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Environmental impacts and food loss and waste in the U.S. aquatic food system

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ABSTRACT

Aquatic food systems support global food and nutrition security, livelihoods, and economies, but put significant environmental pressure on the planet. The United States (U.S.) is the world's fourth largest consumer and the largest importer of aquatic food, which makes it a good case for studying aquatic food systems. Here, we estimate the energy use, greenhouse gas emissions (GHGe) and blue water use by species, production method, product form, and stage of the U.S. supply chain, while accounting for trade and food loss and waste. We identified wide variation across species for energy use (40.2 to 259.1 MJ/kg), GHGe (3.7 to 22.2 kg CO2 eq/kg), and blue water use (15.8 to 1,851 l/kg). Capture fisheries and aquaculture on average used similar amounts of energy per unit of edible aquatic food; however, aquaculture emitted 54 % more GHGe and consumed 784 % more blue water than capture fisheries, due to the high GHGe and blue water intensity of aquaculture feed. Products with the lowest energy use were canned, fresh, and frozen sockeye salmon, frozen pollock, and frozen catfish. Products with the lowest GHGe were canned, fresh, and frozen sockeye salmon, frozen pollock, canned and frozen tuna, and frozen Atlantic salmon, All wild caught species had significantly lower blue water use impacts than farmed products. The production stage had the largest environmental impacts, but measuring production alone would miss 64 % of the energy, 36 % of the GHGe, and 21 % of the blue water used in the remainder of the supply chain. The processing stage was an important contributor to resource use for species with energy and water efficient production practices. Aquatic food in the U.S. supply is lost and wasted at an overall rate of 23 %; lost and wasted seafood contains 22 % to 24 % of the embodied energy, GHGe, and blue water in aquatic food systems. Compared to findings identified in the literature, aquatic foods in this study were lower in GHGe than beef, had a range of GHGe that extended above and below pork and poultry, and had higher GHGe than most legumes, and nuts. Estimating the environmental impacts and food loss and waste in the U.S. aquatic food system can help identify opportunities to enhance sustainability and resilience and support science communication about lower-impact foods and dietary patterns.

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1. Introduction

Aquatic and terrestrial food systems put significant, cumulative environmental pressure on the planet (Halpern et al., 2022) emitting 34 % of anthropogenic greenhouse gasses (GHG) (Crippa et al., 2021) and using 70 % of global freshwater (Rosegrant et al., 2009). Food systems are also undermined by conflicts (Kuemmerle and Baumann, 2021), climate change (Wheeler and von Braun, 2013), food loss and waste (Gustavsson et al., 2011; Xue et al., 2021) and inequity (Hicks et al., 2022). Aquatic foods play a key role in food systems by providing 17 % of global animal protein and 7 % of total protein (FAO, 2022a) as well as critical micronutrients and omega-3 polyunsaturated fatty acids (Golden et al., 2021). Aquatic foods come in equal parts from wild-capture fisheries and aquaculture (farmed aquatic products), but future growth in the sector will mainly come from aquaculture (FAO, 2022a; Garlock et al., 2022). Calls to transition food systems (and aquatic foods) to become more efficient, resilient, inclusive and sustainable (FAO, 2022b) have focused on technology and innovation solutions (Herrero et al., 2020), policy (Candel, 2022; Gaupp et al., 2021), and social/behavioral approaches (Reisch, 2021; Willett et al., 2019). Understanding where the leverage points exist within food systems to achieve maximal returns is critical for targeting interventions.

Here, we use life cycle analysis and concepts from the food-energy-water nexus (D'Odorico et al., 2018) to identify leverage points within aquatic food systems to increase resource use efficiency and reduce food loss and waste. This study uses the U.S. as an example system, as it is the world's fourth largest consumer and largest importer of aquatic foods (FAO, 2022a) and a significant share of the U.S. aquatic food supply comes from imports making the sourcing highly diverse (Gephart et al., 2019; Shamshak et al., 2019). Diversity of aquatic species, production methods, supply chains, and product forms is notable (Naylor et al., 2021). This diversity creates large knowledge gaps with respect to the environmental impacts of aquatic foods (Halpern et al., 2019) and linkages between aquatic food, energy, and water systems (Gephart et al., 2017). Most previous studies focus on the production stage (Gephart et al., 2021; Hilborn et al., 2018) and do not assess downstream stages (i.e., processing, transportation, wholesale, retail, consumption), this are missing a full accounting of impacts. For example, transportation contributes nearly a fifth of GHG emissions in global food systems (Li et al., 2022). It is important for aquatic foods as they are among the most highly traded commodities (Anderson et al., 2018), and the impacts vary significantly with transportation mode (Ziegler et al., 2022). Consumers have some of the highest rates of food loss and waste (Xue et al., 2021; Love et al., 2023) and products that make it to the consumer stage have the highest embodied resources when wasted, highlighting the importance of studying the intersection of waste and resource use across the supply chain.

The aim of this study is to estimate energy, GHGe, and blue water use in the U.S. aquatic food system based on the top ten most consumed species groups while accounting for the large share of imports and food loss and waste. The analysis was done by species, production method, and product form along the supply chain. We also look at interdependence, synergies and tradeoffs between resource use and food loss and waste, and identify priority opportunities for improving resource use efficiency.

2. Materials and methods

2.1. System description

The boundaries of this analysis are the U.S. aquatic food supply chain from production to consumption, including imports, in the years 2016 to 2018 (Fig. S1). Production was divided into aquaculture (i.e., aquatic animal farming) and capture fisheries. Consistent with other aquaculture life cycle analyses, we included the energy, GHGe, and blue water embodied in aquaculture feed, operating feed mills, and transporting feed to farms. Processing (i.e., animal slaughter) included the energy, GHGe, and blue water to create different product forms and the packaging used to hold products. As roughly 70 % of U.S. aquatic foods are imported (Gephart et al., 2019) we also included the energy and GHGe associated with international transport of these products. Imported and domestically processed aquatic foods are sold to wholesale businesses that transport products to either retail or food service facilities. At the retail and food service stages we consider resource use in aquatic food storage (i.e., cooling), and at the food service stage we also consider resource use in food preparation (i.e., cooking). At the consumer stage we consider home storage and preparation of aquatic foods purchased from retail. At all stages we considered product forms (i.e., fresh, frozen, canned) and incorporated food loss rates into estimates of energy, GHGe, and blue water use.

2.2. Life cycle approach

We assessed the energy, GHGe, and blue water that is embodied in 1 kg of wet weight edible aquatic food in the U.S. aquatic food supply. To do this, we evaluated direct and indirect inputs of energy, GHGe, and water along the entire supply chain from production to the consumer plate for the top ten species consumed in the U.S. (Table S1). We ignored environmental contributions (e.g., sunlight, environmental support) and evaluated only the energy, GHGe, and blue water used in processes under human control. For direct inputs we relied on primary data collected from businesses and secondary data from the literature. For indirect inputs (i.e., energy, GHGe, and water embodied in infrastructure, equipment, vehicles etc.) we relied on SimaPro software version 9.0.0.30 (Amsterdam, The Netherland), the Ecoinvent database version 3.6 (Wernet et al., 2016), and the ReCiPe Midpoint v.1.13 method (Goedkoop et al., 2009) for fossil depletion, global warming, and water depletion potential,which yielded kg of oil equivalent (or MJ), kg CO_2 eqivalent, and m^3 of water, respectively.

Different forms of energy were transformed to MJ based on standard engineering conversion coefficients. For water consumption, we adhered to the definition of "blue water" (Hoekstra and Chapagain, 2011), defined as water that has been sourced from surface or groundwater resources and has either evaporated or been incorporated into a product or taken from one body of water and returned to another. We did not account for grey water use in aquaculture since there was limited data on water quality of discharges from farm operations or processing facilities.

Energy, GHGe, and blue water impact potentials (impacts per kg edible food) are reported for each species group, production method, product form and supply chain stage (Dataset S1). Estimates were adjusted using food loss rates (Dataset S2) and weighted by various weighting factors (Dataset S3) to estimate the share of each species group, production method, or product form contributed to overall impacts potentials. The analysis accounted for species with multiple production methods (i.e., farmed vs wild caught), product forms (i.e., fresh, frozen, canned), product flows through supply chains, and food loss. Data collection methods, secondary data, and weighting factors for each species group and supply chain stage are described below and in the Supporting Information section Tables S1-6 and Datasets S1-3.

2.3. Data collection and inventory

Primary and secondary data collection was performed for each stage of the U.S. aquatic food supply chain from 2019 to 2021. Quantitative surveys were distributed to participants and collected in person or by Follow-up interviews were used to discuss survey responses. Multiple note-takers were used during in-person meetings, phone calls or online video calls, when available, and notes were compared for accuracy after the meetings. Semi-structured qualitative interviews were performed as described previously (Fry et al. 2024). Excel spreadsheets (Redmond, WA) were constructed for data storage, processing, and analysis of primary and secondary data. The project was approved by the Institutional Review Boards at Johns Hopkins School of Public Health (IRB # 8345) and University of Florida (IRB # 201901559).

2.3.1. Production and processing

At the production and processing stage, energy, GHGe, and water use data were collected using surveys, semi-structured qualitative interviews, and literature for the top ten species groups, which account for 79 % of the U.S. aquatic food supply. The top ten species groups (ranked in order of supply) are: shrimp, salmon, tuna, tilapia, catfish & pangasius, Alaska pollock, cod, crab, flatfish and scallops (Table S1). Catfish and pangasius were combined because they are both a type of catfish and U.S. food service and consumers often do not distinguish these products in the marketplace. The remaining 21 % of U.S. aquatic food supply was assigned a global average of the top ten species groups.

Seven species groups were selected for in-depth analysis (listed as “primary data” in Table S1), which represented 61 % of the U.S. aquatic food supply. Within these seven species groups, we selected sectors and sampling locations that were representative of the types of products that are supplied to the U.S. market. Primary data (life cycle inventories) were collected from the following sectors:

- Vietnam farmed shrimp (*Penaeus monodon*, *Litopenaeus vannamei*)
- Vietnam farmed pangasius (*Pangasius hypophthalmus*)
- Southern U.S. farmed channel and hybrid catfish (*Ictalurus punctatus; I. punctatus* x *I. furcatus)* (Viglia et al. 2022a)
- Norway farmed Atlantic salmon (*Salmo salar)*
- U.S. Alaska wild capture sockeye salmon (*Oncorhynchus nerka*) (Viglia et al. 2022b)
- U.S. Alaska wild capture Alaska pollock (*Gadus chalcogrammus*)
- Pacific tuna (*Thunnus* spp.)

In total, 24 producers and 20 processors participated in primary data collection, which represented over 24 % of total systemwide harvesting and processing for the seven sectors listed above. These data were collected in-person during site visits in 2019 except for the Alaska pollock and tuna fisheries which were collected remotely. The energy, GHGe, and water embodied in boats, buildings, equipment, and infrastructure materials, were obtained from the Ecoinvent® v3.6 database and depreciated using accepted depreciation rates. Analyses were based on averages of a 3-year period (2016–2018).

For species groups in which we did not do in-depth analysis, listed as “secondary data” in Table S1, we relied on data from the literature. A literature search spanning 2003 to 2021 was performed in Google, Google Scholar, Science Direct, and Web of Science using a targeted list of keywords for specific species groups. We identified a total of 913 journal articles that were relevant to our study. The majority (98 %) reported data for fishing/aquaculture production only and 2 % had data on processing. Most data were reported in units of CO_2 equivalents. Some earlier studies (early 2000 s) provided data in energy units. Of the total papers reviewed, 28 papers contained energy data on the species groups for which we did not do in-depth analysis: farmed tilapia (n = 4), wild caught cod (n = 10), wild caught crab (n = 5), wild caught flatfish (n = 3), wild caught scallops (n = 2), and wild caught shrimp (n = 6). (Some papers cover multiple species).

Food loss in production and processing included physical and quality loss, such as discards, mortalities, oversized or undersized harvests, temperature abuse, damaged or decomposing products and other forms of loss. For aquaculture, estimates were made of the biomass lost when harvestable-size animals died before harvest, as previously described (Love et al. 2023).

Greenhouse gas emissions (GHGe, kg CO_2 eq) associated with aquaculture feed for each species per edible kg were computed based on the following: share of feed ingredients by species, feed ingredient energy, GHGe, water intensity, feed conversion ratio, and edible yield. Standard GHGe intensities for fuels and energy were used to compute global warming potential for energy and electricity (see Table S6). Where possible regionalized GHGe intensities for electricity were used (Table S6) to compute global warming potential from electricity use.

2.3.2. International transport

Imports of the top ten aquatic food species groups were compiled using trade data (United States Census Bureau, 2022) from six exporting regions: Africa, Asia, Australia & Oceania, Europe, North America, and South/Central America. We computed energy embodied in international transport for aquatic foods shipped by air (fresh forms) and by sea (frozen and canned forms). We did not compute imports by truck as this travel mode is not tracked by USA Trade, although this is important for some fresh fish from Canada and Mexico. Quantities of aquatic food by species and product form imported from each of the 6 global regions were summarized from U.S. trade data for the years 2017–2019.

We used the following energy intensities for air transport (8.23E-03 MJ/kg-km) (Peeters et al., 2005; Ziegler et al., 2013) and sea transport (4.0 E-04 MJ/kg-km) (Ziegler et al., 2013). To evaluate air distances, we selected a single large metropolitan area with an international airport in each of the 6 regions as the departure location and a single centroid location in the U.S. (Kansas City, MO) as the destination, and air distances and energy (MJ/kg) were computed for aquatic food transported by air (Table S2). To evaluate sea distances, we used the same metropolitan areas as departure ports and three different coastal U.S. ports (NewYork, NY; San Francisco, CA; or Savannah, GA) in the U.S. depending on shortest transport distance to port city (Table S2). Sea miles were computed using standard shipping lanes. Total energy embodied in imported aquatic food from international transport for each species group was the sum of the energy expended in sea and air transport.

2.3.3. Wholesale

Aquatic food that is imported or produced in the U.S. is sold through wholesale businesses destined to either retail or food service establishments. At the wholesale stage, water and energy use data and food loss were obtained from detailed surveys of wholesale aquatic food companies (n = 5) representing a total of 32,000 tonnes/yr of aquatic food (max: 14,500 tonnes/yr; min: 1,200 tonnes/yr).

2.3.4. Domestic transport

In our model, we place domestic transport after the wholesale stage, however, transport is needed to deliver goods from ports to wholesalers and from wholesalers to retailers. To model the average energy per kilogram of product, we first divided the continental U.S. into four census regions (United States Census Bureau, 2010), geo-referenced the population centroid for each of the four regions, and computed straight line distances between each centroid. We then summarized aquatic food consumption by region using data from Love and colleagues (Love et al., 2020) and U.S. trade data by region (United States Census Bureau, 2022) and developed a “shift-share” analysis by species where each region either imported or exported aquatic food from/to other regions to meet their consumption. Regions with more imports than consumption were presumed to exported to surrounding regions. Quantity exported from a region to other regions was computed using a gravity model where closer regions received more proportionally than distant regions. The energy intensity of truck transport was calculated as 0.002 MJ/kg-km (Kannan et al., 2016; Wakeland et al., 2012).

2.3.5. Retail, food Service, and home preparation

In our model, wholesale aquatic food is transported to either retail or food service establishments. The share of each species group sold by retail and food service, by volume, was based on findings from a nationally representative dietary intake survey (Love et al., 2020). We assumed that retail aquatic food is sold for in-home food preparation and consumption, and food service meals were consumed in the food service establishment. The energy, GHGe, and blue water required at these stages were modeled using data that included energy required to refrigerate and cook 1 kg of fresh and frozen aquatic food in both food service and residential settings (Bell, 2022). Tables S3 and S4 summarize the cooking and cooling energy requirements in retail and food service establishments and home preparation. Water use in retail, food service and home preparation was not available specifically for aquatic foods and these stages were assumed to be zero. Food loss at retail was based on using a national survey of US grocery store chains conducted by the Food Marketing Institute in 2014, 2016, and 2018 (n = 90 total responses). Loss at food service was estimated using published values in the literature as previously described (Love et al. 2023). At home consumer waste was derived using a food diary survey of US aquatic food consumers (n = 70) as previously described (Love et al. 2023).

2.3.6. Calculation of energy, GHGe, and water used in each stage of the US aquatic food system

Primary and secondary data were collated in inventory tables. Each of the inventory items (foreground inputs) to each species and stage was multiplied by an energy, GHGe, and blue water characterization factor (Supporting Information Table S5) derived from EcoInvent database. The equations are as follows:

$$FossilFuelDepletionPotential(kg_{oilequivalent}) = CF_E * InputItem \tag{1}$$

$$Energy(MJ) = FDP(kg_{oilequivalent}) * 42MJ/kg_{oilequivalent} \tag{2}$$

where:

$CF_E = energycharacterizationfactor$

$$FreshwaterDepletionPotential(m^3) = CF_W * InputItem \tag{3}$$

$$Water(l) = Water(M^3) * 1000l/m^3 \tag{4}$$

where:

$CF_W = watercharacterizationfactor$

$$GlobalWarmingPotential(kgCO_2eq) = CF_c * InputItem \tag{5}$$

$$Water(l) = Water(M^3) * 1000l/m^3 \tag{6}$$

where:

$CF_c = CO_2eqcharacterizationfactor$

A weighted average for each stage and for each species was computed as the weighted average of the data collected from business as follows:

$$\text{Weighted Average} = \frac{\sum_{i=1}^{n}(w_i * x_i)}{\sum_{i=1}^{n} w_i}$$

where:w_i = weight of data point ix_i = data pointn = total number of data points

2.3.7. Calculation of the energy, GHGe, and water each species contributes to the U.S. Aquatic food supply

The contribution of each species to the overall energy, GHGe, and water embodied in the U.S. aquatic food supply was computed using a weighted average of each species where the weighting factor is the species percent of the U.S. supply by weight.

$$\text{Weighted Average Energy Contribution} = \frac{\sum_{i=1}^{n}(P_i * E_i)}{\sum_{i=1}^{n} P_i}$$

where:

P_i represents the percent of species *i* in the US diet by weight,
E_i represents the energy embodied in species *i*,
n is the total number of species

$$\text{Weighted Average Water Contribution} = \frac{\sum_{i=1}^{n}(P_i * W_i)}{\sum_{i=1}^{n} P_i}$$

where:

P_i represents the percent of species *i* in the US diet by weight,
W_i represents the water embodied in species *i*,
n is the total number of species

$$\text{Weighted Average GHGe Contribution} = \frac{\sum_{i=1}^{n}(P_i * GHG_i)}{\sum_{i=1}^{n} P_i}$$

where:

P_i represents the percent of species *i* in the US diet by weight,
GHG_i represents the CO_2 eq embodied in species *i*,
n is the total number of species.

3. Results and Discussion

3.1. Resource use and GHGe in U.S. Aquatic food system

An increasing number of life cycle analyses have been performed for aquatic foods (Halpern et al. 2019), however, few studies assess the entire supply chain. This is the first study to assess energy use, GHGe, and blue water use for the U.S. aquatic food supply. We found a wide range of impacts across species and impact categories (Fig. 1). Characterizing the environmental impacts by species, production methods, product forms, and supply chains is key to identifying actions that can be taken to reduce those impacts and transitioning to a more sustainable food system.

3.1.1. Capture fisheries

Capture fisheries use on average of 127.0 MJ of energy and emit 10.8 kg CO_2 eq to produce 1 kg of edible aquatic food (Fig. 1). Diesel fuel is the main input for capture fisheries production and the largest contributor to GHGe. The lowest GHGe products was canned sockeye salmon (3.7 kg CO_2 eq/kg) and the highest GHGe product was fresh scallops (22.4 CO_2 eq/kg). It takes less energy per unit of production to catch fish that return en masse to spawning grounds (e.g., salmon) or schooling fish (e.g., Alaska pollock) and more energy to catch crustaceans, scallops and flatfish that use fuel-intensive methods such as traps, pots, bottom trawls, and dredges (Parker and Tyedmers, 2015; Parker et al., 2018). Adoption of fuel-efficient gears, fisher behaviors, and low-emission technologies are opportunities for improving harvesting efficiency. Improved fishery management can also facilitate reductions in energy use given that fuel use intensity is often linked to stock levels (Byrne et al., 2021). Energy use is not only an indicator of environmental sustainability but also an indicator of vulnerability (e.g., to rising energy prices).

3.1.2. Aquaculture

Aquaculture uses on average 122.6 MJ/kg energy and emits on average 16.6 kg CO_2 eq/kg to produce 1 kg of edible aquatic food (Fig. 1). The lowest energy use was frozen catfish (65.5 MJ/kg) and the highest energy use was fresh Atlantic salmon (157.1 MJ/kg). These differences are mainly due to varying amounts of energy used in production, but also other differences in processing, product forms, and supply chains. The lowest GHGe was frozen Atlantic salmon (7.0 kg CO_2 eq/kg) and the highest was for fresh catfish (22.4 kg CO_2 eq/kg).

Compared to capture fisheries, aquaculture uses 54 % less energy overall but emits 54 % more GHGe. This finding is primarily due to the higher GHGe intensity of the main inputs into aquaculture production (e.g. animal feed, electricity) compared to the main inputs for capture fisheries (e.g. diesel fuel). Fig. S2 compares GHGe and energy use for species in the study showing that energy use is a good predictor of GHGe for capture fisheries but not for aquaculture, which agrees with our re-

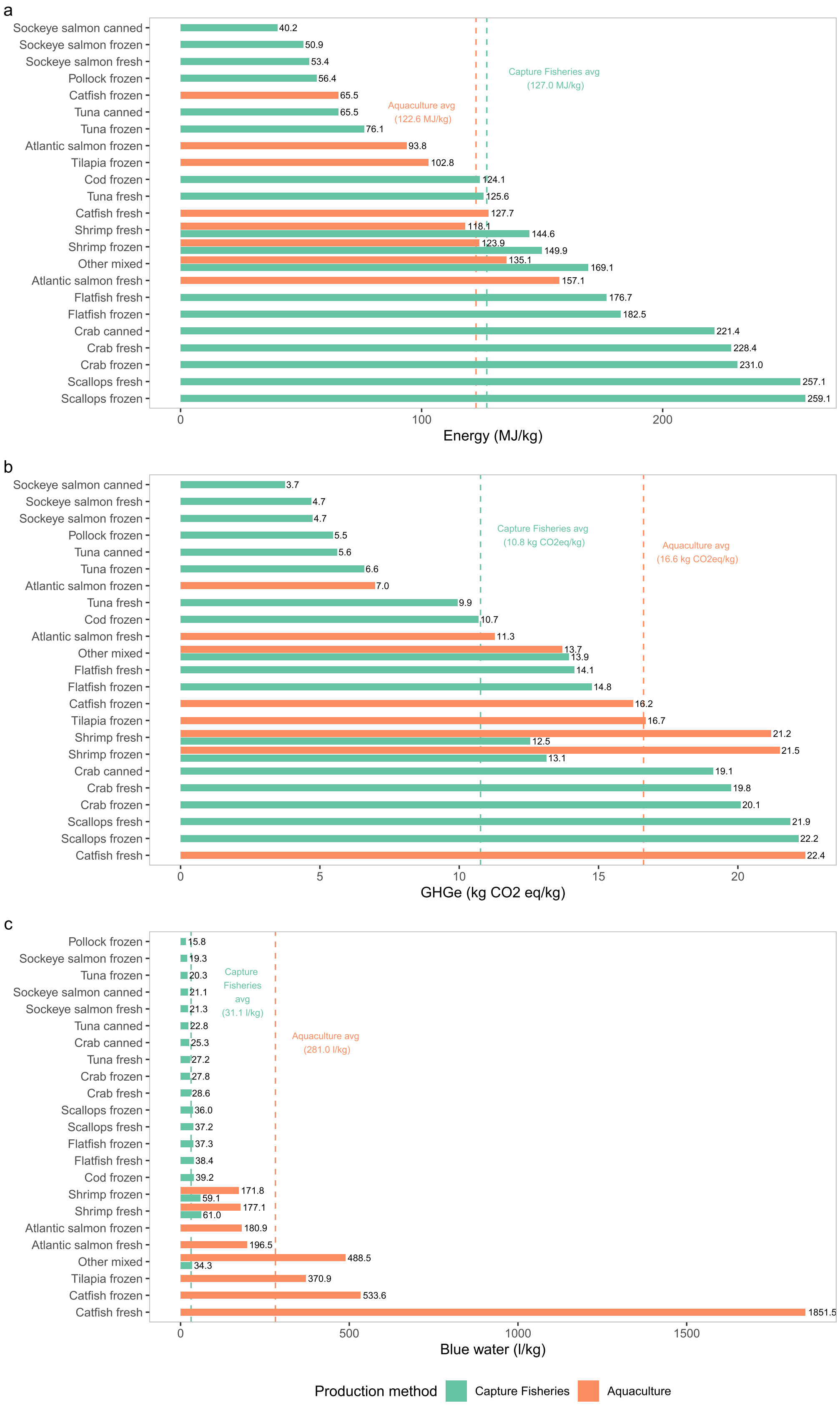

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Fig. 1. Environmental impacts of the top-10 aquatic food species in the United States by production method and product form. a) energy (MJ/kg), b) greenhouse gas emissions (kg CO_2 eq/kg), and c) blue water (l/kg). The dashed lines are the weighted averages for capture fisheries and aquaculture, weighted by the share of consumption. Catfish includes pangasius. Estimates include food loss and waste. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

analysis of a published dataset (Heller et al. 2018).

We found that aquaculture feed is a significant contributor to energy use (66 % of total) and GHGe (67 % of total) for the production stage, which agrees with previous findings for GHGe (Gephart et al., 2021). From farm to plate, feed accounts for 35 % of total energy and 45 % of total GHGe in aquaculture products. Fig. S3 helps explain differences in feed-related GHGe among species. Fig. S3a presents the feed-related GHGe at the production stage for species in the study, which is the product of the species-specific feed conversion ratio (Fig. S3b), the inverse of the edible yield (Fig. S3c), and the GHGe intensity of the feed ingredients (Fig. S3d) weighted by the share of the feed ingredients in an animal's diet (Fig. S3e). For example, Atlantic salmon has a lower GHGe for feed (3.4 kg CO_2 eq/ton edible fish) compared to other aquaculture species, because Atlantic salmon has a lower feed conversion ratio, higher edible yield, and a feed mix using lower intensity feed ingredients. All species in this study were fed commercial diets and produced in industrial-style operations. As a relatively young industry, there are many promising opportunities to reduce GHGe in aquaculture such as through development of novel feeds, increased utilization of byproducts (Love et al., 2024), as well as improving feed conversion ratios through selective breeding and genetic improvements, and selecting feeds with lower GHGe intensities (Asche et al., 2022a). Such improvements are critical for realizing future growth in sustainable aquaculture.

3.2. Comparing environmental impacts between aquatic and terrestrial protein foods

We compared our findings to two studies (Gephart et al. 2021; Heller et al. 2018), which were selected based on their robustness. (Gephart et al 2021 reviewed and extracted data from studies representing 1,690 farms and 1,000 fishery records around the world. Heller et al. 2018 reviewed and extracted data from over 400 studies including over 40 studies of aquatic foods.) Based on these studies and our own, capture fisheries and aquaculture are among the most energy intensive protein foods to produce. In our study, the median energy in capture fisheries production was similar to beef, and higher than pork, chicken, and legumes and nuts (Fig. S4a,b), while the median energy in aquaculture production was less than beef, but higher than pork, chicken, and legumes and nuts (Fig. S4a,b). Heller and colleagues' median values are lower for capture fisheries and higher for aquaculture than ours. The disagreement could be due to the wide range of species and production practices in the literature versus those species and practices that are representative of the U.S. supply.

Considering GHGe, all studies agreed that capture fisheries and aquaculture have lower GHGe than beef (Gephart et al. 2021, Heller et al. 2018) (Fig. S4c,d,e). In our study and Gephart et al. 2021, the median GHGe for capture fisheries and aquaculture was higher than pork, chicken, and legumes and nuts (Fig. S4c,d). In Heller et al., the median for aquaculture was similar to pork, and higher than chicken and legumes and nuts, while the median for capture fisheries was similar to pork and chicken and higher than legumes and nuts (Fig. 4e). The wide range of GHGe and energy estimates for aquatic foods is notable. However, it is not too surprising given the high diversity of species in aquatic production (Garlock et al., 2023) and in U.S. consumption (Love et al., 2022b). We did not assess farmed seaweed or farmed molluscan bivalves (i.e., oysters, clams, mussels), however, other studies have shown that these products have lower GHGe than most capture fisheries and fed aquaculture species (Gephart 2021). When GHGe impacts of foods are combined with dietary patterns, we see that pescatarian diets are lower in GHGe than omnivore diets (due to high GHGe content of beef) but are higher in GHGe than plant-based diets (Kim 2019; Heller et al., 2018; O'Malley et al., 2023).

Capture fisheries are remarkably water efficient; our analyses found they used only 31.8 l/kg blue water in the entire supply chain (Fig. 1), with most of that usage in the processing stage (Fig. S5c). Aquaculture used significantly more blue water (281.0 l/kg) than capture fisheries and had a much wider range of use (171.8 to 1,851 l/kg) (Fig. 1), depending upon the species, farming methods, and water requirements for the feed. Both freshwater and marine aquaculture use blue water in hatcheries and to grow crops as feed ingredients, however, only freshwater aquaculture (i.e., catfish, tilapia) used blue water in the grow-out phase. Catfish aquaculture was the largest water user in our study, which includes production systems in Vietnam on the Mekong River and the Southeast U.S. Our median estimates for blue water use in aquaculture in the U.S. supply were greater than estimates from aquaculture in China (Pahlow et al. 2015), within the range of estimates for aquaculture in Indonesia (Henriksson et al. 2019) and are in the same range but slightly lower than global estimates (Gephart et al. 2021) (Fig. S6). Compared to other foods, aquaculture uses less blue water than terrestrial animal production, while capture fisheries use the least blue water of any plant or animal food group (Kim et al., 2020; Mekonnen and Hoekstra, 2012).

3.3. By stage of the supply chain

Most life cycle studies of aquatic foods only focus on the production stage (Gephart et al., 2021; Hilborn et al., 2018, Parker et al. 2018), and some continue through the transport stage (Ziegler and Hilborn, 2022), but few studies cover the entire supply chain. Our study measured impacts across the entire supply chain and found that the production stage (e.g., capture fisheries and aquaculture production) is the largest user of energy, GHGe, and water (56 %, 64 %, and 79 %, respectively), however, studies that stop at the production stage will miss the remaining 64 % of the energy, 36 % of the GHGe and 21 % of the blue water used in downstream stages (Fig. 2). For fisheries such as Alaska sockeye salmon that expend little energy capturing fish, stopping at the production stage misses the largest share of the overall energy, GHGe, and blue water use, which exists at the processing stage (Fig. 3). In other fisheries, such as Alaska pollock, fish can be processed and frozen aboard fishing vessels (called catcher-processors) and it is not easy to separate out resources used in production versus processing.

Overall, for the U.S. seafood supply, the processing stage was responsible for 13 % of energy, 13 % of GHGe, and 19 % of blue water (Fig. 2). Transport was responsible for 20 %, 13 %, and 2 % of total energy, GHGe, and blue water (Fig. 2), which is similar to previous GHGe estimates for transport-related GHG emissions in the global food system (Li et al., 2022). The wholesale stage was responsible for 2 %, 2 %, and 1 % of the total energy, GHGe, and blue water to store and cool products (Fig. 2). Retail and food service was responsible for 6 %, 5 %, and < 1 % of total energy, GHGe and blue water, which included energy to cool and cook aquatic foods. Consumers were responsible for 3 % of the total energy and GHGe and < 1 % of the blue water to cool and cook aquatic foods at home. For the wholesale, retail, and food service stages, cooling made up a larger share of energy and GHGe, while at the consumer stage, cooking was the largest share of energy and GHGe.

3.4. Transport of aquatic foods

The U.S. imports about 70 % of its aquatic food from other countries

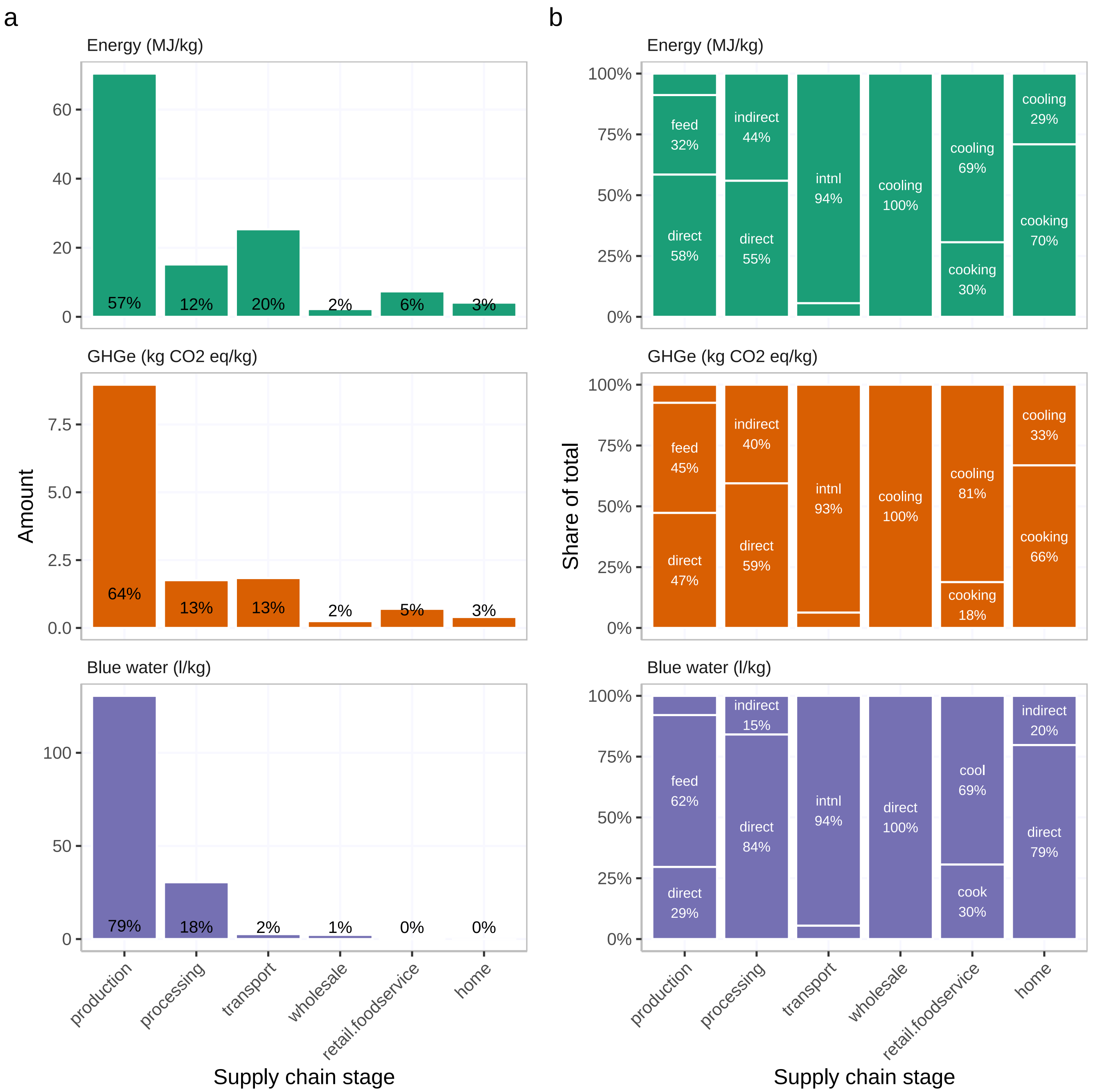

Fig. 2. Energy (MJ/kg), greenhouse gas emissions (kg CO_2 eq/kg), and blue water (l/kg) by stage in the United States aquatic food supply chain. Estimates for a) total and b) share of total energy, greenhouse gas emissions, and blue water. b) for ease of reading only values > 10 % are labeled. Estimates include food loss and waste. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Gehpart 2019) making trade and transport a key component in aquatic food life cycle analyses. After accounting for regional trade patterns, we estimated that international transport was responsible for 94 % of overall transport energy and 89 % of overall transport GHGe while domestic transport is responsible for the remaining 6 % of transport energy and 11 % of transport GHGe (Fig. 2). Transport was an insignificant user of blue water. On a weight basis, 17 % of international transport came by air freight and 83 % by cargo vessel (Fig. S7). Air freight uses 21 times more energy than cargo vessels to travel the same distance and thus even though it is used less, it contributes a disproportionately high amount of energy (56 %) and GHGe (52 %) within international transport (Fig. S7).

Asia exports the largest volumes of aquatic food to the U.S. and overwhelmingly (99 %) uses cargo vessels (Fig. S7). Fresh and frozen shrimp are the largest volume exports from Asia to the U.S. Fresh shrimp is shipped frozen and thawed or “refreshed” at retail), and therefore international transport of shrimp contributes a somewhat smaller amount of energy (7 % to 14 %) and GHGe (5 % to 7 %) compared to products shipped by air. Europe and South America export a large volume by air freight to the U.S., with 53 % and 42 % of their total exports to the U.S., by weight, coming by air (Fig. S7). This is explained by their proximity to the U.S. market and the higher unit prices for fresh forms (Asche and Smith, 2018; Love et al., 2022b), but it also contributes a large share to the overall GHGe of these products.

We explore the impact of air shipping using salmon as an example (Fig. 3). Farmed Atlantic salmon makes up 59 % of global air-freighted aquatic food exports to the U.S., including 74 % and 62 % of air exports

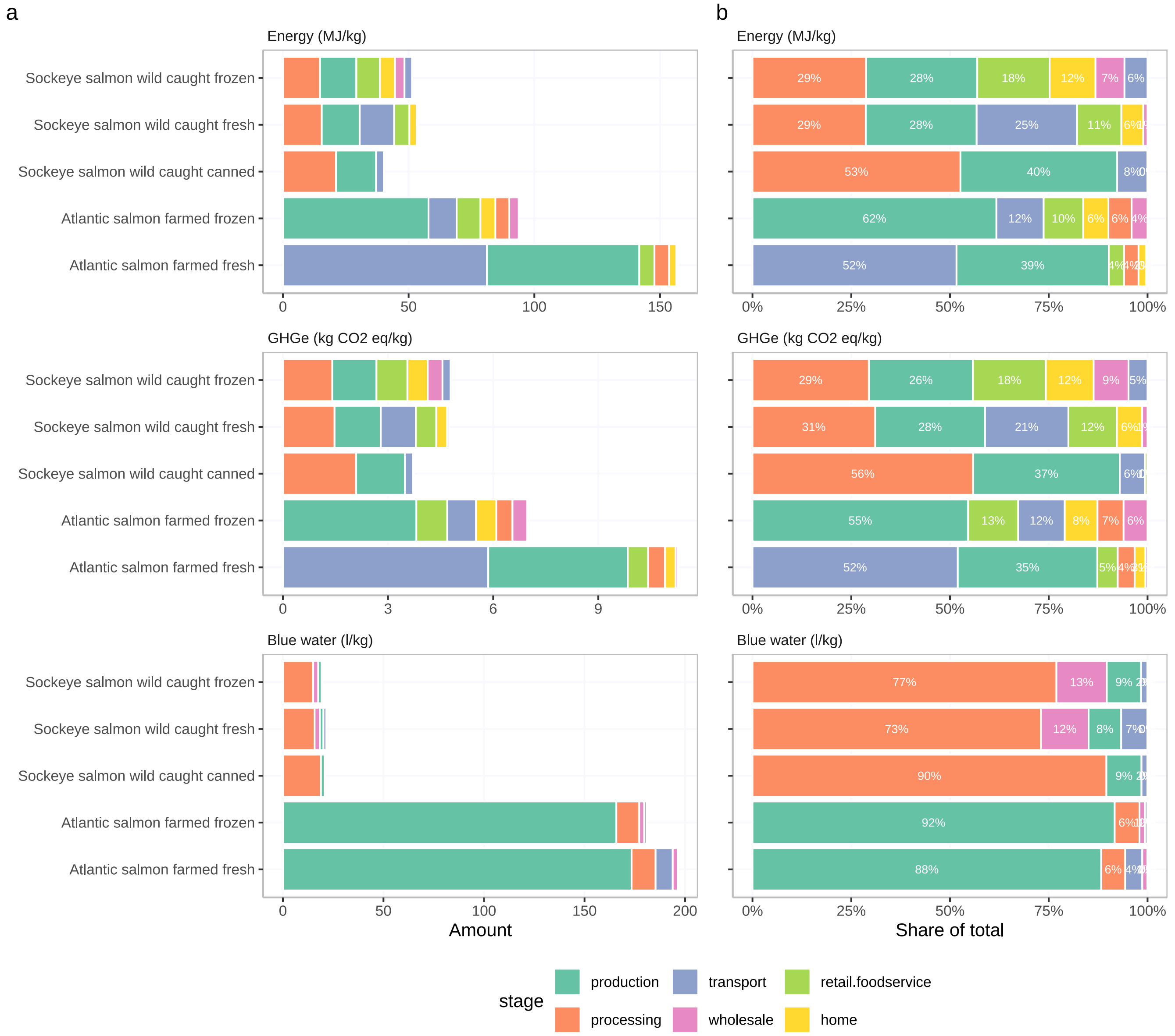

Fig. 3. Comparison of farmed and wild caught salmon. Estimates for a) total and b) share of total energy (MJ/kg), greenhouse gas (GHG) emissions (kg CO_2 eq/kg), and blue water (l/kg) by species, production method, product form, and stage of the supply chain. Estimates include food loss and waste. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from Europe and South America (Fig. S7), making fresh farmed Atlantic salmon the largest contributor to air-related emissions in the U.S. aquatic food supply. Air transport contributes over half of overall energy (53 %) and GHGE (53 %) of farmed Atlantic salmon (Fig. 3), which agrees with previous findings (Ziegler and Hilborn, 2022). Switching from fresh air freighted Atlantic salmon to frozen Atlantic salmon would reduce U.S. consumers' GHGE by 38 % (fresh farmed Atlantic salmon: 11.3 kg CO_2 eq/kg, frozen farmed Atlantic salmon: 7.0 kg CO_2 eq/kg) (Fig. 3). Fresh salmon from Canada and domestic producers are shipped by truck, and will also have a transportation footprint more aligned with frozen seafood (Ziegler et al., 2022). The lowest GHGE of any salmon product was wild caught canned Sockeye salmon (3.7 kg CO_2 eq/kg). although fresh and frozen wild caught Sockeye salmon were only slightly higher with 4.7–4.8 kg CO_2 eq/kg (Fig. 3). From a supply perspective, wild caught salmon stocks are fully exploited and account for 7 % of the salmon consumed in the U.S. with the remaining 93 % being farmed Atlantic salmon.

3.5. Food loss and waste

Approximately 23 % of aquatic food in the U.S. supply chain is estimated to be lost or wasted, including during the supply chain and by consumers (Love et al., 2023). When aquatic foods are lost or wasted they lead to secondary losses of embodied energy and blue water, as well as increased GHGE. We estimated environmental impacts with and without food loss and waste and found that accounting for loss and waste increased overall estimates of energy use by 22 %, GHGE by 24 %, and blue water use by 24 % (Fig. 4a). For example, the average GHGE for all aquatic food was 11.4 kg CO_2 eq/kg without accounting for loss and waste and increased by 24 % to 14.0 kg CO_2 eq/kg when loss and waste was included in the model. Food loss was largest at the production stage (Love et al. 2023). The production stage had the largest percent increase in environmental impacts when loss and waste was included in the estimate (Fig. 4b). By species, accounting for loss and waste increased environmental impacts by 12 % to 41 % (Fig. 4c). These findings suggest that life cycle analyses of aquatic foods that do not include food loss and

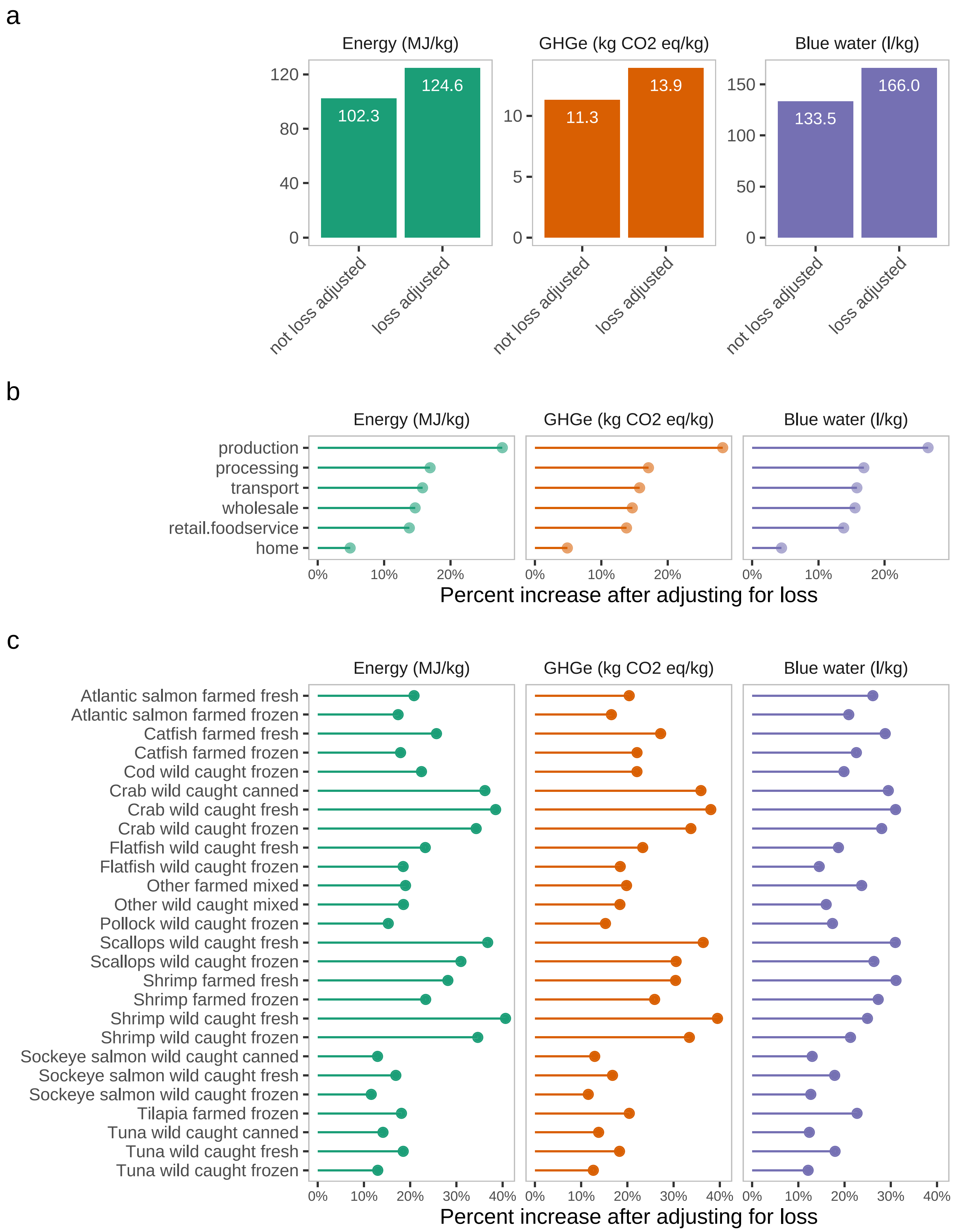

Fig. 4. Comparison of methods to estimate energy (MJ/kg), greenhouse gas emissions (kg CO_2 eq/kg), and blue water (l/kg). a) overall estimates for the U.S. seafood supply with and without adjusting for food loss and waste. Percent increase in estimates after adjusting for food loss and waste reported by b) stage of the supply chain and c) species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waste may significantly underestimate environmental impacts.

3.6. Consumption patterns and preferences influence resource use

Aquatic foods come in a variety of product forms with different environmental impacts. We found that canned forms were significantly lower in energy (65.5 MJ/kg), GHGe (5.6 kg CO_2 eq/kg), and blue water (22.8 l/kg) than fresh or frozen forms (Fig. 5a). This is largely due to canned tuna being the primary canned seafood product consumed in the U.S. and the fact that canned tuna has relatively low energy, GHGe, and blue water use as well as low rates of food loss because it is stable at room temperature. Fresh forms, on average, used more energy than frozen, but counterintuitively, frozen produced more GHGe and used more blue water than fresh forms. This is partly due to inherent differences in how these products are shipped and stored (i.e., fresh products have more energy intensive shipping methods, while frozen forms are maintained for longer periods of time in cold chains), and additionally the species mix differs among fresh and frozen forms (Fig. 5b). These findings suggest that choosing products based solely on their form is not a comprehensive solution for reducing consumer environmental impacts, except in the case of canned products. Instead, species-specific factors must be taken into account.

Fillets are responsible for the use of considerably more resources than whole fish, kilogram for kilogram, because we assign all the impacts from the full weight of the fish to the edible portion typical for U.S. consumers. Edible yield also varies by species, as some fish are easier to debone or have a higher muscle content than others. Consumer preferences for specific species and product forms (and the assumptions researchers make about consumer choices) can significantly impact resource use efficiency.

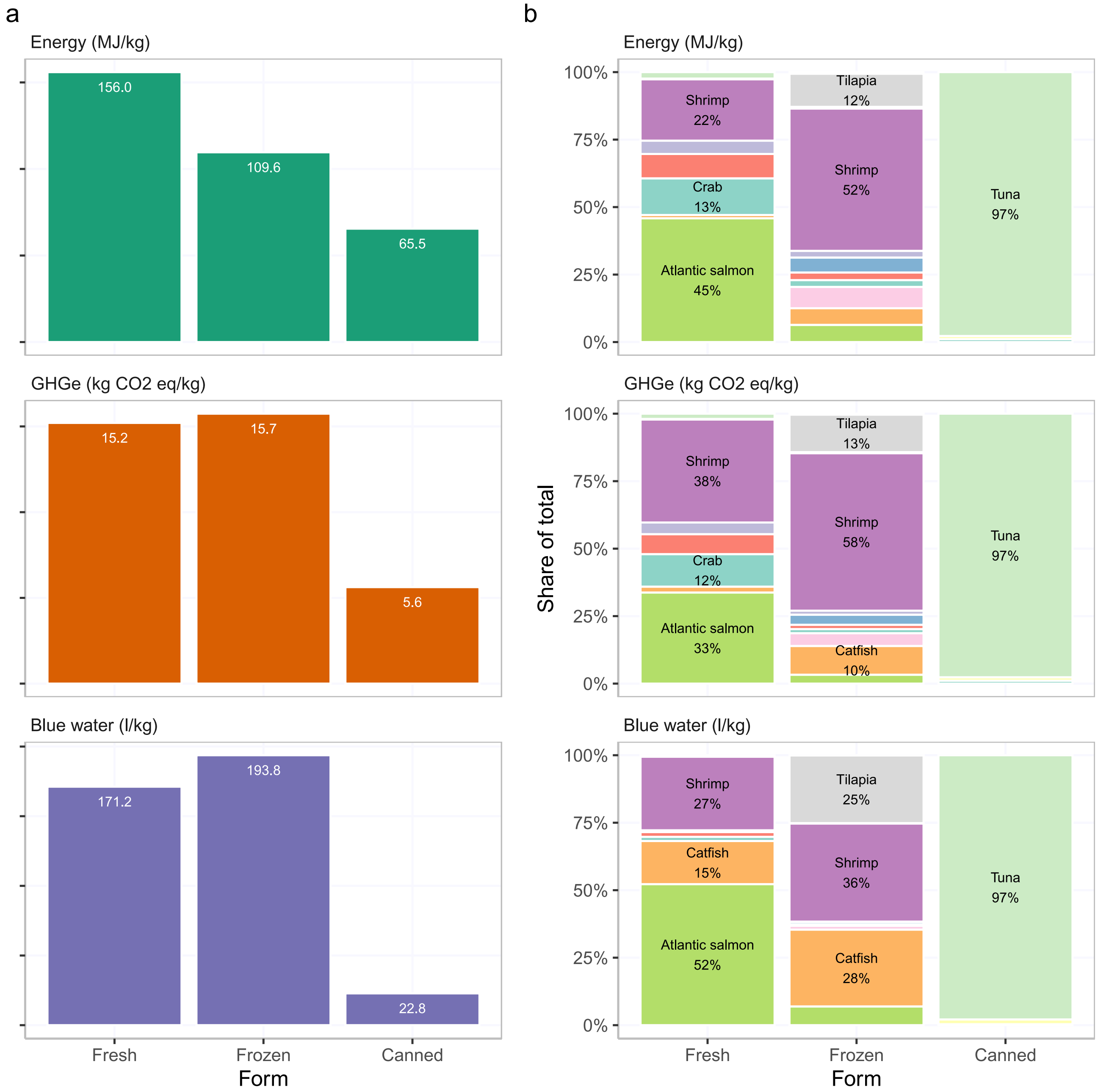

Fig. 5. Energy (MJ/kg), greenhouse gas emissions (kg CO_2 eq/kg), and blue water (l/kg) by product form. Estimates for a) total and b) share of total energy, greenhouse gas emissions, and blue water. b) broken out by species group; values > 10 % are labeled. Estimates include food loss and waste. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.7. Summary

This study provides a comprehensive assessment of resource use and food loss and waste in the U.S. aquatic food system, showing how resource use varies by supply chain stage, species, production methods, form, and mode of transportation. The findings suggest priority leverage points for intervention. For aquatic food production, which was the stage with the highest energy footprint, priorities for intervention include, for aquaculture, improving sustainability of aquaculture fish feeds and technology adoption (Boyd et al., 2020; Kumar et al., 2018); and for capture fisheries, adopting fuel efficient gears, behaviors, and fishery management for capture fisheries (Byrne et al., 2021; Parker et al., 2018). In transporting aquatic food, the study draws attention to the disproportionate energy use for air freighting of fresh aquatic food, indicating need for continued efforts to market high quality frozen and shelf-stable aquatic food to consumers, and increasing growth in regional and domestic aquaculture production to meet demand for fresh fish in the U.S. (Asche et al., 2022b; Love et al., 2022a). It also suggest that regulations that limit domestic aquaculture production due to environmental concerns in the production process (Rubino, 2023) may increase the total environmental cost if this leads to the products being imported and transported by air. Key opportunities for reducing aquaculture water footprints include improving feed conversion ratios, using land-based aquaculture systems that recirculate water, and reducing pond seepage and evaporation. Where feasible, shifts to renewable energy are warranted throughout the aquatic food supply chain (Scroggins et al., 2022).

This study found that 21 % to 23 % of the resources embodied in aquatic foods are discarded via loss and waste, with the greatest embodied resources at the end of the supply chain. Thus, the findings underline calls for prioritizing consumer behavior research, aquatic food management guidance, and upstream strategies to help consumers and retailers, such as portioned packaging and improved preservation. Seafood losses need to be accounted for in life cycle research. Lastly, reflecting the complexity at the heart of the seafood-energy-water nexus, the modeling identifies tradeoffs in resource impacts between interventions, such as those we describe between forms (i.e., fresh vs frozen vs canned). Further data are needed to assist industry stakeholders, policy-makers and advocates in optimizing across systems to address these resource use tradeoffs. The research also informs future life cycle assessment work. While most life cycle studies stop at production, the results underline the need for better accounting of energy and GHGe in post-production stages of the supply chains in life cycle assessment research. We suggest that ‘production through wholesale distribution’ provides a reasonable approximation for energy use in aquatic food supply chains, although complete analyses of the supply chain and consumption are preferred.

Key strengths of the study are its reliance on substantial primary data, both quantitative and qualitative, collected in sectors and enterprises across the supply chains serving the U.S., a rigorously-developed model supported in prior publications, estimation to reflect the entire U.S. aquatic food supply, and incorporation of trade patterns and food loss and waste. This research also has several limitations. Modeling requires many assumptions, and the limited number of data points means results may not appropriately represent practices across enterprises and production systems. Fugitive emissions from refrigerants were not considered in GHGe estimates, although Ziegler found that at the production stage refrigerant leakage accounts for 13 % to 37 % of GHGe in fisheries production (Ziegler et al. 2013) and more refrigerants are also lost in cold chains. Transportation analyses are based on selected locations and may not reflect true distances. Further, we could not account for every source of resource usage. The analysis is based on mainstream U.S. conceptions of edible aquatic food, however, these norms could be expanded to include more whole fish. This study provides the most comprehensive and robust assessment to date of the environmental footprint of the US seafood supply. The findings highlight considerable variation in resource use and GHGe between capture fisheries and aquaculture, and based on production location, product type, and form. The nuances revealed in the analysis point to multiple opportunities to reduce the sector’s footprint. Further, our estimates provide a baseline against which to track the impacts of future efforts to improve environmental outcomes.

Author Contributions.

DCL and MB conceived of the manuscript. DCL, MB, FA, JF, LN, EMN, and RN collected the data. MB, SV and DL analyzed the data. All authors contributed to writing and reviewing the manuscript.

CRediT authorship contribution statement

David C. Love: . **Mark Brown:** Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing. **Silvio Viglia:** Formal analysis, Methodology, Software, Writing – review & editing. **Frank Asche:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing. **Jillian Fry:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Taryn M. Garlock:** Writing – review & editing. **Lekelia D. Jenkins:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing. **Ly Nguyen:** Investigation, Methodology, Writing – review & editing. **James Anderson:** Funding acquisition, Methodology, Writing – review & editing. **Elizabeth M. Nussbaumer:** Investigation, Project administration, Writing – review & editing. **Roni Neff:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – review & editing.

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.

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Appendix A. Supplementary data

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References

Anderson, J.L., Asche, F., Garlock, T., 2018. Globalization and commoditization: the transformation of the seafood market. J. Commod. Mark. 12, 2–8.
Asche, F., Smith, M.D., 2018. Induced innovation in fisheries and aquaculture. Food Policy 76, 1–7.
Asche, F., Eggert, H., Oglend, A., Roheim, C.A., Smith, M.D., 2022a. Aquaculture: externalities and policy options. Reviews in Environ. Economics and Policy. 16 (2), 282–305.
Asche, F., Garlock, T., Camp, E., Guillen, J., Kumar, G., Llorente, I., Shamshak, G., 2022b. Market opportunities for US aquaculture producers: the case of branzino. Mar. Resour. Econ. 37, 221–233.
Bell, T., 2022. John hopkins university seafood energy & water use study in commercial, retail and residential market segments. Frontier Energy – Food Service Technology Center.
Boyd, C.E., D’Abramo, L.R., Glencross, B.D., Huyben, D.C., Juarez, L.M., Lockwood, G.S., McNevin, A.A., Tacon, A.G.J., Teletchea, F., Tomasso Jr, J.R., Tucker, C.S.,

Valenti, W.C., 2020. Achieving sustainable aquaculture: historical and current perspectives and future needs and challenges. J. World Aquac. Soc. 51, 578–633.

Byrne, C., Agnarsson, S., Davidsdottir, B., 2021. Fuel Intensity in Icelandic fisheries and opportunities to reduce emissions. Mar. Policy 127, 104448.

Candel, J., 2022. EU food-system transition requires innovative policy analysis methods. Nat. Food 3, 296–298.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat. Food 2, 198–209.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G.K., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. 56, 456–531.

FAO, 2022a. The State of World Fisheries and Aquaculture 2022. https://doi.org/.

FAO, 2022b. The State of Food Security and Nutrition in the World 2022.

Fry, Jillian P., Rachel E. Scroggins, Taryn M. Garlock, David C. Love, Frank Asche, Mark T. Brown, Elizabeth M. Nussbaumer, et al. 2024. "Application of the Food-Energy-Water Nexus to Six Seafood Supply Chains: Hearing from Wild and Farmed Seafood Supply Chain Actors in the United States, Norway, and Vietnam." *Frontiers in Sustainable Food Systems* 7 (January). https://doi.org/10.3389/fsufs.2023.1269026.

Garlock, T., Asche, F., Anderson, J., Ceballos-Concha, A., Love, D.C., Osmundsen, T.C., Pincinato, R.B.M., 2022. Aquaculture: the missing contributor in the food security agenda. Glob. Food Sec. 32, 100620.

Garlock, T.M., Asche, F., Anderson, J.L., Hilsenroth, J., Lorenzen, K., Pincinato, R.M., Tveteras, R., 2023. Global and regional determinants of diversity in blue foods. Rev. Fish. Sci. Aquacult.. 31 (4), 523–534.

Gaupp, F., Ruggeri Laderchi, C., Lotze-Campen, H., DeClerck, F., Bodirsky, B.L., Lowder, S., Popp, A., Kanbur, R., Edenhofer, O., Nugent, R., Fanzo, J., Dietz, S., Nordhagen, S., Fan, S., 2021. Food system development pathways for healthy, nature-positive and inclusive food systems. Nat. Food 2, 928–934.

Gephart, J.A., Troell, M., Henriksson, P.J.G., Beveridge, M.C.M., Verdegem, M., Metian, M., Mateos, L.D., Deutsch, L., 2017. The 'seafood gap' in the food-water nexus literature—issues surrounding freshwater use in seafood production chains. Adv. Water Resour. 110, 505–514.

Gephart, J.A., Froehlich, H.E., Branch, T.A., 2019. To create sustainable seafood industries, the United States needs a better accounting of imports and exports. Proc. Natl. Acad. Sci. 116, 9142–9146.

Gephart, J.A., Henriksson, P.J.G., Parker, R.W.R., Shepon, A., Gorospe, K.D., Bergman, K., Eshel, G., Golden, C.D., Halpern, B.S., Hornborg, S., Jonell, M., Metian, M., Mifflin, K., Newton, R., Tyedmers, P., Zhang, W., Ziegler, F., Troell, M., 2021. Environmental performance of blue foods. Nature 597, 360–365.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, The Netherlands.

Golden, C.D., Koehn, J.Z., Shepon, A., Passarelli, S., Free, C.M., Viana, D.F., Matthey, H., Eurich, J.G., Gephart, J.A., Fluet-Chouinard, E., Nyboer, E.A., Lynch, A.J., Kjellevold, M., Bromage, S., Charlebois, P., Barange, M., Vannuccini, S., Cao, L., Kleisner, K.M., Rimm, E.B., Danaei, G., DeSisto, C., Kelahan, H., Fiorella, K.J., Little, D.C., Allison, E.H., Fanzo, J., Thilsted, S.H., 2021. Aquatic foods to nourish nations. Nature 598, 315–320.

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., 2011. Global food losses and food waste. FAO.

Halpern, B.S., Cottrell, R.S., Blanchard, J.L., Bouwman, L., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., Kuempel, C.D., McIntyre, P.B., Metian, M., Moran, D.D., Nash, K.L., Többen, J., Williams, D.R., 2019. Putting all foods on the same table: achieving sustainable food systems requires full accounting. Proc. Natl. Acad. Sci. 116, 18152–18156.

Halpern, B.S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J.L., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., Kuempel, C.D., McIntyre, P.B., Metian, M., Moran, D., Nash, K.L., Többen, J., Williams, D.R., 2022. The environmental footprint of global food production. Nat. Sustainability 5, 1027–1039.

Heller, M.C., Willits-Smith, A., Meyer, R., Keoleian, G.A., Rose, D., 2018. Greenhouse gas emissions and energy use associated with production of individual self-selected US diets. Environ. Res. Lett. 13, 044004.

Henriksson, P.J.G., Banks, L.K., Suri, S.K., Pratiwi, T.Y., Fatan, N.A., Troell, M., 2019. Indonesian aquaculture futures- identifying interventions for reducing environmental impacts. Environ. Res. Lett. 14 (12), 124062.

Herrero, M., Thornton, P.K., Mason-D'Croz, D., Palmer, J., Benton, T.G., Bodirsky, B.L., Bogard, J.R., Hall, A., Lee, B., Nyborg, K., Pradhan, P., Bonnett, G.D., Bryan, B.A., Campbell, B.M., Christensen, S., Clark, M., Cook, M.T., de Boer, I.J.M., Downs, C., Dizyee, K., Folberth, C., Godde, C.M., Gerber, J.S., Grundy, M., Havlik, P., Jarvis, A., King, R., Loboguerrero, A.M., Lopes, M.A., McIntyre, C.L., Naylor, R., Navarro, J., Obersteiner, M., Parodi, A., Peoples, M.B., Pikaar, I., Popp, A., Rockström, J., Robertson, M.J., Smith, P., Stehfest, E., Swain, S.M., Valin, H., van Wijk, M., van Zanten, H.H.E., Vermeulen, S., Vervoort, J., West, P.C., 2020. Innovation can accelerate the transition towards a sustainable food system. Nat. Food 1, 266–272.

Hicks, C.C., Gephart, J.A., Koehn, J.Z., Nakayama, S., Payne, H.J., Allison, E.H., Belhbib, D., Cao, L., Cohen, P.J., Fanzo, J., Fluet-Chouinard, E., Gelcich, S., Golden, C.D., Gorospe, K.D., Isaacs, M., Kuempel, C.D., Lee, K.N., MacNeil, M.A., Maire, E., Njuki, J., Rao, N., Sumaila, U.R., Selig, E.R., Thilsted, S.H., Wabnitz, C.C. C., Naylor, R.L., 2022. Rights and representation support justice across aquatic food systems. Nat. Food 3, 851–861.

Hilborn, R., Banobi, J., Hall, S.J., Pucylowski, T., Walsworth, T.E., 2018. The environmental cost of animal source foods. Front. Ecol. Environ. 16, 329–335.

Hoekstra, A.Y., Chapagain, A.K., 2011. Globalization of water: sharing the Planet's freshwater resources. John Wiley & Sons.

Kannan, N., Saleh, A., Osei, E., 2016. Estimation of energy consumption and greenhouse gas emissions of transportation in beef cattle production. Energies 9, 960.

Kim, B.F., Santo, R.E., Scatterday, A.P., Fry, J.P., Synk, C.M., Cebron, S.R., Mekonnen, M. M., Hoekstra, A.Y., de Pee, S., Bloem, M.W., Neff, R.A., Nachman, K.E., 2020. Country-specific dietary shifts to mitigate climate and water crises. Glob. Environ. Change 62, 101926.

Kuemmerle, T., Baumann, M., 2021. Shocks to food systems in times of conflict. Nat. Food 2, 922–923.

Kumar, G., Engle, C., Tucker, C., 2018. Factors driving aquaculture technology adoption. J. World Aquac. Soc. 49, 447–476.

Li, M., Jia, N., Lenzen, M., Malik, A., Wei, L., Jin, Y., Raubenheimer, D., 2022. Global food-miles account for nearly 20% of total food-systems emissions. Nat. Food 3, 445–453.

Love, D.C., Asche, F., Conrad, Z., Young, R., Harding, J., Nussbaumer, E.M., Thorne-Lyman, A.L., Neff, R., 2020. Food sources and expenditures for seafood in the United States. Nutrients 12. https://doi.org/10.3390/nu12061810.

Love, D.C., Asche, F., Gephart, J.A., Zhu, J., Garlock, T., Stoll, J.S., Anderson, J., Conrad, Z., Nussbaumer, E.M., Thorne-Lyman, A.L., Bloem, M.W., 2022a. Identifying opportunities for aligning production and consumption in the U.s. fisheries by considering seasonality. Rev. Fish. Sci. Aquac. 1–15.

Love, D.C., Asche, F., Young, R., Nussbaumer, E.M., Anderson, J.L., Botta, R., Conrad, Z., Froehlich, H.E., Garlock, T.M., Gephart, J.A., Ropicki, A., Stoll, J.S., Thorne-Lyman, A.L., 2022b. An overview of retail sales of seafood in the USA, 2017–2019. Rev. Fish. Sci. Aquacult. 30, 259–270.

Love, D.C., Asche, F., Fry, J., Brown, M., Nguyen, L., Garlock, T.M., Nussbaumer, E.M., Sarmiento, G.L., Tveteras, S., Neff, R., 2024. Fisheries and aquaculture by-products: Case studies in Norway, United States, and Vietnam. Marine Policy 167, 106276.

Love, D.C., Asche, F., Fry, J., Nguyen, L., Gephart, J., Garlock, T.M., Jenkins, L.D., Anderson, J.L., Brown, M., Viglia, S., Nussbaumer, E.M., Neff, R., 2023. Aquatic food loss and waste rate in the united states is half of earlier estimates. Nat. Food 4 (22), 1058–1069.

Mekonnen, M.M., Hoekstra, A.Y., 2012. A global assessment of the water footprint of farm animal products. Ecosystems 15, 401–415.

Naylor, R.L., Hardy, R.W., Buschmann, A.H., Bush, S.R., Cao, L., Klinger, D.H., Little, D. C., Lubchenco, J., Shumway, S.E., Troell, M., 2021. A 20-year retrospective review of global aquaculture. Nature 591, 551–563.

O'Malley, K., Willits-Smith, A., Rose, D., 2023. Popular diets as selected by adults in the United States show wide variation in carbon footprints and diet quality. Am. J. Clin. Nutr. 117, 701–708.

Pahlow, M., van Oel, P.R., Mekonnen, M.M., Hoekstra, A.Y., 2015. Increasing pressure on freshwater resources due to terrestrial feed ingredients for aquaculture production. Sci. Total Environ. 536, 847–857.

Parker, R.W.R., Blanchard, J.L., Gardner, C., Green, B.S., Hartmann, K., Tyedmers, P.H., Watson, R.A., 2018. Fuel use and greenhouse gas emissions of world fisheries. Nat. Clim. Chang. 8, 333–337.

Parker, R.W., Tyedmers, P.H., 2015. Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish Fish. 16 (4), 684–696.

Peeters, P.M., Middle, J., Hoolhorst, A., 2005. Fuel efficiency of commercial aircraft: an overview of historical and future trends, 2005. National Aerospace Laboratory NLR, Amsterdam.

Reisch, L.A., 2021. Shaping healthy and sustainable food systems with behavioural food policy. Eur. Rev. Agric. Econ. 48, 665–693.

Rosegrant, M.W., Ringler, C., Zhu, T., 2009. Water for agriculture: maintaining food security under growing scarcity. Annu. Rev. Environ. Resour. 34, 205–222.

Rubino, M., 2023. Policy consideerations for marine aquaculture in the United States. Reviews in Fishheries Sci. and Aquaculture. 31 (1), 86–102.

Scroggins, R.E., Fry, J.P., Brown, M.T., Neff, R.A., Asche, F., Anderson, J.L., Love, D.C., 2022. Renewable energy in fisheries and aquaculture: case studies from the United States. J. Clean. Prod. 376, 134153.

Shamshak, G.L., Anderson, J.L., Asche, F., Garlock, T., Love, D.C., 2019. U.S. seafood consumption. J. World Aquac. Soc. 50, 715–727.

United States Census Bureau, 2010. Census Regions and Divisions of the United States [WWW Document]. URL https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf (accessed 5.19.20).

United States Census Bureau, 2022. USA Trade [WWW Document]. URL https://usatrade.census.gov/.

Viglia, S., Brown, M.T., Love, D.C., Fry, J.P., Scroggins, R., Neff, R.A., 2022a. Analysis of energy and water use in USA farmed catfish: toward a more resilient and sustainable production system. J. Clean. Prod. 379, 134796.

Viglia, S., Brown, M.T., Love, D.C., Fry, J., Neff, R.A., Hilborn, R., 2022b. Wild caught Alaska sockeye salmon: a case study of the food energy water nexus for a sustainable wild catch fishery. J. Clean. Prod. 369, 133263.

Wakeland, W., Cholette, S., Venkat, K., 2012. Food transportation issues and reducing carbon footprint. In: Boye, J.I., Arcand, Y. (Eds.), Green Technologies in Food Production and Processing. Springer, US, Boston, MA, pp. 211–236.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.

Wheeler, T., von Braun, J., 2013. Climate change impacts on global food security. Science 341, 508–513.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393, 447–492.

Xue, L., Liu, X., Lu, S., Cheng, G., Hu, Y., Liu, J., Dou, Z., Cheng, S., Liu, G., 2021. China's food loss and waste embodies increasing environmental impacts. Nat. Food 2, 519–528.

Ziegler, F., Hilborn, R., 2022. Fished or farmed: life cycle impacts of salmon consumer decisions and opportunities for reducing impacts. Sci. Total Environ. 854, 158591.

Ziegler, F., Winther, U., Hognes, E.S., Emanuelsson, A., Sund, V., Ellingsen, H., 2013. The carbon footprint of Norwegian seafood products on the global seafood market. J. Ind. Ecol. 17, 103–116.

Ziegler, F., Jafarzadeh, S., Hognes, E.S., Winther, U., 2022. Greenhouse gas emissions of Norwegian seafoods from comprehensive to simplified assessment. J. Ind. Ecol.. 26 (6), 1908–1919.