support (Fig. 2) the terrestrial emergy required to produce sockeye

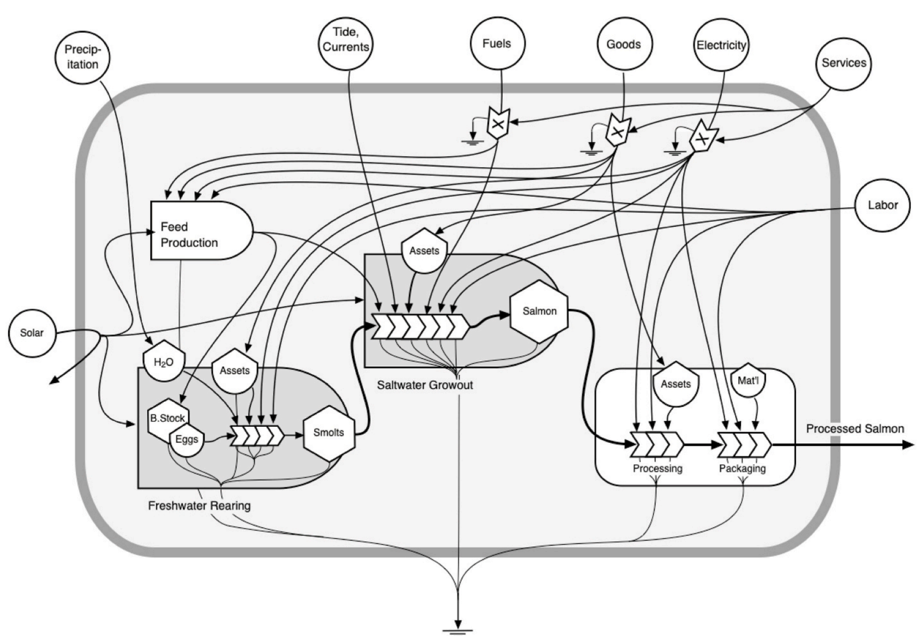

Fig. 4. Systems diagram of Norwegian farmed Atlantic salmon. Production of salmon feed from ingredients is included. The output from freshwater rearing is salmon smolts which enter the saltwater grow out phase. The time frame from egg hatching to processed salmon products is about 24 months.

salmon smolts and the oceanic productivity to grow out returning salmon as well as the water used in processing phase. Renewable environmental support of the farmed Atlantic Salmon (Fig. 4) included fresh water used in all phases of the production chain and the ocean currents necessary to flush salmon net pens during the grow out phase. A secondary focus was to quantify the labor and service inputs to both production chains.

2.2. Data collection and inventory

All primary data for the sockeye salmon fishery are based on averages of a 3-year period (2016–2018) obtained from 3 seafood companies (which represented over 24% of total systemwide harvesting and processing) and the Alaska Departments of Fish and Game and Public Safety. The breakdown of data sources by phase of the production chain was as follows:

Environmental support – extensive literature review of sockeye life history and the Environmental Impact document prepared by the USEPA (2014),
Fishing – the fishing fleets of three companies representing almost 600 contract driftnet vessels and 84 tender vessels,
Processing and Packaging - four shore based and 2 floating processing facilities representing about 24% of total sockeye salmon production.

Primary data for the farmed Atlantic salmon production chain were from various companies within each phase as follows:

Salmon feed – three companies with a combined total production of over 57 thousand MT of feed,
Egg production - one company with total production of over 100 million eggs per year,
Freshwater rearing – five companies with combine total production of 30 million smolts
Saltwater grow out – three grow out facilities with a combined production of 36 thousand MT wet weight Atlantic Salmon,
Processing & Packaging – three companies with a combined total production 95 thousand MT of H & G Atlantic salmon.

It should be noted that data collected from firms in the Atlantic salmon production chain represent industry averages, as each of the companies and production facilities used different production technologies, especially the freshwater rearing facilities, where some were using water recirculating systems while others were using flow though systems.

2.2.1. Infrastructure – quantities and UEVs

Infrastructure includes fishing vessels, equipment, buildings, and machinery. Inventory data were collected as primary data from companies and facilities interviewed. UEVs were computed using SimaPro software version 9.0.0.30 (https://simapro.com/), the Ecoinvent database version 3.6 (Wernet et al., 2016), and the ReCiPe Midpoint (H) v.1.13 method (Goedkoop et al., 2013) for area of buildings and type of construction and weight of equipment and machinery. We computed UEVs based on Fossil Depletion Potential (FDP) and Water Depletion Potential (WDP) impact categories, calculated in kg of oil equivalent (or MJ) and m^3 of water using the ReCiPe Midpoint (H) v.1.13 method (Goedkoop et al., 2013). Energy and water quantities were then multiplied by appropriate UEVs from De Vilbiss and Brown (2015).

2.2.2. Energy – quantities and UEVs

There were two main sources of energy, electricity and diesel fuel. Data on quantities consumed in each phase of the production processes were obtained from companies and facilities interviewed. UEVs for electricity were computed based on the mix of source energy in Bristol Bay Alaska (100% distillate fuel oil and diesel fuel) and Norway (92% hydro, 6.4% wind). UEV for distillate fuel oil and diesel fuel were from De Vilbiss and Brown (2015).

2.2.3. Packaging – quantities and UEVs

Quantities of packaging materials were obtained from processing companies and facilities interviewed. UEVs of packaging materials were computed using SimaPro software and Ecoinvet database as outlined above.

2.2.4. Labor – quantities and UEVs

Data on the labor hours in each phase were obtained from companies and facilities as total labor hours per year. We computed UEVs for labor in Alaska and Norway using emergy per capita (NEAD, 2022) for each country, average number people per household, number of full-time workers per household and number of hours worked per year (2000 h/yr) as follows:

$$Em_{hr} = Em_{capita} * \frac{P_{household}}{W_{household}} \bigg/ 2000 hr\ yr^{-1}$$

Where:
Em_{hr} = emergy per worker hour.
Em_{capita} = country emergy per capita.
$P_{household}$ = average people per household.
$W_{household}$ = average number of workers per household.

2.2.5. Services – quantities and UEVs

We defined services as the human input of information and labor that is required in the background to supply all materials, energy and information purchased for the production of salmon (Brown and Ulgiati, 2014). Services were computed as the economic price of products at the processing gate minus the economic costs of labor, and then multiplied by the emergy money ratio for each country's economy (NEAD, 2022).

2.2.6. Environmental support

We computed environmental support for sockeye salmon based on the area required to support the salmon smolts during their freshwater life stage in rivers and lakes and the area required for the maturing salmon in the ocean. Area required was computed using estimates of NPP for freshwaters and ocean systems from the literature. The UEV of support areas were computed from the driving emergy of the freshwater and ocean systems. We added to this support the water used in processing, since as surface water, we treated it as renewable. Environmental support for Atlantic salmon was computed using the ocean currents driving the quantity of sea water flushing salmon pens during the grow out phase. The UEV of ocean currents was taken from De Vilbiss and Brown (2015). We added to this support the water used in all phases since the water used was from rivers that discharge to the ocean.

2.2.7. Emergy sustainability indices

Several indices and ratios were computed for assessment of the performance and the sustainability of both production systems (Brown and Ulgiati, 1997; Ulgiati and Brown, 1998; Brown and Ulgiati, 2004) as follows:

Fraction renewable (% R) – percent of total required emergy that is from renewable emergy sources,
Emergy yield ratio (EYR) – the ratio of total emergy required to the purchased emergy required,
Environmental loading ratio (ELR) – the ratio of the purchased emergy required to the renewable emergy sources,
Emergy sustainability index (ESI) – the ratio of the EYR to the ELR; essentially the ESI is an index of the yield of a process per "load" on the environment.

3. Results

3.1. Alaskan wild caught salmon

Emergy analysis of Alaskan wild caught sockeye salmon is given in Table 1. The analysis is divided into three phases, environmental support, fishing, and processing & packaging. The phases are sequential, so that the output of each phase is the input to the next phase. The column labeled quantity is the primary data we collected during interviews with managers of companies and facilities that agreed to participate in this study.

The environmental support (Phase 1) in Table 1 represents the renewable energies driving the terrestrial and ocean environments that are embodied in the sockeye salmon upon their return to the rivers of the Bristol Bay watershed to spawn. Combined, the freshwater and ocean environmental support was 31% of the total emergy required to produce the finished salmon product. The time spent in the ocean was the largest input totaling over 85% the environmental support. The specific emergy and transformity of returning salmon were 2.11 E13 sej kg^{-1} and 5.0 E6 sej J^{-1} respectively.

The fishing phase added 14% to the emergy required to produce final product, of which labor represent over 80% of the emergy inputs and fuel represents about 13%. At this point in the production chain the specific emergy and transformity of the landed salmon increased 45% to 3.1 E13 sej kg^{-1} and 7.3 E6 sej J^{-1} respectively.

Since it requires 1.35 kg of landed salmon to produce 1 kg of final H & G product, the salmon input to the processing and packaging phase is shown as 1.35 kg of landed salmon. The processing and packaging phase added another 55% to the emergy required to produce the final product, of which labor represented about 22%, services represented about 38%, and energy represented about 6%. The final specific emergy and transformity for H & G Alaskan Salmon increased 120% from the landed salmon to 6.8 E13 sej kg^{-1} and 1.6 E7 sej J^{-1} respectively. Overall the specific emergy and transformity of the salmon H&G product increased 84% from the wild salmon that was caught as it returned to spawn.

Fig. 5 shows the percent of total emergy for categories of inputs for the entire production chain of wild caught Alaskan sockeye salmon. Fig. 5a shows the percentages each input is of the total emergy when labor and services are included, while Fig. 5b shows the percentages without labor and services. Environmental support was the largest emergy input equaling 37% of inputs when labor and services are included, and 79% when labor and services are excluded. Labor and services combined equaled 53% of total emergy inputs (Fig. 5a). Energy (sum of electricity and diesel fuel) was 6% and 8% of total inputs when labor and services are included or not included. Infrastructure represented only 3% or 7% of total inputs.

3.2. Farmed Atlantic salmon

The emergy analysis of farmed Atlantic salmon is given in Table 2. While the table lists the phases of the production sequentially, they are not directly additive. For instance, the first phase is the production of salmon feed, and the result is 1 kg of feed. Egg production required only a minor amount of feed for broodstock (feed is not included in the table because it represents less than 1% of total inputs). Freshwater rearing required 1.35 kg feed to produce 1 kg of smolts and saltwater grow out required 1.43 kg feed to produce 1 kg of mature salmon.

The result of egg production was one salmon egg and the emergy required to produce one egg was 1.33 E11 sej. It required an input of 21.6 eggs to the freshwater rearing phase to produce 1 kg of smolts, and it required 0.652 kg smolts to produce 1 kg of mature salmon. And finally, it required 1.27 kg of mature salmon to produce 1 kg of H&G salmon product.

The freshwater rearing phase contributed 8.9% of emergy inputs to the final product, resulting in a specific emergy and transformity of salmon smolts of 7.26 E13 sej kg^{-1} and 1.73 E7 sej J^{-1} respectively. The emergy inputs to saltwater grow out were 40.2% of total inputs and resulted in a specific emergy and transformity of mature salmon of 2.62 E13 sej kg^{-1} and 6.25 E6 sej J^{-1} respectively. The processing phase was responsible for 50.9% of total emergy inputs, of which the mature salmon were 62% of the inputs to processing and packaging. Reflecting the level of automation in Norwegian salmon processing, labor amounted to less than 25% of the inputs in the processing phase. The final specific emergy and transformity of the H&G Atlantic salmon were 5.32 E13 sej kg^{-1} and 1.27 E7 sej J^{-1} respectively.

Shown in Fig. 6 is the percent of total emergy for categories of inputs to the farmed Atlantic Salmon system with labor and services (Fig. 6a) and without labor and services (Fig. 6b). Depending on inclusion of labor and services, environmental support contributed between 42% and 74% of total emergy inputs. Services contributed 39% of total inputs while labor contributed 5%. The emergy in feed contributed between 8% and 15% depending on inclusion of labor and services.

3.3. Comparing wild caught sockeye and farmed Atlantic salmon

Table 3 summarizes the UEVs of wild caught and farmed salmon along stages of the production chains when labor and services are included. Sockeye salmon smolts had a transformity of 5.1 E7 sej J^{-1} computed using the emergy of freshwater environmental support and average weight of smolts. Overall the transformity of wild caught sockeye salmon decreased 70% from smolts (5.1 E7 sej J^{-1}) to processed and packages H&G salmon product (1.6 E7 sej J^{-1}). Transformities of farmed Atlantic salmon did not follow the same pattern. Farmed salmon smolts (1.7 E7 sej J^{-1}) decreased 27% from smolts to processed and packages H&G product (1.3 E7 sej J^{-1}). The transformity of harvested farmed salmon (6.2 E6 sej J^{-1}) was about 15% lower than the transformity of harvested wild caught sockeye (7.3 E6 sej J^{-1}) and the final Atlantic salmon H & G product was about 19% lower than the wild caught salmon (1.3 E7 sej J^{-1}vs 1.6 E7 sej J^{-1}).

The differences in transformities for salmon products without labor and services followed the same basic patterns as described above. While labor added about 6% to the transformities of salmon products, services added nearly 50% to the final H&G products.

3.4. Measures of salmon sustainability

Table 4 lists several measures of sustainability of the wild caught and farmed salmon with labor and services included. The indices were computed for landed salmon (the first set of numbers) and processed salmon (the second set). The first set of numbers (landed salmon) show EYRs for sockeye and Atlantic salmon of 3.2 and 2.3 and ELRs of 0.45 and 0.76 respectively. The ESI for sockeye was 7.2 while that of Atlantic salmon was 3.0. ESIs greater than 5.0 are generally found for processes that provide a boost to the economy, providing net yields without significant environmental impact. The percent renewable at this stage of the process chain was 69% for sockeye and 57% for Atlantic salmon.

After processing, EYRs were reduced since processing requires relatively large amounts of nonrenewable resources and labor and services. The yield ratio for Sockeye (1.6) was lower than that of Atlantic Salmon (1.7) and the ELR of sockeye (1.69) was higher than that of Atlantic salmon (1.40) yielding ESIs that were reversed from the landed salmon. The ESI of sockeye (0.9) was lower than that of Atlantic salmon (1.23) and the percent renewable of sockeye (37%) was somewhat lower than Atlantic (42%).

Table 1
Emergy of inputs to produce 1 kg of H & G sockeye salmon at each phase.

Item		Units	Quantity	UEV (sej/unit)	Emergy (E12 sej)	Percent of Total
Environmental Support						
1	Freshwater lakes & streams	m2	5.7E+00	5.38E+11	3.05	
2	Ocean	m2	6.67E+02	2.71E+10	18.06	
	Returning salmon	kg	1.0	**2.11E+13**	21.11	**31.3%**
	Transformity	J	1.00E+00	**5.04E+06**		
Fishing						
3	Monitoring activities (diesel)	kg	4.69E-03	7.26E+12	0.03	
4	Drift net & tender vessels	kg	1.68E-02	2.40E+13	0.40	
5	Diesel fuel	kg	1.66E-01	7.26E+12	1.21	
6	Labor (air transport-jet fuel)	kg	1.78E-03	7.40E+12	0.01	
7	Labor	(p*hrs)	6.36E-02	1.23E+14	7.82	
8	Output salmon, (live weight)	kg	1.0	**3.06E+13**	30.60	**14.0%**
	Transformity	J	1.0	**7.31E+06**		
Processing & Packaging						
9	Landed sockeye salmon	kg	1.35	3.06E+13	41.30	
10	Building (steel & concrete)	m2	9.61E-05	1.4E+16	1.35	
11	Machinery	kg	1.25E-03	2.39E+13	0.03	
12	Water	m3	3.32E-02	6.81E+11	0.02	
13	Diesel	kg	1.73E-01	7.26E+12	1.26	
14	Electricity (USA)	kWh	3.51E-01	2.36E+12	0.83	
15	Plastic	kg	1.12E-02	9.66E+12	0.11	
16	Cardboard	kg	2.43E-02	7.00E+12	0.17	
17	Pallets (wood)	kg	2.94E-02	2.89E+11	0.01	
18	Labor (air transport-jet fuel)	J	1.83E-02	7.40E+12	0.14	
19	Labor	p*hrs	6.69E-02	1.23E+14	8.23	
20	Services (minus labor costs)	$	7.57E+00	1.86E+12	14.08	**54.7%**
21	Output processed product	kg	1	**6.75E+13**	67.52	**100.0%**
	Transformity	J	1.0	**1.61E+07**		

Notes to Table 1

1	Environmental support (freshwater)			
	Precipitation =	800	mm	USEPA (2014)
	Evaporation =	400	mm	USEPA (2014)
	Watershed area =	1.16E+11	m^2	USEPA (2014)
	Stream and lake area =	9.16E+09	m^2	USEPA (2014)
	Density water =	1000	kg m^{-3}	
	Gibbs energy of rain =	4.72E+03	J/kg	
	Transformity Precipitation =	2.25E+04	sej/J	(De Vilbiss and Brown, 2015)
	Energy of water in lakes & streams =	(0.8 m - 0.4m) * 1.16 E11 m^2 * 1000 kg m^{-2} * 4.72 E3 J kg^{-1}		
	=	2.19E+17	J yr^{-1}	
	Emergy freshwater =	(2.19 E17 J yr^{-1} * 22.5E3 sej J^{-1})/9.16 E9 m^2		
	=	5.38E+11	sej m^{-2} yr^{-1}	
	NPP lakes and streams =	25	gC m^2 yr^{-1}	(Goldman, 1960; Gough et al., 2016)
	trophic efficiency =	1.0%	Estimate average 2 trophic levels	
	Weight of exiting smolts =	14.20	g wet weight	(Martin and Lloyd, 2006)
	Carbon in smolts =	1.42	g C/smolt	20% dry weight and 50% C (Czamanski et al., 2011)
	NPP required to support 1 smolt =	1.42 gC fish/1.0% efficiency		
	=	1.42E+02	gC yr^{-1}	
	Area required to support 1 smolt =	1.42 E2 gC yr^{-1}/25 gC m^{-2} yr^{-1}		
	=	5.68E+00	m^2	
	Emergy to support 1 smolt =	5.68 m^2 * 5.38 E11 sej m^{-2} yr^{-1}		
	=	3.05E+12	sej/smolt	
	Specific Emergy smolt =	1.08E+15	sej/kg	
	Transformity smolt =	3.05E12 sej/smolt/(14.2 g/smolt *0.2% dry weight * 5 Cal g^{-1} * 4186 J Cal^{-1})		
	=	5.14E+07	sej/J	
2	Environmental Support (ocean)	Quantity of NPP to support 1 kg live weight sockeye salmon		
	Energy input to ocean			
	Sunlight =	7.42E+13	J/ha	Lee and Brown (2021)
	Geothermal =	2.057E+10	J/ha	Lee and Brown (2021)
	Tidal =	3.104E+09	J/ha	Lee and Brown (2021)
	Solar transformities ocean inputs			
	Sunlight =	1	seJ/J	Brown et al.,2016
	Geothermal =	4900	seJ/J	Brown et al.,2016
	Tidal =	30,900	seJ/J	Brown et al.,2016
	Emergy input to ocean =	Sunlight * solar Tr + Geothermal energy * geothermal Tr + Tidal energy * tidal Tr		
	=	(7.42 E13 J ha^{-1} *1.0 seJ J^{-1} + 2.06 E10 J ha^{-1} * 4900 seJ J^{-1} + 3.1 E09 J ha^{-1} * 30,900 seJ J-[1])/10,000 m^2 ha^{-1}		
	=	2.71E+10	seJ m^{-2}	
	Shelf NPP =	150	gC m^{-2} yr^{-1}	Link & Marshak (2019)
	Salmon mass =	1.00	kg	landed mass
	Carbon in 1 kg Salmon =	100.00	gC	20% dry weight and 50% C (Czamanski et al., 2011)
	Trophic efficiency	0.10%	Estimate based on 10% trophic efficiency and average ocean trophic level of 3.0 (Qin and Kaeriyama, 2016)	
	NPP required to support 1 kg fish =	100gC fish/0.1% efficiency		
	=	1.00E+05	gC yr^{-1}	
	Ocean area required =	NPP required/Artic ocean NPP		

(continued on next page)

Table 1 (*continued*)

Item		Units	Quantity	UEV (sej/unit)	Emergy (E12 sej)	Percent of Total
	=	1.35 E5 gC yr^{-1}/150.0 gC m^{-2} yr^{-1}				
	=	6.67E+02	m^2			
	Specific emergy (salmon) =	2.11E+13	sej kg^{-1} sum of environmental emergy			
	Transformity (salmon) =	2.11 E13 sej kg^{-1}/1000 g kg $^{-1}$ * 0.2 * 5 Cal g^{-1} * 4186 J Cal^{-1}				
	=	5.04E+06	sej/J			
3	Monitoring Activities (Diesel)					
	Diesel fuel =	4.69E-03	kg	Primary data, this study.		
	Specific Emergy =	7.26E+12	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
4	Drift Net & Tender Vessels					
	Quantity of boats & gear =	1.68E-02	kg	Primary data, this study.		
	Specific Emergy =	2.40E+13	sej kg^{-1}	See supplemental material		
5	Diesel Fuel	1.66E-01	kg	Primary data, this study.		
	Specific Emergy =	7.26E+12	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
6	Labor (Air transport-jet fuel)					
	passenger * km =	6.36E-02	p *km	Primary data, this study.		
	Fuel use =	0.035	l p*km^{-1}	(EcoInvent, 2022)		
	density jet fuel =	0.8	kg l^{-1}			
	energy intensity jet fuel =	4.82E+07	J kg^{-1}			
	=	4.48e-01 p km^{-1} * 0.035l p km* 0.8 kg l $^{-1}$				
	=	1.78E-03	kg			
	Unit emergy value =	7.40E+12	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
7	Labor	6.36E-02	p*hrs	Primary data, this study.		
	Unit Emergy Value (UEV) =	1.23E+14	sej p*hr^{-1}	See supplemental material		
8	Output (Sockeye salmon, live weight)	1.0	kg			
	Specific Emergy =	3.06E+13	sej kg^{-1} sum of emergy inputs to fishing phase			
	Transformity =	3.06 E13 sej kg^{-1}/(1000 g kg $^{-1}$ * 20% *5.0 Cal g-1 * 4186 J Cal-1)				
	=	7.31E+06	sej/J			
9	Landed sockeye salmon	1.35	kg	1 kg of finished H&G product requires 1.35 kg of landed salmon		
	Specific Emergy =	3.06E+13	sej kg^{-1}	Item 8		
10	Building (Steel & Concrete)	9.61E-05	m^2	Primary data, this study.		
	Unit emergy value =	1.4E+16	sej m^{-2}	See supplemental material		
11	Machinery	1.25E-03	kg	Primary data, this study.		
	Specific Emergy =	2.39E+13	sej kg^{-1}	See supplemental material		
12	Water	1.82E-02	m^3	Primary data, this study.		
	Unit emergy value =	6.81E+05	sej g^{-1}	(De Vilbiss and Brown, 2015)		
	=	6.81E+11	sej m^{-3}			
13	Diesel	1.73E-01	kg	Primary data, this study.		
	Specific Emergy =	7.26E+12	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
14	Electricity (USA)	3.51E-01	kWh	Primary data, this study.		
	Unit emergy value =	1.80E+12	sej kWh^{-1}	See supplemental material		
15	Plastic	1.12E-02	kg	Primary data, this study.		
	Specific emergy =	9.66E+12	sej kg^{-1}	See supplemental material		
16	Cardboard	2.43E-02	kg	Primary data, this study.		
	Specific emergy =	7.00E+12	sej kg^{-1}	See supplemental material		
17	Pallets (Wood)	2.94E-02	kg	Primary data, this study.		
	Specific emergy =	2.89E+11	sej kg^{-1}	See supplemental material		
18	Labor (Air transport-jet fuel)					
	passenger * km =	6.54E-01	p*km	Primary data, this study.		
	Fuel use =	0.035	l p*km^{-1}	(EcoInvent, 2022)		
	density jet fuel =	0.8	kg l^{-1}			
	energy =	6.54 E−02 p*km * 0.035 l p*km $^{-1}$* 0.8 kg l $^{-1}$				
	=	1.83E-02	kg			
	Specific Emergy =	7.40E+12	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
19	Labor	6.69E-02	p*hrs	Primary data, this study.		
	Unit Emergy Value (UEV) =	1.23E+14	sej p*hr^{-1}	See supplemental material		
20	Services	4.63E+00	$ lb^{-1}	Avg. wholesale price (ADFG, 2020b)		
	=	1.02E+01	$ kg^{-1}			
	Labor costs =	4.86E+12	sej kg^{-1}			
	=	2.61E+00	$ kg^{-1}	(McKinley Research, 2021)		
	services (minus labor) =	7.57E+00	$ kg^{-1}			
	UEV =	1.86E+12	sej $$^{-1}$	USA-EMR (NEAD v 2.0, 2022)		
	total emergy services =	1.41E+13	sej			
24	H & G Salmon Product (kg)	1.00	kg			
	Specific emergy =	6.75E+13	sej kg^{-1} sum of emergy inputs to packaging phase			
	Transformity =	6.75 E13 sej kg^{-1}/1000 g kg $^{-1}$ * 20% *5.0 Cal g^{-1} * 4186 J Cal^{-1}				
	=	1.61E+07	sej/J			

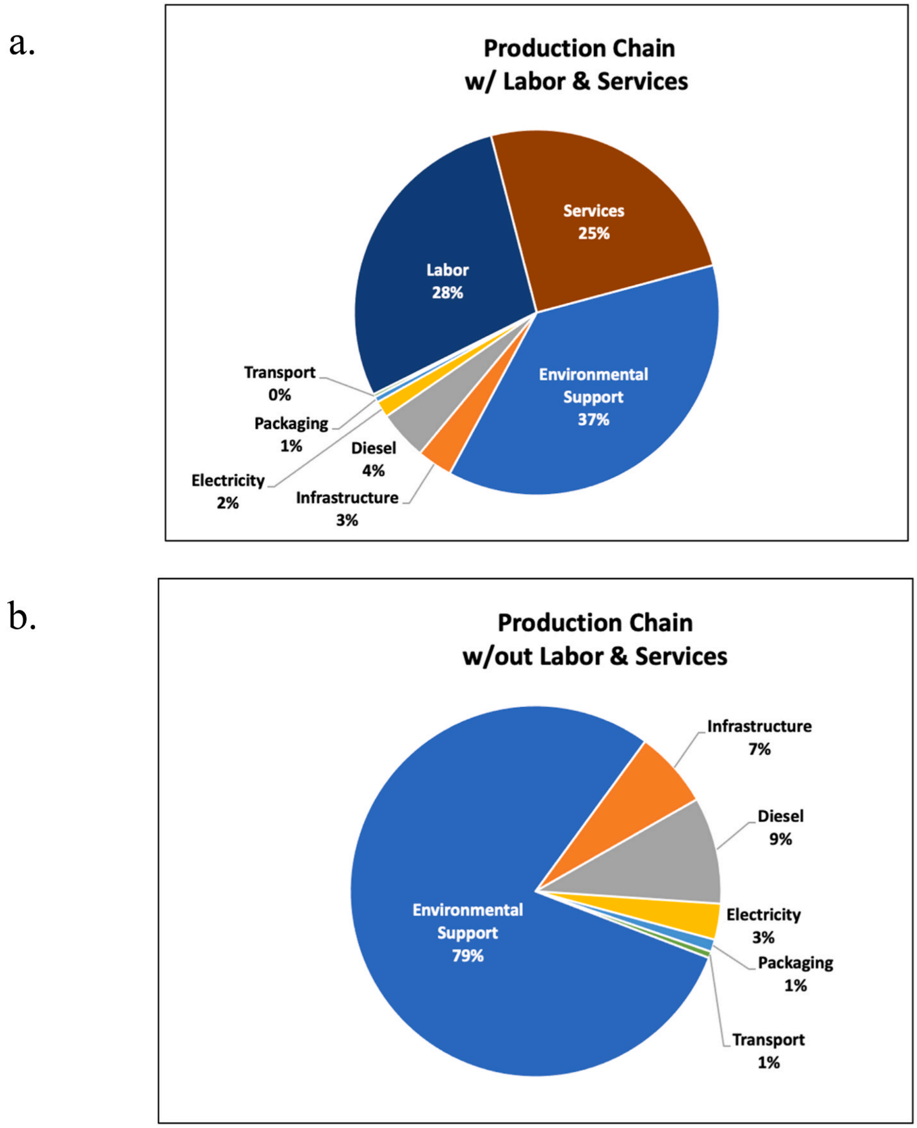

Fig. 5. Percent of final total emergy required to produce wild caught Alaskan sockeye salmon H & G product with labor and services included (a) and without labor and services (b).

4. Discussion

4.1. Environmental support

Both wild caught and farmed salmon had significant environmental support. Wild caught salmon benefitted from 37% (with L&S) and 79% (without L&S) of total emergy inputs from environmental support (Fig. 5). Nearly 100% of the support was the result of the years spent in freshwater as growing smolts and the years spent in the ocean as maturing salmon before their return to spawn. A very small portion (<1%) of environmental support was obtained in the form of freshwater used in processing and packaging. Since we considered the freshwater that was obtained from surface water sources as a renewable source, we included used water as environmental support. While it made very little difference in the total environmental support of wild caught sockeye salmon, Norwegian farmed salmon used larger quantities of fresh surface water.

In the case of Norwegian farmed salmon (Fig. 6), environmental support was 42% (with L&S) and 74% (without L&S) of total emergy inputs. Of the total environmental support, 79% was from ocean currents during the saltwater grow out phase. These currents are an important input as they maintain high water quality within ocean net pens. The remaining 21% of environmental support resulted from use of fresh water in egg production (6%) and freshwater rearing (15%) phases.

Overall both wild caught sockeye and Atlantic farmed salmon benefited from significant quantities of environmental support. The implications of both salmon products having such high environmental support will become more apparent when we discuss the sustainability indices below.

4.2. Labor and services

Labor and services, combined, provided about 44% of total emergy inputs to farmed Atlantic salmon (Fig. 6) and about 53% of total inputs for wild caught sockeye salmon (Fig. 5). In emergy terms, the quantity of labor and services in farmed Atlantic salmon was 24.4 E12 sej kg^{-1}, while the labor and services input to wild caught sockeye salmon was 30.1 E12 sej kg^{-1}. Overall, the higher labor and service inputs to the sockeye salmon system translated directly into higher transformities for sockeye over farmed Atlantic salmon (1.6 E7 sej kg^{-1} compared to 1.3 E7 sej kg^{-1}).

Table 2
Emergy inputs required to produce 1 kg H&G Norwegian Atlantic Salmon.

	Activity Name	Units	Quantity	UEV (sej/unit)	Emergy (E12 sej)	Percent of Total
Feed Production						
1	Feedmill	unit	8.63E-07	1.40E+16	0.01	
2	Soy	kg	2.78E-01	7.34E+11	0.20	
3	Fava bean	kg	3.72E-02	5.33E+11	0.02	
4	Wheat Gluten	kg	1.94E-01	9.73E+11	0.19	
5	Sunflower seed	kg	3.88E-02	1.29E+12	0.05	
6	Fish meal	kg	1.19E-01	4.23E+12	0.50	
7	Fish oil	kg	1.20E-01	4.23E+12	0.51	
8	Vegetable oil	kg	1.91E-01	4.00E+12	0.76	
9	Packaging (plastic)	kg	1.86E-03	9.66E+12	0.02	
10	Transport packaging (ship)	ton*km	6.10E+00	1.20E+10	0.07	
11	Electricity	kWh	9.17E-02	8.00E+11	0.07	
12	Natural gas	m3	1.12E-02	5.40E+12	0.06	
13	LPG	kg	3.52E-05	8.77E+14	0.03	
14	Labor	p*hr	6.52E-04	2.10E+14	0.14	
	Product (Salmon Feed)	**kg**	**1.00**	**2.50E+12**	2.50	
Egg Production						
15	Fiberglass	kg	2.53E-04	2.40E+13	0.01	
16	Salmon	kg	7.14E-04	2.80E+13	0.02	
17	Water	m^3	2.48E-02	2.24E+12	0.06	
18	Electricity	kWh	9.52E-03	3.57E+11	0.00	
19	Labor	p*hr	2.29E-04	2.10E+14	0.05	
	Product (Salmon Eggs)	**n.**	**1.00**	**1.33E+11**	0.13	
Freshwater Rearing						
20	Eggs	n	2.16E+01	1.33E+11	2.87	
21	Feed	kg	1.30E+00	2.50E+12	3.26	
22	Water	m3	2.04E+01	2.24E+12	45.75	
23	Electricity	kWh	4.80E+01	3.57E+11	17.13	
24	Labor	p*hr	1.70E-02	2.10E+14	3.57	
	Product (Salmon Smolts)	**kg**	**1.00**	**7.26E+13**	72.57	**8.9%**
		J	**1.00**	**1.73E+07**		
Saltwater Grow Out						
25	Environmental support [1.]	J	2.05E+08	76,200	15.60	
26	Building (steel)	m2	4.26E-06	1.40E+16	0.06	
27	Building (wood)	m2	9.24E-07	1.20E+16	0.01	
28	Steel	kg	5.05E-04	1.07E+13	0.01	
29	Concrete	m3	1.22E-04	3.76E+15	0.46	
30	Fiberglass	kg	5.36E-03	2.40E+13	0.13	
31	Nylon	kg	1.03E-02	9.66E+12	0.10	
32	Salmon smolts	kg	6.52E-02	7.26E+13	4.73	
33	Feed	kg	1.43E+00	2.50E+12	3.58	
34	Transport (ship)	t*km	4.77E+00	1.20E+10	0.06	
35	Electricity	kWh	5.13E-02	3.57E+11	0.02	
36	Diesel	kg	2.11E-02	7.26E+12	0.15	
37	Labor	p*hr	5.95E-03	2.10E+14	1.25	
	Product (Salmon)	**kg**	**1.00**	**2.62E+13**	26.15	**40.2%**
		J	**1.00**	**6.25E+06**		
Processing & Packaging						
38	Salmon from grow out	kg	1.27E+00	2.62E+13	33.13	
39	Building (steel)	m^2	3.30E-06	1.40E+16	0.05	
40	Styrofoam boxes	kg	3.58E-02	1.00E+13	0.36	
41	Cardboard	kg	9.37E-04	7.00E+12	0.01	
42	Transport packaging (ship)	t*km	1.34E+00	1.20E+10	0.02	
43	Electricity	kWh	1.22E-01	3.57E+11	0.04	
44	Labor	p*hr	4.20E-03	2.10E+14	0.88	
45	Services	kr	5.78E+01	3.24E+11	18.75	**50.9%**
	Product (Processed Salmon)	**kg**	**1.00**	**5.32E+13**	**53.23**	**100%**
		J	**1.00**	**1.27E+07**		

Notes to Table 2

Feed Production (ingrediants required to produce 1 kg feed)

1	Feedmill			
	Quantity of feedmill =	8.63E-07	unit	(Ecoinvent, 2022)
	UEV =	1.40E+16	sej unit^{-1}	See Suplimental material
2–8	Ingrediants			
	Quantity of ingrediants =	9.70E-01	kg	Primary data, this study
	Specific emergy =	varies	sej kg^{-1}	See Suplimental material
9	Packaging			
	Plastic =	1.86E-03	kg	Primary data, this study
	Specific emergy =	9.66E+12	sej kg^{-1}	See Suplimental material
10	Transport (ship)			
	Quantity feed & packaging/km =	6.10E+00	ton km^{-1}	Primary data, this study
	UEV =	1.20E+10	sej t*km^{-1}	See Suplimental material
11	Electricity	9.17E-02	kWh	Primary data, this study
	UEV =	1.80E+12	sej kWh^{-1}	(De Vilbiss and Brown, 2015)

(continued on next page)

Table 2 (*continued*)

	Activity Name	Units	Quantity	UEV (sej/unit)	Emergy (E12 sej)	Percent of Total
12	Natural gas	1.12E-02	m3	Primary data, this study		
	UEV =	5.40E+12	sej m^{-3}	See Suplimental material		
13	LPG	3.52E-05	kg	Primary data, this study		
	UEV =	8.77E+14	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
14	Labor	6.52E-04	p*hr	Primary data, this study		
	UEV =	1.00E+14	sej p^*hr^{-1}	See Suplimental material		
Egg Production (inputs required to produce 1 egg)						
15	Fiberglass (tanks)	2.53E-04	kg	Primary data, this study		
	UEV =	2.40E+13	sej kg^{-1}	See Suplimental material		
16	Brood salmon	7.14E-04	kg	Primary data, this study		
	UEV =	2.80E+13	sej kg^{-1}	See Suplimental material		
17	Water	2.48E-02	kg	Primary data, this study		
	UEV =	2.24E+06	sej g^{-1}	(De Vilbiss and Brown, 2015)		
	=	2.24E+12	sej m^{-3}			
18	Electricity	9.52E-03	kWh	Primary data, this study		
	UEV =	1.80E+12	sej kWh^{-1}	See Suplimental material		
19	Labor	1.70E-02	p*hr	Primary data, this study		
	UEV =	1.00E+14	sej p^*hr^{-1}	See Suplimental material		
Freshwater Rearing (inputs required to produce 1 kg smolts)						
20	Eggs	2.16E+01	n.	Primary data, this study		
	UEV =	8.34E+10	sej egg-1	Computed this study		
21	Feed	1.30E+00	kg	Primary data, this study		
	UEV =	2.60E+12	sej kg^{-1}	Computed this study		
22	Water	2.04E+01	m^3	Primary data, this study		
	UEV =	2.24E+06	sej g^{-1}	(De Vilbiss and Brown, 2015)		
		2.24E+12	sej m^{-3}			
23	Electricity	4.80E+01	kWh	Primary data, this study		
	UEV =	1.80E+12	sej kWh^{-1}	See Suplimental material		
24	Labor	1.70E-02	p*hr	Primary data, this study		
	UEV =	1.00E+14	sej p^*hr^{-1}	See Suplimental material		
Saltwater Grow Out (inputs required to produce 1 kg salmon)						
25	Environmental support					
	current velocity =	0.1	m/s	(Asplin et al., 2020)		
	density of water =	1000	kg/m3			
	volume water =	1.3	m3/kg fish			
	time =	3.15E+07	sec/yr			
	energy =	1/2 m*V2* time				
	=	1/2 * 1.3 m^3 * 1000 kg/m^3 * 0.03 ^{2} m^2/s^2 *3.5 E7 sec/yr				
	=	2.05E+08	J/yr			
	Transformity =	76,200	sej/J	(De Vilbiss and Brown, 2015)		
26	Building (steel)	4.26E-06	m2	Primary data, this study		
		1.40E+16	sej m^{-2}	See Suplimental material		
27	Building (wood)	9.24E-07	m2	Primary data, this study		
		1.20E+16	sej m^{-2}	See Suplimental material		
28	Steel	5.05E-04	kg	Primary data, this study		
	UEV =	1.07E+13	sej kg^{-1}	See Suplimental material		
29	Concrete	1.22E-04	m^3	Primary data, this study		
	UEV =	3.76E+15	sej kg^{-1}	See Suplimental material		
30	Fiberglass	5.36E-03	kg	Primary data, this study		
	UEV =	2.40E+13	sej kg^{-1}	See Suplimental material		
31	Nylon	1.03E-02	kg	Primary data, this study		
	UEV =	9.66E+12	sej kg^{-1}	See Suplimental material		
32	Salmon smolts	6.52E-02	kg	Primary data, this study		
	UEV =	7.26E+13	sej kg^{-1}	Computed this study		
33	Feed	1.43E+00	kg	Primary data, this study		
	UEV =	0.00E+00	sej kg^{-1}	See Suplimental material		
34	Transport (ship)					
	Quantity feed & packaging/km =	4.77E+00	ton km^{-1}	Primary data, this study		
	UEV =	1.20E+10	sej t^*km^{-1}	See Suplimental material		
35	Electricity	5.13E-02	kWh	Primary data, this study		
	UEV =	1.80E+12	sej kWh^{-1}	See Suplimental material		
36	Diesel	2.11E-02	kg	Primary data, this study		
	UEV =	7.26E+12	sej kg^{-1}	(De Vilbiss and Brown, 2015)		
37	Labor	5.95E-03	p*hr	Primary data, this study		
	UEV =	1.00E+14	sej p^*hr^{-1}	See Suplimental material		
Processing & Packaging						
38	Salmon from grow out	1.27E+00	kg	Primary data, this study		
	UEV =	2.62E+13	sej kg^{-1}	Computed this study		
39	Building (steel)	3.30E-06	m^2	Primary data, this study		
	UEV =	1.40E+16	sej m^{-2}	See Suplimental material		
40	Styrofoam boxes	3.58E-02	kg	Primary data, this study		
	UEV =		sej kg^{-1}	See Suplimental material		
41	Cardboard	9.37E-04	kg	Primary data, this study		
	UEV =		sej kg^{-1}	See Suplimental material		
42	Transport packaging (ship)	1.34E+00	t*km	Primary data, this study		
	UEV =	1.20E+10	sej t^*km^{-1}	See Suplimental material		

(*continued on next page*)

Table 2 (*continued*)

	Activity Name	Units	Quantity	UEV (sej/unit)	Emergy (E12 sej)	Percent of Total
43	Electricity	1.22E-01	kWh	Primary data, this study		
	UEV =	1.80E+12	sej kWh^{-1}	See Suplimental material		
44	Labor	4.20E-03	p*hr	Primary data, this study		
	UEV =	1.00E+14	sej p*hr^{-1}	See Suplimental material		
45	Services	5.78E+01	kr	Primary data, this study		
	UEV =	3.24E+11	sej kr-1			

a.

b.

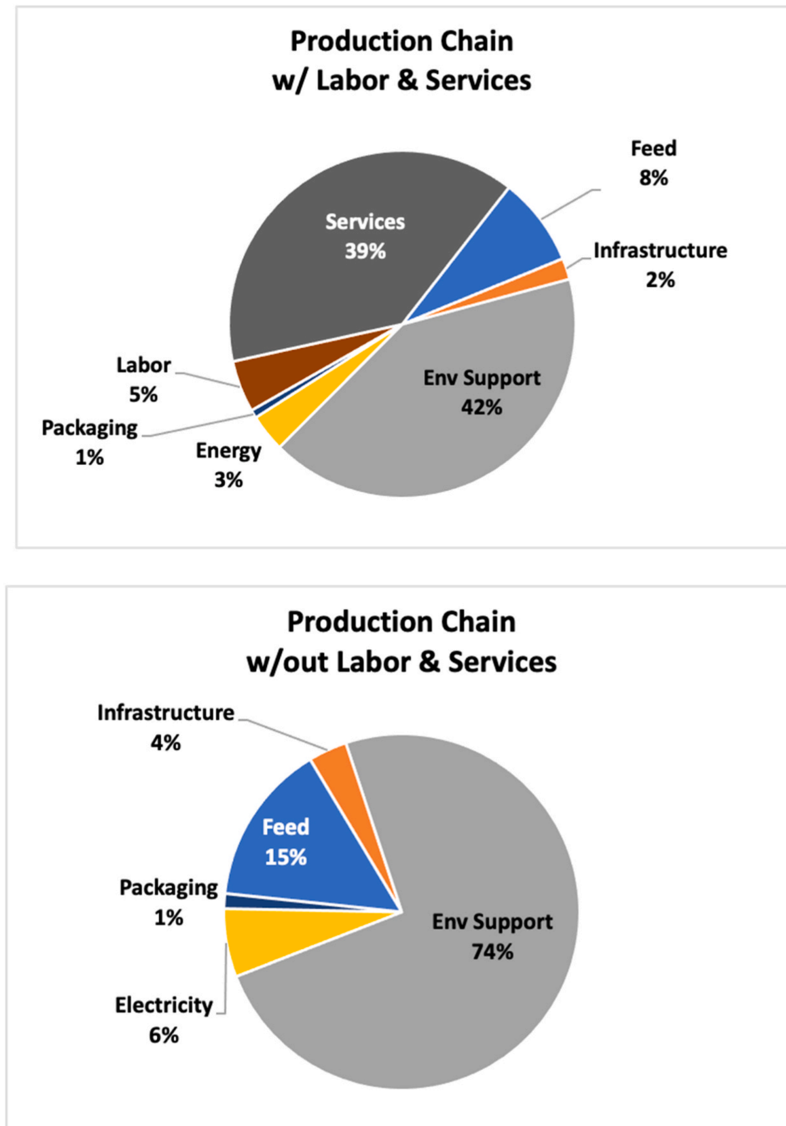

Fig. 6. Percent of final total emergy required to produce farmed Norwegian Atlantic salmon H & G product with labor and services included (a) and without labor and services (b).

The quantities of labor and services reflect the importance of automation to the farmed salmon system which resulted in lower labor inputs per unit of output than wild caught salmon system, but higher service inputs. Labor accounted for 28% of emergy inputs for sockeye salmon (16.1 E12 sej kg^{-1}), while labor was only 5% of inputs to farmed Atlantic salmon (2.3 E12 sej kg^{-1}). Reflecting the higher costs associated with automation, services were 39% of inputs for Atlantic salmon (18.5 sej kg^{-1}), and about 24% for sockeye salmon system (14.1 E12 sej kg^{-1}). Further reinforcing the effect of automation is the fact that emergy of energy inputs was 6% of total sockeye inputs (2.4 E12 sej J^{-1}) while only 3% of Atlantic salmon inputs (1.65 E12 sej J^{-1}).

4.3. *Transformities of salmon and salmon products*

We were able to compute transformities of salmon throughout the stages of growth and processing which provide some interesting insights and comparative differences between the two production systems (Table 3). The transformity of sockeye smolts (5.1 E7 sej J^{-1}) was

Table 3
Specific emergy and transformity of sockeye salmon at each phase, including labor and services.

Phase	Specific Emergy (sej kg^{-1})	Transformity (sej J^{-1})
Alaskan Wild Caught Sockeye Salmon		
Salmon smolts	1.1E+15	5.1E+07
Returning salmon	2.1E+13	5.0E+06
Harvested salmon	3.1E+13	7.3E+06
Processed & packaged salmon	6.8E+13	1.6E+07
Norwegian Farmed Atlantic Salmon		
Salmon smolts	7.3E+13	1.7E+07
Mature salmon[a]	2.5E+13	6.0E+06
Harvested salmon	2.6E+13	6.2E+06
Processed & packaged salmon	5.3E+13	1.3E+07

[a] Estimate assuming that harvesting requires1.0 E12 sej kg^{-1}.

Table 4
Emergy indices of landed and processed wild caught Alaska sockeye and farmed Norwegian Atlantic salmon, including labor and services.

Index	Alaskan Wild Caught Salmon	Norwegian Farmed Atlantic Salmon
Landed Salmon		
Energy Yield Ratio (EYR)	3.23	2.31
Environmental Loading Ratio (ELR)	0.45	0.76
Emergy Sustainability Index (ESI)	7.19	3.03
Percent Renewable	69%	57%
Processed Salmon		
Energy Yield Ratio (EYR)	1.59	1.71
Environmental Loading Ratio (ELR)	1.69	1.40
Emergy Sustainability Index (ESI)	0.94	1.23
Percent Renewable	37%	42%

greater than Atlantic salmon smolts (1.7 E7 sej J^{-1}).[2] For two comparable products, a higher transformity means that the product requires more emergy to produce. Odum (2000) hypothesized, as a general principle, that comparable products produced by natural processes and human dominated processes would be such that the product produced by nature would have a lower transformity than the human dominated product. Counter to that general principle, the transformity of wild sockeye salmon smolts in this study was 3 times that of the farmed Atlantic salmon.

We think there are two factors that help explain the apparent dichotomy in transformities between farmed and wild salmon smolts. The first is a theory of why salmon are anadromous, which relates to the differences in productivity between freshwater and marine ecosystems (Gross et al., 1988). Anadromy is found in northern latitudes where marine productivity significantly exceeds that of freshwater. Productivity of the marine waters of the eastern Bering Sea is about 6 times that of the freshwater lakes in the Bristol Bay watershed (notes to Table 1). This is directly related to the second factor, the differences in size and growth rates between farmed and wild smolts. The average size of sockeye smolts as they migrate to the ocean was 14.9 g and required an average of 2 years of growth in the freshwater lakes and streams of the watershed to produce them. On the other hand, the average size of farmed Atlantic smolts in this study when released to ocean pens was over 100 g and that size was obtained in less than 2 years. Thus, the faster growth rates of the farmed smolts more than made up for the increase emergy inputs required.

This is also an example of a phenomena we discovered while computing transformities for global biomes (Lee and Brown, 2021). The lowest productivity biomes (i.e. deserts, rock & ice, tundra, and montane grasslands) had highest transformities for NPP, the result of relatively high driving emergy, and low productivity. So, while the freshwater lakes in the Bristol bay watershed have comparatively low productivities, the emergy driving the landscape is relatively high. The low productivity of the freshwater systems translates directly into slow growth rates. Thus, it requires 1.1 E15 sej of emergy to produce 1 kg of wild sockeye smolts while it only requires 2.1 E13 sej kg^{-1} to mature sockeye salmon at sea for their return (Table 3).

Considering the transformity as a measure of efficiency (Brown and Ulgiati, 1997), on a per kilogram basis, the transformities of sockeye salmon smolts were higher than the Atlantic salmon smolt, suggesting that the technologically enhanced Atlantic salmon system of growing smolts is more efficient. With the technology of recirculating water systems, ocean pen culture, computer driven feed allocation, and disease and parasite treatment, all driven by electricity and diesel fuel and including labor, it is a relative surprise that the transformity of sockeye smolts is so much higher than that of farmed Atlantic salmon smolts, but testament to the concept of economies of scale and its conflict with ecology of scale (Gwehenberger et al., 2007).

Returning sockeye salmon had a transformity of 5.0 E6 sej J^{-1} a significant reduction from that of smolts which was the result of the accumulation of biomass while at sea and the NPP of the eastern Bering Sea. At this same level of maturity, farmed Atlantic salmon had a transformity of about 6.0 E6 sej J^{-1}, a difference of about 20%. The difference results from the technology, energy, and labor and services required in the saltwater growout phase compared to the absence of such inputs to mature sockeye salmon in the Bering Sea.

The transformity of harvested sockeye salmon (7.3 E6 sej J^{-1}) is about 18% higher than harvested Atlantic farmed salmon (6.2 E6 sej J^{-1}). The reversal from the mature salmon transformities results from the quantities of labor and energy necessary to catch the returning sockeye. Compared to other aquaculture products that have been evaluated using emergy (David et al., 2018; Vassallo et al., 2007; Wilfart et al., 2013; Zhang et al., 2011), the transformity of harvested Atlantic salmon (6.2 E6 sej J^{-1}) is similar to the more intense processes studied. The transformities in the studies just mentioned ranged between 1.53 E5 sej J^{-1} to 8.9 E6 sej J^{-1} with the lowest transformities characteristic of what we would call artisanal aquaculture using bamboo cages, small ponds, etc. and the higher transformities characteristic of more intensive aquaculture systems. Odum (2000) computed a transformity of estuarine pen raised salmon in British Columbia of 9.5 E6 sej J^{-1}), comparable to that of the harvested salmon in this study.

Processed and packaged H&G sockeye salmon transformity (1.6 E7 sej J^{-1}) was about 120% greater than the transformity for the harvested sockeye and that of Atlantic salmon was 110% greater due primarily to the input of services at this point of the production chain. We computed services based on wholesale price at the processing gate and therefore assigned all services to the final phase of the production chain. The result, of course, is that instead of adding services at each stage, they are all added in this last stage which unfolds as a noticeable increase in transformity.

4.4. Emergy indices of sustainability

When compared to farmed Atlantic salmon, landed sockeye salmon had a higher EYR (3.2 compared to 2.3) and a lower ELR (0.45 compared to 0.76). Considering the energy intensive nature of wild catch fisheries, in general (Viglia et al., 2022, *this issue*), it is somewhat surprising that

[2] As an interesting aside, Odum (2000) in an unpublished manuscript, computed a transformity of smolts in the Umpqua watershed of Oregon, USA of 1.0 E7 sej J^{-1} and returning salmon equal to 1.5 E7 sej J^{-1}. While he did not mention the species by name, the watershed supports both coho and chinook salmon. Odum assumed one trophic level for smolts, while we assume an average of 2 trophic levels.

the yield ratio is relatively high (3.2/1), but demonstrates the productivity of the fishery and the fact that it is so concentrated in time and space. Compared to other wild catch fisheries, the fishing effort per unit of catch is relatively low. In our recent paper evaluating the energy, water nexus of sockeye salmon (Viglia et al., 2022, *this issue*), energy use in the sockeye fishery was in the lower quartile of other studies we were able to compare with.

In all, the sustainability of wild caught sockeye salmon fishery prior to processing was higher than farmed Atlantic salmon (Table 4) when labor and services were included (7.2 compared to 3.0), the direct result of the higher EYR and lower ELR of sockeye compared to Atlantic salmon.

At the processing gate the sustainability indicators were switched with higher EYR (1.7 compared to 1.6) and lower ELR (1.4 compared to 1.7) exhibited by processed Atlantic salmon compared to sockeye. High labor and services associated with sockeye compared to farmed Atlantic salmon were the main reasons for lower EYR and higher ELR. The higher labor and services were due primarily to two factors, the age of equipment in the Bristol Bay facilities and the relatively large distances required to transport materials compared to the Norweigen facilities. While these differences in EYR and ELR are minor and should be taken to mean that the processed products are essentially equal in their contributions to the economy and their impacts on the environment, they translate into a slightly larger ESI for Atlantic salmon (1.23) compared to wild catch sockeye (0.94).

Compared to previous emergy based studies of aquacultural systems, both the farmed Atlantic salmon and wild caught sockeye salmon had higher ESIs. Previous studies of aquaculture (David et al., 2018; Vassallo et al., 2007; Wilfart et al., 2013; Zhang et al., 2011) computed ESIs between 0.13 and 0.85, with one exception. In the study by Zhang et al. (2011), a carp farm within Nansi Lake in Shandong Province, consisting of 5000 m^2 of bamboo cages and yielding 25,000 kg of fish had an ESI of 4.6. This high ESI resulted from the fact that caged fish subsisted on lake plankton with no additional feed supplied and very little energy, labor, or services. In the study of British Columbia farmed salmon (Odum, 2000) the ESI computed from a given EYR (1.23) and ELR (4.2) was 0.3, about 13% of the ESI of the farmed Atlantic salmon (landed). It should be pointed out that none of these previous studies included processing and packaging. Even including processing and packaging, both sockeye and Atlantic salmon had higher ESIs than these previous studies.

In summary, the sustainability indices including labor and services for both sockeye and Atlantic salmon at the first step in the supply chain (landed salmon) are typical of products that provide long term sustainable production and provide good opportunity for downstream "value added" which translates into many prospects for matching of labor and services (Brown and Ulgiati, 1997). Sustainability of the farmed Norwegian Atlantic salmon system was better than most aquaculture systems evaluated to date, and while this may be due, in part, to the differing methods of computing environmental support, none the less, the large differences suggest that farmed Atlantic salmon is a relatively efficient production system.

4.5. Sensitivity of indices and transformities

The majority of data needed for this study was collected from individual companies and facilities as primary data and we have a high degree of confidence that they represent industry averages. On the other hand, data necessary to compute environmental support were obtained from the literature. The difficulty of obtaining data for computing environmental support, especially when that support is over large areas and relatively long time frames becomes paramount for interpretation of results. The ecological productivity of the freshwater and ocean ecosystems expressed as Net Primary Production (NPP) is the fundamental property required to compute environmental support of sockeye salmon and ocean currents necessary to flush salmon net pens during the grow out phase of Norwegian Atlantic salmon production cannot be measured in a study such as this. Instead, data from the literature must be relied upon, the more data the better. We have combed the literature to extract what we believe are the best data obtainable for these fundamental properties of environmental support.

Changes in the values selected for NPP of the freshwater and oceanic ecosystems or ocean currents can shift the results of the analysis. Higher NPP increases sustainability of wild caught sockeye as does higher ocean currents for farmed salmon. After a great deal of review of literature values, we have selected the values used in this study, yet we provide a word of caution that the results of this analysis are so close that to suggest one system of producing the finished salmon product is undeniably better than the other would be an inaccuracy.

5. Concluding remarks

We have provided a detailed model for the evaluation of environmental support of wild catch fisheries and marine based aquaculture and have shown that environmental support is a significant input that must be carefully considered. Our results are particularly sensitive to the level of environmental support, shifting sustainability indices and transformities with changes in the productivity values chosen for the freshwater and ocean ecosystems. All other data are relatively straight forward, and we have a high degree of confidence in them since they were primary data representing industry averages, collected from fishers, growers, and processors who participated in our study.

Numerous studies have hinted at the unsustainable nature of aquaculture, but mostly from the perspective of feed formulations that require protein, often sourced from ocean fisheries, or released waste, antibiotics and pesticides, or escaped fish affecting genetic resources. This study has not taken into account any of these "indicators of unsustainability", but rather focused on environmental support to emphasize the links between human food systems and the support from the environment necessary to sustain them. Still, our analysis showed that Norwegian farmed Atlantic salmon, because of the environmental support provided to the saltwater grow out phase had an ESI of about 3.0 as landed fish and 1.7 as processed fish. The high level of technology used in the production process required a relatively large amount of services but reduced the quantity of labor necessary and thereby increased the EYR, lowering the ERL, and increasing the ESI.

The Bristol Bay sockeye fishery appears not to be overfished and in fact, has been described as biologically sustainable (Hilborn, 2006) due in large part to management practices. We believe that this study of Alaskan sockeye salmon is the first wild catch fishery that has been evaluated using emergy. Our analysis reveals a production system that is relatively labor intensive, requires a great deal of environmental support, and provides a relatively high net yield. It's sustainability, based on the ESI is good having and ESI of landed fish of 7.2 even while depending on relatively large quantities of energy and labor inputs to fishing effort. It should be noted however, that other factors, especially climate change which has been suggested as a major driver of change in all the Alaskan fisheries could easily change its biological sustainability. Sockeye's ESI, after processing, drops significantly to 0.9, in keeping with that of other refined products, and is the result of large inputs of labor and services. The quantity of labor supported by the fishery is quite large, partially the result of fisheries management that limits the size of fishing vessels, thus requiring more labor and also because many of the processing plants are quite old (1950s) and are more labor intensive than more modern facilities.

Finally, it is an open question, which of the two species and methods of production yields the better fish. Atlantic salmon have more fat, with thick flakey flesh and a pale orange color, while sockeye, on the other hand, are smaller with deep orange coloring and less fat. Sockeye have about 23 g protein per serving while Atlantic has about 19 g. Fresh sockeye are only available following their short season in late June early July, while fresh Atlantic salmon are generally available year round. As for taste, the better of the two fish depends on taste. Bon Appetite!

CRediT authorship contribution statement

Mark T. Brown: Conceptualization, Writing – original draft, Methodology, Formal analysis, Validation. **Silvio Viglia:** Formal analysis. **Dave Love:** Investigation, Writing – review & editing. **Frank Asche:** Investigation, Writing – review & editing. **Elizabeth Nussbaumer:** Investigation, Writing – review & editing. **Jillian Fry:** Investigation, Writing – review & editing. **Ray Hilborn:** Writing – review & editing. **Roni Neff:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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