Globalization of wild capture and farmed aquatic foods

Jessica Gephart[1], Rahul Agrawal Bejarano[1], Kelvin Gorospe[1], Alex Godwin[2], Christopher D Golden[3], Rosamond L Naylor[4], Kirsty L Nash[5], Michael L Pace[6], and Max Troell[7,8]

[1]Department of Environmental Science, American University
[2]Department of Computer Science, American University
[3]Department of Nutrition, Harvard T.H. Chan School of Public Health
[4]Department of Global Environmental Policy and Center on Food Security and Environment, Stanford University
[5]Centre for Marine Socioecology, University of Tasmania
[6]Department of Environmental Sciences, University of Virginia
[7]Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences
[8]Stockholm Resilience Centre, Stockholm University

April 29, 2023

Title: Globalization of wild capture and farmed aquatic foods

Authors: Jessica A. Gephart*[1], Rahul Agrawal Bejarano[1], Kelvin Gorospe[1], Alex Godwin[2], Christopher D. Golden[3], Rosamond L. Naylor[4], Kirsty L. Nash[5], Michael L. Pace[6], Max Troell[7,8]

1. Department of Environmental Science, American University, Washington, DC, USA
2. Department of Computer Science, American University, Washington, DC, USA
3. Department of Nutrition, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA
4. Department of Global Environmental Policy and Center on Food Security and Environment, Stanford University
5. Centre for Marine Socioecology, University of Tasmania, Hobart TAS, Australia
6. Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA
7. Beijer Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Stockholm, Sweden
8. Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

*Corresponding author

Abstract

Aquatic foods are highly traded foods, with nearly 60 million tonnes exported in 2020, representing 11% of global agriculture trade by value[1]. Despite the vast scale, basic characteristics of aquatic food trade, including species, origin, and farmed versus wild sourcing, are largely unknown. Consequently, we have a coarse picture of aquatic food consumption patterns[2]. Here, we present results from a new database of species trade and compute consumption for all farmed and wild aquatic foods from 1996-2020. Over this period, aquatic foods became increasingly globalized, with the share of production exported increasing 40%. Importantly, trends differ across aquatic food sectors. Global consumption also increased 33% despite declining marine capture consumption and some regions became increasingly reliant on foreign-sourced aquatic foods. As we look for sustainable diet opportunities among aquatic foods, our findings and underlying database enable greater understanding of the role of trade in rapidly evolving aquatic food systems.

Key words

Aquaculture; Aquatic foods; Fisheries; Globalization; Trade; Seafood

1. Introduction

Aquatic food systems are an important source of human nutrition[3], livelihoods[4], and revenue[1] throughout the world. Aquatic foods also show promise to reduce environmental pressures of food production due to low average resource use and emissions[5]. However, aquatic foods are incredibly diverse, comprising over 2500 marine and freshwater species that are captured and farmed with a range of methods[6]. Consequently, aquatic foods vary widely in their nutrient composition[3] and associated environmental pressures[5]. This has prompted work to identify and support aquatic food systems that improve nutrition, sustainability, and human well-being[7–10]. With 40% of aquatic food production traded internationally[1], trade is central to meeting these objectives.

Trade brings a range of benefits and risks for food security, resilience, and sustainability. Benefits include providing consumers with diverse and out-of-season foods, supplying products at lower prices, stimulating local economic growth, diversifying sourcing in the face of local shocks, and reducing environmental impacts when products are sourced from regions better suited for production[11]. However, risks include accelerating the nutrition transition to unhealthy diets[12], undermining domestic production by suppressing prices[13], exposing local markets to international shocks[14], degrading local environments to meet distant market demand[15,16], and facilitating shifting production to locations with relaxed environmental and labor regulations[17,18].

Which trade-related benefits and risks are experienced, and by who, is context dependent. Unfortunately, our understanding of the distribution of global benefits and risks is limited by low species resolution of global trade data relative to the vast diversity of aquatic foods. Consequently, we only have a coarse picture of basic features of aquatic food trade, including the geographical origin and production method (wild or farmed)[2,19]. Coarse trade data further places profound constraints on understanding aquatic food consumption patterns and therefore the potential role of aquatic foods in sustainable and resilient food systems.

Coarse aquatic food trade data arises from a fundamental mismatch between production and trade data: production from capture fisheries and aquaculture is reported as species or species groups (e.g., *Salmo salar* or *Oncorhynchus spp.*) in terms of live weights whereas trade is reported as commodities (e.g., canned salmon) in terms of product weight, generally without farmed versus wild designations. Converting commodity trade to species trade is difficult because one species can contribute to multiple commodities (e.g., *Salmo salar* can be converted into whole frozen salmon or salmon filets), a single commodity can be made up of multiple species (e.g., salmon filets can be made from *Salmo salar* or *Oncorhynchus tshawytscha*), and a traded commodity can be converted through processing and exported again (e.g. whole frozen salmon processed into salmon filets).

To improve understanding of global aquatic food trade and the associated implications for food security, resilience, and sustainability, we present a new global database of species trade flows for all farmed and wild aquatic foods from across marine and inland waters from 1996-2020. The Aquatic Resource Trade in Species (ARTIS) database consists of over 2400 species/species groups, 193 countries, and over 35 million bilateral records. We estimated species trade flows by modeling each country's conversion of wild and farmed production into commodities, conversion of imported commodities through processing, and apparent consumption. We then connected estimated species mixes and processing of foreign-sourced products to bilateral trade data to disaggregate global flows of aquatic foods. ARTIS improves upon previous efforts by estimating annual species-level trade across production methods and habitats rather than providing an aggregate snapshot of capture and aquaculture trade[20], and by accounting for processing losses and foreign processing[21]. The resulting data and code accompanying this paper will serve as a critical resource for future research.

Using ARTIS, we characterize global farmed and wild aquatic food trade, including all fish and aquatic invertebrate species destined for human consumption. We first detail the evolution of trade in marine and inland capture and aquaculture products, providing new measures of the degree of globalization across aquatic foods. Second, we evaluate how bilateral flows of aquatic foods have shifted since 1996. Finally, we present trends in aquatic food apparent consumption, including shifts in import dependence. Across each of these areas, we contextualize our findings with the implications for food security, sustainability, and resilience.

2. Results

2.1 Trends in aquatic food globalization

Globalization describes the degree of international connectedness, which can be characterized by increasing flows of input, intermediate and final products among countries. Aquatic food exports more than doubled from 1996-2019 (27.7 to 59.5 mil t; Fig 1a). Over that period, both farmed and wild exports increased, though aquaculture grew faster, more than tripling, whereas capture exports grew by 77%. Corresponding with the start of the COVID-19 pandemic, global aquatic food exports declined 4% in 2020 relative to 2019, with a 4% decline in capture exports, but a 3.1% increase in aquaculture exports, highlighting differential impacts by sector (Fig 1a). Despite aquaculture comprising half of aquatic food production, capture fishery products still constitute 60% of exports.

Another measure of the degree of globalization is the share of production exported. Domestic exports increased from 15% to 22% of production between 1996 and 2019, while total exports, which include export of foreign-sourced products, reached

34% of all production in 2019. For comparison, the share of cereal production exported grew from around 10% in the late 1990s to 17% in the 2020s[22]. Increasing marine capture exports despite stagnating production resulted in marine capture products having the greatest share of production destined for export (33% of production) and the largest increases in the share exported (Fig 1b). Aquaculture production more than doubled from 1996 to 2019, but aquaculture exports grew even faster, increasing the share exported (Fig 1b). Despite increases, inland aquaculture still had the lowest share of production destined for export in 2019 (domestic exports represented only 6.7% of production) (Fig 1b). This finding clarifies standing debates about the orientation of aquaculture and export trends suggest a need to consider international markets when crafting nutrition-sensitive policies[23–25].

Globalization exposes countries to external shocks, while also serving as a buffer against local shocks. Recent work on trade characteristics associated with systemic risk to shocks suggests higher exposure when networks are densely connected and concentrated, and when countries are highly dependent on imports[26–28]. By disaggregating aquatic food trade, we can evaluate the structural features of aquatic food trade associated with resilience to shocks. First, we found that aquatic food trade became more connected with the average number of export partners nearly doubling from 1996-2019 (from 21.9 to 41.4; Fig 1c). Marine capture networks are most highly connected, followed by marine aquaculture, with inland capture and aquaculture trade being the least connected.

Since 1996, aquatic food exports have become moderately less concentrated, with only 18 countries comprising 75% of exports in 1996 versus 21 countries in 2019. Compare this with crops where just 7 countries and the EU account for 90% of wheat exports and just four countries accounting >80% of maize exports[22]. Declining concentration is driven by capture fishery exports, whereas aquaculture exports became somewhat more concentrated (Fig 1d). Aquaculture export concentration corresponds to high concentration of aquaculture production in a few regions. Similarly, the concentration of trade for individual species tends to be much higher. Divergent trends in trade features and differences among aquatic food groups suggests differences in the degree and types of trade shock risks across aquatic foods. Such differences were observed in responses to COVID-19[29]. Understanding risk to shocks across foods is a priority research area, as trade-related risks and aquatic food systems are underrepresented in the food systems shock literature[14].

Though aquatic food production, distribution, and consumption remain highly uneven[30], we found declining import concentration, with 12 countries comprising 75% of imports in 1996 versus 21 countries in 2019 (Fig 1e). More dispersed import patterns are likely associated with growing populations and expanding middle classes and urbanization, particularly in low- and middle-income countries, which often drive increasing aquatic food demand[1,31]. Yet, the relationship between aquatic food demand and income varies across aquatic foods, with demand generally increasing with income for higher quality fish but falling for lower quality fish[31].

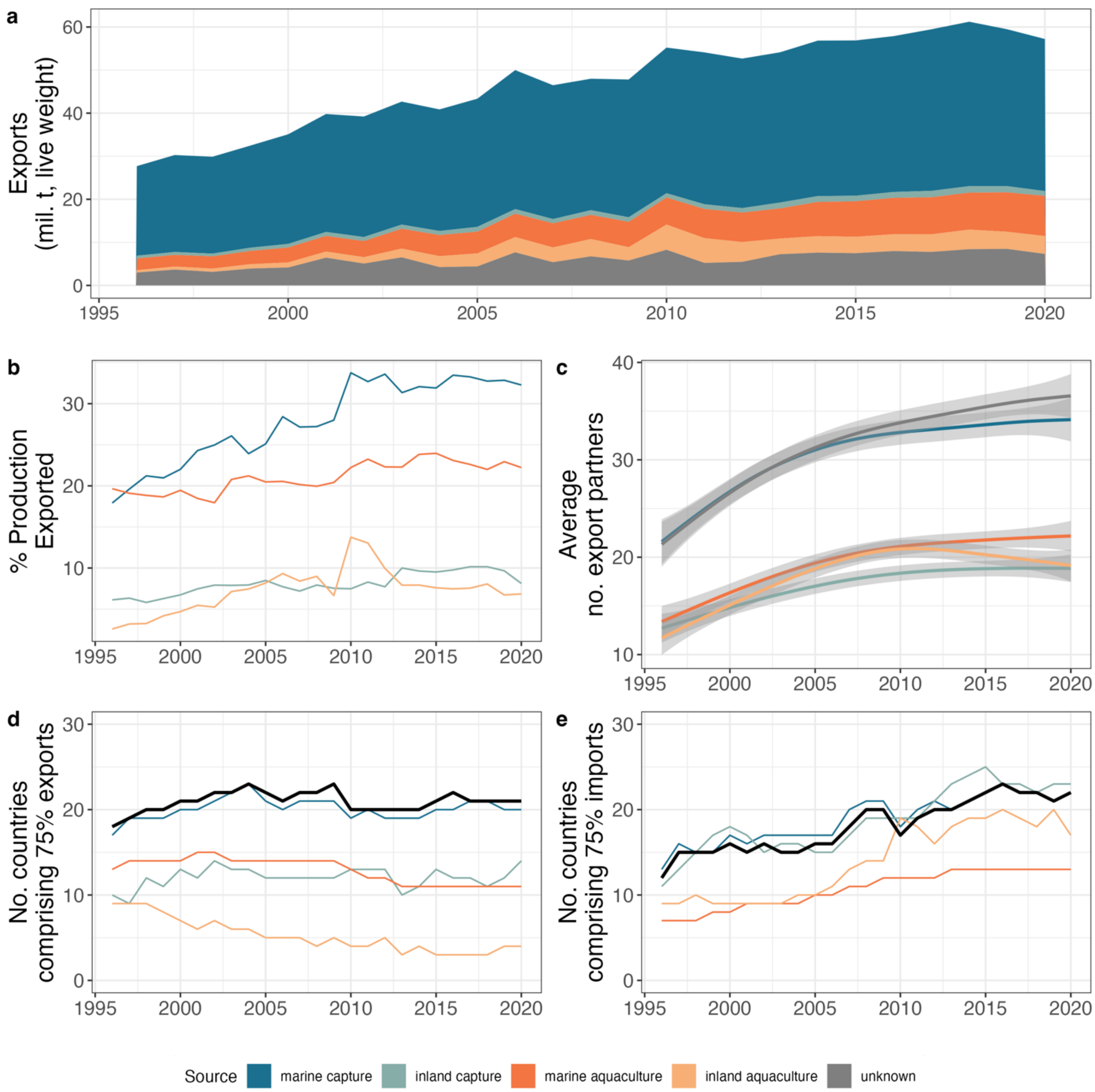

Figure 1: Increases in global export of aquatic foods. a) Exports of global marine and freshwater aquaculture and fishery products (t live weight equivalent) from 1996-2019. b) Percent of global marine and freshwater aquaculture and fishery production exported, excluding re-exports. c) Average number of export partners (out degree) by production method and environment. d) Number of countries comprising 75% of global exports by production method and environment with the global total in the black line. e) Number of countries comprising 75% of global imports by production method and environment with the global total in the black line.

2.2 Shifts in global flows of aquatic foods

Given the geographic patchiness of capture and aquaculture production, trade helps meet aquatic food demand in many countries. Aquatic food imports are especially important where per capita demand is rising, aquaculture is limited, wild fishery catch is stagnant, and where aquatic foods play an important nutritional role. Corresponding to the geographical variability, we find the top importers, exporters, and bilateral flows to differ by habitat and farmed versus wild source, underscoring the importance of disaggregating trade (Fig S1-3). For example, Asia and Europe, and to a lesser extent, North America recently dominated marine capture and aquaculture trade networks whereas Asia dominates all inland aquatic food trade (Fig S1).

At the country level, although some countries rank among the top traders across all production methods, such as China for exports and China and the United States for imports, many countries are only top traders for one. China and Russia are the top marine capture aquatic food exporters, with China and the United States as the top importers (Fig S2-3). Meanwhile, Norway and Chile rank highest in marine aquaculture exports, with the United States and Japan leading imports (Fig S2-3). Inland aquatic food trade is dominated by aquaculture, with the highest exports from Vietnam and China and highest imports by the United States, Japan, and South Korea (Fig S2-3). In general, inland production is oriented more toward domestic consumption and what is exported tends to stay within the region, particularly within Asia (Fig 2; Fig S1).

Intraregional trade is generally higher than interregional trade due to shorter transport distances, historical ties, patterns of aquatic food preferences and established regional trade agreements[32]. We find this pattern largely holds for aquatic food trade as intraregional trade is the highest for Asia, Africa, and Europe (Fig 2b). However, Oceania and North and South America all have the largest export to Asia (Fig 2b). Since 1996, trade increased or remained approximately stable between nearly all regional trade pairs, other than within North America (Fig S4). At the country level, trade increased between two thirds of trade pairs. Despite trade increasing with partners across the globe, trade within Asia, Europe and Africa grew faster. The largest average annual growth increases occurred for trade within Asia and Europe, followed by trade between Europe and Asia (Fig 2b; Fig S4). Our trade estimates are ultimately from reported trade and therefore do not capture informal and unreported trade networks. Though estimated unreported trade is not globally available, it can be significant, especially for neighboring countries. For example, informal exports from Benin to Nigeria are estimated to be more than five times the formal exports[33]. Including informal trade would therefore likely strengthen intraregional trade patterns.

Increasing global trade, along with distant water fishing, drive an expanding divide between aquatic food production and consumption[34]. Complex international supply chains pose a challenge for traceability, raising sustainability concerns, including risk of mislabeled[35] and illegally sourced[36] products entering markets. We find increasing volumes of products moving through intermediate countries, either in transit or imported for processing and re-exported, which poses a traceability challenge (Fig S5). Certification and import monitoring schemes represent two tools aimed at improving traceability, and ultimately, sustainable sourcing. However, evidence of the effectiveness of aquatic food supply chain transparency initiatives is mixed[37]. Our findings on increasing globalization across the aquatic food sector underscores the importance of evaluating the effectiveness and social impacts of these sustainability tools across a range of settings, while the ARTIS database enables future work on this topic.

Across regions, Europe and North America have the highest net imports while South America has the highest net exports (Fig 2a). Least developed countries collectively are net exporters of aquatic foods across all production methods, with net exports more than tripling between 1996 and their 2018 peak (Fig S6). Least developed country net exports are dominated by marine capture products and transfer of aquatic foods from least developed countries are likely even higher when catch by distant water fleets are considered. Net exports of aquatic foods may be economically beneficial to least developed countries where high value species are exported and revenue used to purchase other foods[38]. However, economic and political barriers inhibit wealth-based benefits from being realized[30,39]. Further, recent work exploring movement of nutrients derived from fisheries suggests international trade is driving redistribution of essential micronutrients from areas of high deficiency in middle- and low-income countries to developed nations with greater nutrient security[40].

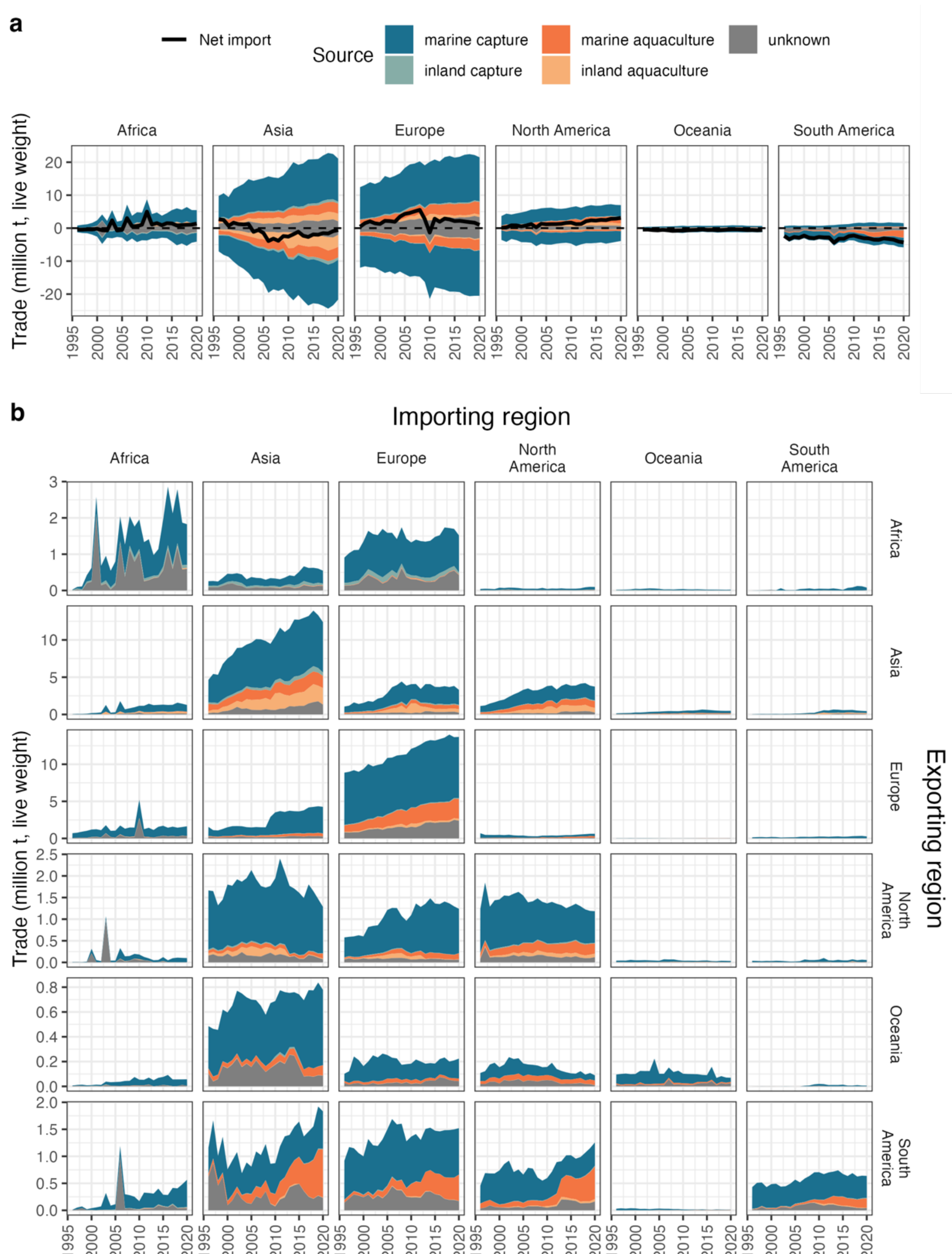

Figure 2: Regional trade flows by production source (habitat and method). a) Total imports (positive) and exports (negative) colored by source, with net import trend in black. b) Bilateral flows colored by production source with exporting region along the rows and importing region along the columns. Values represent million tonnes in live weight equivalents. Note the y-axis scale differs for each row.

2.3 Aquatic food consumption

Since direct measurements of human food consumption (e.g., dietary intake) are not collected globally, it is often represented by apparent consumption. Apparent consumption is calculated as production plus imports minus exports and waste. Trade is therefore central to estimating consumption and has historically limited understanding of aquatic food consumption patterns. By estimating species level trade, we estimate apparent consumption of aquatic foods by species/species group, production method, and geographical origin.

Globally, annual aquatic food apparent consumption increased from 15.1 kg per capita in 1996 to 19.7 kg per capita in 2019 (Fig 3a). Our estimates are slightly lower than FAOSTAT[41], which reports global aquatic food consumption at 15.6 kg/capita/year in 1996 and 20.7 kg/capita/year in 2019. We found aquatic food consumption increased across all regions outside of North America, which was relatively stable, and South America, where aquatic food consumption declined 33.1%% (Fig 3b). Global increases were driven by inland and marine aquaculture, which increased by 164% (from 2.43 kg/capita/year in 1996 to 6.43 kg/capita/year in 2019) and 69.7% (from 2 kg/capita/year in 1996 to 3.39 kg/capita/year in 2019), respectively. Meanwhile, inland capture consumption grew from 0.65 kg/capita/year in 1996 to 0.81 kg/capita/year in 2019, while marine capture consumption declined 14.7% (from 9.66 kg/capita/year in 1996 to 8.25 kg/capita/year in 2019). Nevertheless, capture still makes up 45% of global aquatic food consumption, with its contribution to regional aquatic food consumption ranging from 71% in Oceania to 36% in Asia, where farmed consumption overtook wild consumption in 2003.

Estimating the foreign versus domestic source of consumption requires identifying the share of production retained in the country and tracking products that undergo foreign processing but are imported again. By estimating the source of traded aquatic foods, we can therefore track changes in reliance on foreign-sourced products. Globally the share of foreign-sourced consumption increased modestly, from 22% in 1996 to 25% in 2019 (Fig 3c). However, patterns vary greatly across regions with countries in Asia and South America dominated by domestic supply (14% and 25% foreign in 2019, respectively), but countries in Europe dominated by foreign supply (73% foreign in 2019) in 2019 (Fig 3d). High reliance on foreign-sourced foods can pose a food security risk[42,43], though it is not clear the extent to which these risks exist across aquatic foods. Nevertheless, countries have enacted policies to protect domestic supplies, including developing food stocks and subsidizing domestic food production[44]. The United States previously used foreign dependence on aquatic foods as motivation for a suite of policy changes to boost domestic production, including expanding aquaculture and opening marine protected areas to fishing[2].

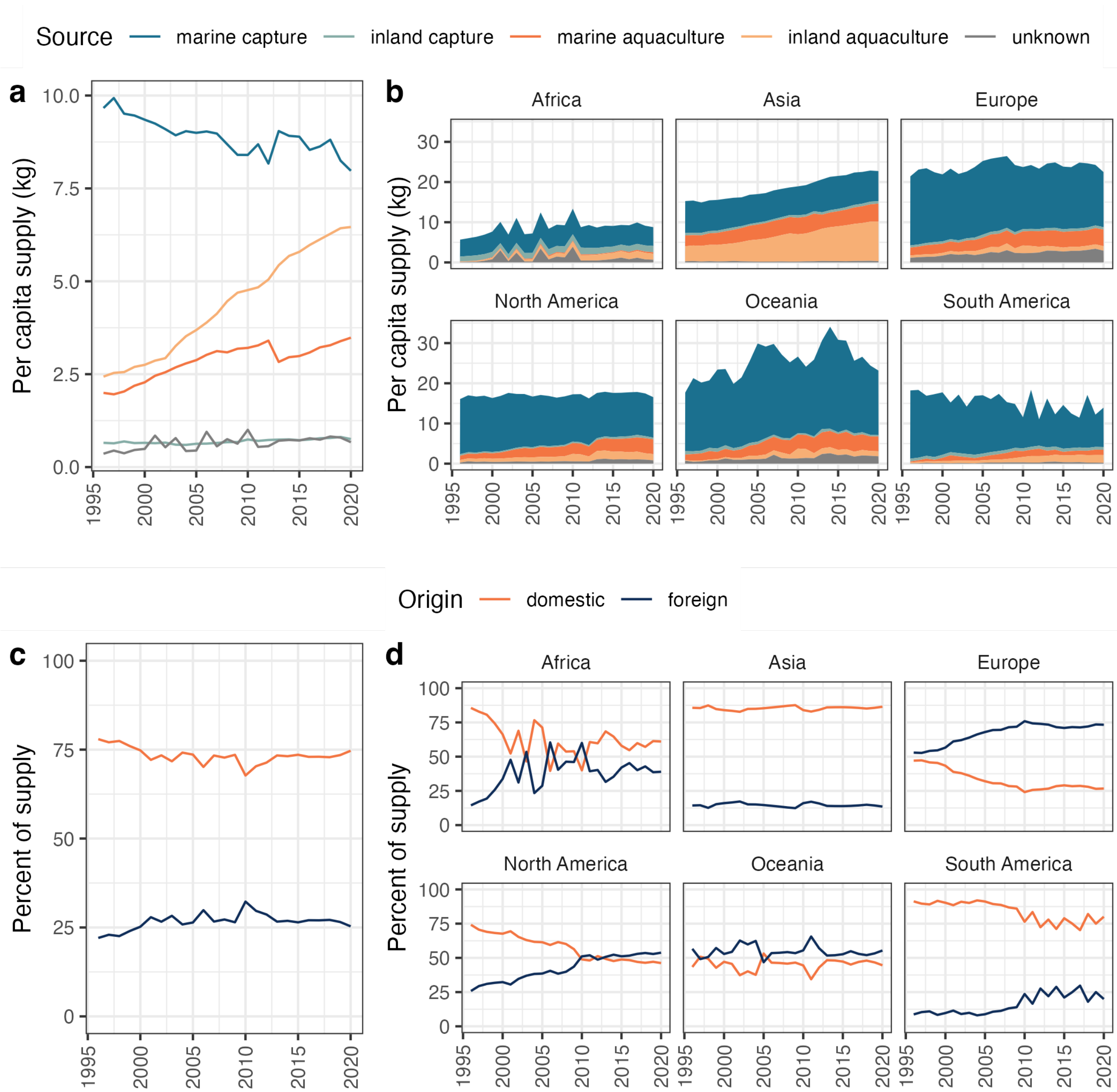

Figure 3: Aquatic food apparent consumption (supply) trends and regional patterns. a) Global aquatic food apparent consumption by production source over time. b) Regional aquatic food apparent consumption by production source over time. c) Global aquatic food domestic versus foreign sourcing over time. d) Regional aquatic food domestic versus foreign sourcing over time. Here, domestic refers to aquatic foods produced by the consuming country and foreign refers to aquatic foods produced by a different country.

3. Conclusion

Aquatic foods have become increasingly globalized. From 1996 to 2019, the share of production exported increased by 40% and the volume and number of trade partnerships approximately doubled. However, trade patterns and trends differ across aquatic food groups, underscoring the value of species-resolved trade data. Marine capture remains the most highly globalized group, but aquaculture trade is growing faster. These trade patterns reflect major trends within the industry, including the rise of foreign processing and growth of aquaculture.

Aquatic food trade increased for nearly all regional pairs and two thirds of all country pairs, but intraregional trade generally remains greater than interregional trade. We found that intraregional trade is particularly strong for aquaculture. Relatedly, we show that inland aquaculture is oriented towards domestic consumption, though the share of production exported increased across all aquatic food groups. Understanding retention and foreign flow of aquatic foods and their associated nutrients is central to current work on equity and justice within blue food systems. Consequently, this information is central to monitoring the progress of nutrition-sensitive policies and for crafting policies that appropriately reflect the global nature of aquatic foods.

We showed that global per capita aquatic food consumption increased from 14 kg/capita/year in 1996 to 17.7 kg/capita/year in 2019 despite declining consumption of marine capture aquatic foods. Globally, the percentage of foreign-sourced supply increased, though regions vary greatly in their foreign dependence, from 9% in Asia to 65% in Europe.

The increasingly globalized aquatic food system poses both challenges and opportunities for food security, sustainability, and resilience. Our work illuminates the evolution of farmed and wild aquatic food trade over the past 24 years, a period of rapid change for the sector. Further, the ARTIS database presented lays the foundation for answering pressing questions about the role of trade in meeting global food system goals.

Methods

To estimate the aquatic food species trade network, we compiled and aligned data on fishery and aquaculture production, live weight conversion factors, and bilateral global trade. The data span the globe and encompass decades of changes in country and species names and product forms. Over 4000 live weight conversion factors were compiled and matched to 2000+ farmed and wild capture aquatic species which in turn were matched to 900+ traded seafood product descriptions. Though we include nonfood (e.g., fish meal, bait, and ornamental trade) production and trade in the database, we exclude this from the analysis of aquatic food production and consumption. We also exclude mammals, reptiles, fowl, or seaweeds, along with co-products (e.g., caviar, shark fins, and fish meat) to avoid double counting, from the model and resulting database.

Species trade flow estimates occur in two steps. First, we take a mass balance approach, where each country's seafood exports must equal the domestic production, plus imports, minus domestic consumption, after accounting for processing losses. For each country, we estimate the proportion of seafood production going into each possible commodity, the proportion of each imported commodity processed and exported, and the domestic consumption of each commodity. We then use these estimates with bilateral trade data to solve for the global species flows. This approach substantially improves upon previous efforts by estimating species-level trade, covering all production environments (marine and freshwater) and production methods (farmed and wild caught), and including the processing and export of imported products.

Data

Production

Aquatic resource production comes from the Food and Agriculture Organization (FAO), which provides national capture and aquaculture production[6]. The Food and Agriculture Organization provides annual capture and aquaculture production data for around 240 countries, territories, or land areas from 1950 to 2020. The FAO data reports production in tonnes (live weight equivalent) of around 550 farmed and 1600 wild capture species and species groups. FAO production data consists primarily of official national statistics, with some verifiable supplemental information from academic reviews, consultant reports, and other specialist literature. Data reported by nations are checked by the FAO for consistency and questionable values are verified with the reporting offices. When countries fail to report production, FAO uses past values to estimate production. For the purposes of this analysis, we do not distinguish between nationally reported, and FAO estimated values.

According to the Coordinating Working Party on Fishery Statistics, catch and landings should be assigned to the country of the flag flown by the fishing vessel irrespective of the location of the fishing. This means that production resulting from a country operating a fishing vessel in a foreign country's territory should be recorded in the national statistics of the foreign fishing vessel. However, if the vessel is chartered by a company based in the home country or the vessel is fishing for the country under a joint venture contract or similar agreement and the operation is integral to the economy of the host country, this does not apply. Consequently, our estimates of source country generally represent who harvested or caught the aquatic resource regardless of where it was produced. In cases of exceptions related to select chartered foreign vessels, joint ventures, or other similar agreements, catch by a foreign vessel but reported by the host country may not match trade reporting if catch does not move through the customs boundary. These instances generate excess apparent consumption.

Bilateral trade data

We use the CEPII BACI world trade database, which is a reconciled version of the UN Comtrade database[45]. Trade data are reported to the UN by both importers and exporters following the Harmonized System (HS) codes. The HS trade code system organizes traded goods into a hierarchy, with the highest level represented by two-digit codes (e.g., Chapter 03 covers "Fish and Crustaceans, Molluscs and Other Aquatic Invertebrates"), which are broken down into 4-digit headings (e.g., heading 0301 covers "Live fish"), which are then subdivided into 6-digit subheadings (e.g., subheading 030111 covers "Live ornamental freshwater fish"). National statistics offices may further subdivide HS codes into 7- to 12-digit codes but since these are not standard across countries, the HS 6-digit codes are the most highly resolved trade codes available globally. HS codes are administered by the World Customs Organization, which updates the codes every five years. HS versions can be used from their introduction through the present, meaning that the HS 2002 version provides a time series of trade from 2002 to the present whereas the HS 2017 version only provides a time series back to 2017. Notably, HS version 2012 included major revisions to the HS codes relevant to fisheries and aquaculture products.

CEPII reconciles discrepancies in mirror trade records, which occur in around 35% of observations (for all traded commodities), by first removing transportation costs and using a weighting scheme based on each country's reporting reliability to average discrepancies in reported mirror flows. BACI data focuses on trade flows between individual countries since 1994 and therefore drops flows within some groups of countries (e.g., Belgium-Luxembourg) to ensure consistent geographies. The resulting data set covers trade for over 200 countries and 5,000 products. Further details on the BACI data set are available in[45]. While BACI resolves many data issues contained in the raw UN Comtrade database, it does not correct for all implausible trade flows, which can especially arise if one country misreports a value and the partner country does not report a value[46]. Further, there are instances where one country reports on trade that is optional to report, and the partner country does not. Here, we do not identify and reestimate any values reported in BACI. Excessively large exports will generally result in high error terms, while high imports will result in high apparent consumption.

Trade statistics are managed by each territory and generally guided by the Kyoto Convention. For the purposes of trade data reporting, imports and exports represent all goods which add or subtract, respectively, from the stock of material resources within an economic territory, but not goods which merely pass through a country's economic territory. The economic territory generally coincides with the customs territory, which refers to the territory in which the country's custom laws apply. Goods which enter a country for processing are included within trade statistics. Fishery products from within the country, the country's waters, or obtained by a vessel of that country are considered goods wholly produced in that country. Catch by foreign vessels and catch by national vessels on the high seas landed in a country's ports are recorded as imports by the country the products are landed in and as exports by the foreign nation, where economically or environmentally significant. For further trade statistic guideline details, see[47].

Live weight conversions

Global trade data is reported in terms of the product weight. To convert from product weight (i.e., net weight) to the live weight equivalent, a live weight conversion factor must be applied for each HS code. Live weight conversion factors are sourced from the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA)[48], along with various national and international governmental report values. EUMOFA data reports live weight conversion factors by CN-8 codes, so the mean of the live weight conversion factors falling within each HS 6-digit code are used. The EUMOFA data assigns products primarily destined for industrial purposes (e.g., fish meal and fish oil), co-products (e.g., caviar) and live trade a value of zero. In this analysis, co-products retained a live weight conversion factor value of zero to avoid double counting, but live animal trade was assigned a live weight conversion factor of 1 and fish meal and fish oil was assigned an average value of 2.98[49]. Data compiled from national and international reports were categorized into taxa types (mollusks, crustaceans, fishes, and other aquatic invertebrates), FAO ISSCAAP groups, species or taxon name, type of processing, and country of processing.

Live weight conversion factors applied to trade data introduce a source of uncertainty and error due to uncertainty in conversion factors is not reported and a single live weight conversion factor is often presented per code, regardless of the species or region of origin. This is a limitation given that there are geographical and temporal variation in live weight conversion factors due to differences in processing technology. Despite this limitation, EUMOFA data offers better documentation and alignment with HS commodity codes than other live weight conversion factor data sources[2] and is updated annually, providing documentation for changes in live weight conversion factors. Additionally, by supplementing the EUMOFA data with the other reported values we can better capture specific species processing into various product forms and some regional variability.

All conversion factors were reported as live weight to product weight ratios. These conversion factors were mapped onto possible species to commodity or commodity to commodity conversions, described below. For commodity-to-commodity conversions, we estimate the conversion factors (i.e., processing loss rate) as the additional mass lost when converting from the live weight to the original product form relative to converting from live weight to the processed product form. This can be calculated as the live weight conversion factor for the original product form divided by the live weight factor for the processed product form. We assume that mass cannot be gained through processing and therefore impose a maximum value of one to this ratio.

Seafood production and commodity conversion

For each country-year-HS version combination, we estimate the proportion of each species going into each commodity and the proportion of each imported commodity processed into each other commodity. Each species can only be converted into a subset of the commodities. For example, Atlantic salmon, *Salmo salar*, can be converted into whole frozen salmon or frozen salmon filets, but cannot be converted to a frozen tilapia filet. Similarly, each commodity can only be converted to a subset of other commodities through processing. For example, whole frozen salmon can be processed into frozen salmon filets, but not vice versa and neither salmon commodity can be converted to a tilapia commodity through processing. Defining possible conversions restricts the solution space to realistic results and improves estimation by reducing the number of unknowns. We describe this assignment process in detail below.

Taxonomic group to commodity assignment

Species production to commodity assignment is a many-to-many matching problem, wherein one commodity can consist of multiple species and one species can be converted to multiple commodities. All taxonomic names reported in the FAO production data were matched to HS 6-digit codes based on the code descriptions and HS system hierarchy.

The first matching step required dividing all taxonomic groups into the broad commodity groups at the 4-digit level (fish, crustaceans, molluscs and aquatic invertebrates). Within each of these groups, taxonomic groups were matched based on 6 types of matching categories:

1. Explicit taxa match - Scientific names are matched based on taxonomic information provided in the code description
2. NEC match - All remaining unmatched species within the 4-digit level are assigned to the “not elsewhere considered” (NEC) code

3. NEC by taxa match - When a code description signifies an NEC group, but limits this based on a taxonomic category (e.g., Salmonidae, N.E.C.), the NEC grouping occurs at this level, rather than the broad NEC match
4. Broad commodity match - Only the broad taxonomic groups inform this assignment since no further taxonomic information is provided
5. Aquarium trade match - Assigned to ornamental species trade based on species found in the aquarium/ornamental trade[50]
6. Fishmeal - Assigned to fishmeal codes if at least 1% of production goes to fishmeal production globally during the study period based on the end use designation from Sea Around Us production data[51]. Although an estimated 27% of fishmeal is derived from processing by-products[1], the species, geographical, and temporal variation in that estimate is currently unknown. Consequently, fishmeal is currently treated as sourced from whole fish reduction. This does not affect the total trade or trade patterns of fishmeal but does result in an overestimate of the proportion of production going to fishmeal in cases where by-products are used.

After all species are matched to the appropriate HS codes, we use the list of species to define codes as inland, marine, diadromous, or mixed. Higher order taxonomic groups are then only matched with HS codes that include their habitat. For example, production of inland *actinopterygii* is matched with codes that include inland species that fall within *actinopterygii*, but not with exclusively marine codes, even if they contain species that fall within *actinopterygii*.

Commodity to commodity processing assignment

As with the species to commodity assignment, the commodity-to-commodity assignment is a many-to-many data problem. Here, one commodity can be processed into multiple other commodities (i.e., frozen salmon can be processed into salmon filets or canned salmon), which also means one commodity could have come from multiple other commodities. To create these assignments, we established rules for which product transformations are technically possible. First, a product cannot transfer outside of its broad commodity group (e.g., fish, crustaceans, mollusc, aquatic invertebrate). Second, where a more refined species or species group was given (e.g., tunas, salmons, etc.) a product cannot be transformed outside that group. Third, products are classified in terms of their state (e.g., alive, fresh, frozen, etc.) and presentation (e.g., e.g., whole, fileted, salted/dried/preserved meats, reductions such as fish meal and fish oil, etc.) and cannot be converted into less processed forms (e.g., frozen salmon filets cannot turn into a frozen whole salmon).

Country standardization and regions

The FAO production and BACI trade datasets do not share the same set of countries and territories. For the production and trade data to balance, it is important for the set of territories falling under a given name to align across the datasets. To avoid instances where, for example, production is reported under a territory, but trade is reported under the sovereign nation, we generally group all territories with the sovereign nation. As countries gain independence, they are added as a trade partner in the database.

Network Estimation

Estimating species bilateral trade flows occurs in two steps: first, solving the national production-trade mass balance, and second, converting reported commodity trade flow estimates to species trade flow estimates based on the estimated species mix going into each domestic and foreign exported commodity.

National mass-balance

We start with the fact that exports must equal production and imports, minus consumption. Since exports are reported as commodities, we solve this mass balance problem in terms of commodities. Production data are reported for each species, so we estimate the elements of a matrix that represents the proportion of production going into each commodity. Since an imported commodity can be processed and exported as a different commodity, we also estimate the proportion of each import being converted into a different commodity. Then for a given country,

$$e = V_1 \circ X \cdot p + V_2 \circ W \cdot g - c + \epsilon$$

If n is the number of species and m is the number of commodities, then: V_1 is a sparse $(m \times n)$ matrix with product conversion factors corresponding to the unknowns in X; X is a sparse $(m \times n)$ matrix of the proportion of each species in each commodity; p is a vector of domestic species production $(n \times 1)$; V_2 is a sparse $(m \times m)$ matrix with product conversion factors corresponding to the entries of W; W is a $(m \times m)$ matrix of the processed imported commodities; g be a vector of imports $(m \times 1)$, c is a vector of domestic consumption $(m \times 1)$, and; ϵ is a vector of error terms $(m \times 1)$.

We compiled reported values for V_1, V_2, e, p and g, and estimate the entries of X, W, c, and ϵ. We first converted this problem to a system of linear equations. Using the property that $vec(ABC) = (C^T \otimes A)vec(B)$, we can create $A_b = (y^T \otimes D_m)D_V$, where D_m is a diagonal matrix of ones, with dimension m and D_V is a diagonal matrix with the elements of $vec(V)$. The vector of unknowns is then $x_b = vec(Z)$. We then solve this system of equations with a quadratic optimization solver such that the mass balance equalities are satisfied, trade codes with higher species resolution in X are prioritized, the elements of X, W, and c are otherwise relatively even (i.e., we assume an even distribution of production among commodities unless the data suggests otherwise), that ϵ is as small as possible (i.e., minimize the error), and all unknowns are greater than or equal to zero.

Positive error terms represent situations where reported production and imports cannot explain exports. This can occur due to under- or un-reported production or imports, over-reporting of exports, errors in the live weight conversion factors, or inconsistencies in the year production and trade are attributed to.

We solve the mass-balance problem for each country-year-HS version combination using the *Python* package "solve_qp." The estimated species mixes in national production (X), processing of imports (W) and the error term (ϵ) are passed to the next stage of the analysis.

Converting the product trade network to a species trade network

First, we compute the mix of species going into each trade code for each country's domestic exports. To do this, we reweight X so it represents the proportion of each species in each code rather than the proportion of production of a species going into each product. Each country's estimated X matrix is multiplied by p to get the mass of each species in each commodity. The total mass of each commodity is found by summing all the species volume grouped by commodity and the proportion of each species within a commodity is then calculated by dividing all volumes by their respective commodity mass totals.

Each country's exports can be sourced from domestic production, imported products that are subsequently exported, with or without processing (i.e., foreign exports), or from an unknown source (i.e., error exports). Since the mix of these sources cannot be derived from the mass balance equation alone, we calculate a range for sourcing following[52]. We calculate the maximum possible domestic exports by taking the minimum between the domestic production and total exports. Similarly, we calculated the maximum volume of exports sourced from imports, by taking the minimum between each product's imports (accounting for processing estimated by W) and exports. The minimum domestic exports are calculated as the minimum between production and the difference in exports and the maximum calculated foreign exports, with the remainder as error exports (minimum foreign exports are calculated in an analogous way). The above results represent midpoint estimates.

$$max\ domestic\ exports\ =\ min(domestic\ production, total\ exports)$$

$$max\ foreign\ exports\ =\ min(imports, total\ exports)$$

$$min\ domestic\ exports\ =\ min(domestic\ production, total\ exports\ -\ max\ foreign\ exports)$$

$$min\ foreign\ exports\ =\ min(imports, total\ exports\ -\ max\ domestic\ exports)$$

$$midpoint\ domestic\ exports\ =\ \frac{max\ domestic\ exports\ +\ min\ domestic\ exports}{2}$$

$$midpoint\ foreign\ exports = \frac{max\ foreign\ exports + min\ foreign\ exports}{2}$$

For these three estimates (maximum, minimum and midpoint) we calculate the domestic and foreign weights by dividing domestic export values and foreign export values by total export. We then distribute each country's exports into domestic, foreign and error exports by multiplying exports by domestic, foreign and error proportions (Fig S8). For each export source, we apply a different species mix to each HS code based on the estimated source country. For domestic exports, we use the exporting country's estimated X matrix (Fig S9). For error exports, the geographical origin is unknown and may arise from unreported production, so we cannot meaningfully assign a species mix to the code. Consequently, we identify the lowest taxonomic resolution common to all species within the code and assign that name to the trade flow.

For foreign exports, we trace the origins back in the supply chain a maximum of three steps (i.e., producer to intermediate exporter to final exporter to final importer), with any remaining foreign export or flows less than 1 tonne left as "unknown" source (Fig S8). The small flows left unresolved comprise around 1% of total trade (Fig S10). To link an export of foreign origin to its source country, we use a reweighted version of W to estimate the original imported product codes and connect those to their source country, using a proportional breakdown of each country's imports of that code. Foreign exports of one country that originated from foreign exports of another country are isolated and undergo the process above to identify the source country. The species mix for foreign trade flows are based on either the source country's estimated X matrix or the method described above for error exports (Fig S9).

Network post-estimation processing

Once the species trade flow network is built, we remove all volumes traded below 0.1 tonnes, as the multiplication by small proportions generates overly specific, and likely unrealistic, small flows.

Next, to generate a complete time series, we need to compile estimates from across the HS versions. All HS versions are reported since they have been created, for example HS96 reports trade from 1996 until the present. However, the more recent HS versions generally include more specific trade codes and therefore are preferred over older versions. It takes a few years before an HS version is fully adopted, resulting in lower total trade volumes for the first few years an HS version is available compared to the previous HS versions (Fig S7). To provide the most accurate representation of trade, we create a continuous time series by adopting the most recent HS version available after its total trade has met up with the total trade reported under previous HS versions. This results in HS96 being used for 1996 - 2004, HS02 for 2004 - 2009, HS07 for 2010 - 2012 and HS12 for 2013 - 2020.

To check the reasonability of estimated trade flows, we first confirmed that all trade flows sum to the original BACI trade flows when grouped by HS code and expressed as product weight. Note that some flows are slightly lower due to the 0.1 tonne threshold. Second, we confirmed that the estimates from the mass balance problem satisfy the problem constraints. Third, we checked that domestic exports of species in live weight equivalent do not exceed production of that species. Fourth, we confirmed that exports of foreign source do not exceed imports of that species. There were 106 cases across all years (0.02% of cases) where a country's foreign export of a species exceeded the total import of that species where the maximum volume difference was 0.4 t.

Analysis

Calculation of apparent consumption (supply)

A country's total supply (in product weight tonnes) by HS code, was estimated with their solution to their mass balance problem described above. We used the live weight conversion factors to transform total supply from product to live weight equivalent. Due to discrepancies in production and trade reporting for select countries, a few countries had unrealistically large estimated per capita consumption, which we then limited to 100 kg per capita, as this is slightly above the upper estimate FAOSTAT[41] and adjusted the supply by HS code for those countries proportionally. For all countries, we divided total supply into domestic and foreign components. As in the case of domestic versus foreign exports above, it cannot be known precisely with existing data whether a given product was sourced domestically or from imports when a country produces, imports, and exports a product again. Therefore, we calculated the range of the proportion of total supply that came from domestic production (domestic supply proportion), and the proportion of total supply that came from imports (foreign supply proportion). The domestic and foreign consumption proportions differed depending on the estimation method (maximum, minimum, midpoint), these differences are reflected in the equations below:

$$min\ remaining\ domestic\ production = domestic\ production - max\ domestic\ exports$$

$$min\ remaining\ imports = imports - max\ foreign\ exports$$

$$max\ remaining\ domestic\ production = domestic\ production - min\ domestic\ exports$$

$$max\ remaining\ imports = imports - min\ foreign\ exports$$

$$midpoint\ \ remaining\ domestic\ production = domestic\ production - midpoint\ domestic\ exports$$

$$midpoint\ remaining\ imports = imports - midpoint\ foreign\ exports$$

Midpoint estimate of domestic and foreign proportion:

$$domestic\ consumption\ weight\ = midpoint\ remaining\ domestic\ /\ consumption$$

$$foreign\ consumption\ weight\ = midpoint\ remaining\ imports\ /\ consumption$$

Maximum estimate of domestic and foreign proportion:

$$domestic\ consumption\ weight\ = max\ remaining\ domestic\ /\ consumption$$

$$foreign\ consumption\ weight\ = min\ remaining\ imports\ /\ consumption$$

Minimum estimate of domestic and foreign proportion:

$$domestic\ consumption\ weight\ = min\ remaining\ domestic\ /\ consumption$$

$$foreign\ consumption\ weight\ = max\ remaining\ imports\ /\ consumption$$

All domestic and foreign supply proportions were calculated by country and HS code.

Domestic consumption weights were further resolved by multiplying them by the proportions found in our X matrix, which represents the estimated proportions of species by habitat and production method that go into each HS code by country. This gives the domestic supply proportions by country, HS code, species, habitat and production method. Domestic consumption was found by taking the total consumptions and multiplying them by the domestic weights.

$$Domestic\ Consumption\ = Consumption \times domestic\ consumption\ weights \times prop\ of\ species\ in\ HS\ code\ (by\ habitat\ method)$$

To resolve foreign consumption based on the species mix of the source country, we found the proportion of imports for each trade record by dividing the import volume by the total imports of each country by year. Foreign consumption was then calculated by multiplying consumption by foreign consumption weights and the proportion of imports. This provided a foreign consumption calculated by source country, exporter, importer, HS code, species, habitat, and production method.

$$Foreign\ consumption = consumption \times foreign\ consumption\ weight \times import\ proportion$$

Foreign consumption was then summarized to country, species, habitat, production method and year.

Acknowledgements

We thank Sauleh Siddiqui and Ian Carrol for their input on the model development and Tess Geers for comments on the manuscript. JAG, JAG, CDG and RAB received support from the National Science Foundation (NSF HNDS-I 2121238). JAG, CDG and RAB received support from the Environmental Defense Fund. JAG, RAB and KDG received support from Oceana and Seafood Watch. KLN received funding from the L'Oreal for Women in Science Fellowship.

Data and code availability

All input data, key intermediate data files, and the final ARTIS database are archived in Zenodo and will be made publicly available upon publication. The code underlying the ARTIS database is available at https://github.com/jagephart/ARTIS and the code generating the analysis and figures in this paper are available at https://github.com/jagephart/ms-seafood-globalization. Both repositories will have an archived version and will made publicly available upon publication.

References

1. *Towards blue transformation*. (2022). doi:10.4060/cc0461en.
2. Gephart, J. A., Froehlich, H. E. & Branch, T. A. Opinion: To create sustainable seafood industries, the United States needs a better accounting of imports and exports. *Proc. Natl. Acad. Sci.* **116**, 9142–9146 (2019).
3. Golden, C. D. *et al.* Aquatic foods to nourish nations. *Nature* **598**, 315–320 (2021).
4. Short, R. E. *et al.* Harnessing the diversity of small-scale actors is key to the future of aquatic food systems. *Nat. Food* **2**, 733–741 (2021).
5. Gephart, J. A. *et al.* Environmental performance of blue foods. *Nature* **597**, 360–365 (2021).
6. FAO. FishStatJ - Software for Fishery and Aquaculture Statistical Time Series. (2020).

7. Gephart, J. A. & Golden, C. D. Environmental and nutritional double bottom lines in aquaculture. *One Earth* **5**, 324–328 (2022).

8. Koehn, J. Z., Allison, E. H., Golden, C. D. & Hilborn, R. The role of seafood in sustainable diets. *Environ. Res. Lett.* **17**, 035003 (2022).

9. Koehn, J. Z. *et al.* Fishing for health: Do the world's national policies for fisheries and aquaculture align with those for nutrition? *Fish Fish.* **23**, 125–142 (2022).

10. Tigchelaar, M. *et al.* The vital roles of blue foods in the global food system. *Glob. Food Secur.* **33**, 100637 (2022).

11. Yang, H., Wang, L., Abbaspour, K. C. & Zehnder, A. J. B. Virtual water trade: an assessment of water use efficiency in the international food trade. *Hydrol. Earth Syst. Sci.* **10**, 443–454 (2006).

12. Popkin, B. M., Corvalan, C. & Grummer-Strawn, L. M. Dynamics of the double burden of malnutrition and the changing nutrition reality. *The Lancet* **395**, 65–74 (2020).

13. De Loecker, J., Goldberg, P. K., Khandelwal, A. K. & Pavcnik, N. Prices, Markups, and Trade Reform. *Econometrica* **84**, 445–510 (2016).

14. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food* **2**, 54–65 (2020).

15. Pace, M. L. & Gephart, J. A. Trade: A Driver of Present and Future Ecosystems. *Ecosystems* **20**, 44–53 (2017).

16. Wiedmann, T. & Lenzen, M. Environmental and social footprints of international trade. *Nat. Geosci.* **11**, 314–321 (2018).

17. Berkes, F. *et al.* Globalization, Roving Bandits, and Marine Resources. *Science* **311**, 1557–1558 (2006).

18. Lambin, E. F. & Meyfroidt, P. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci.* **108**, 3465–3472 (2011).

19. Cawthorn, D.-M. & Mariani, S. Global trade statistics lack granularity to inform traceability and management of diverse and high-value fishes. *Sci. Rep.* **7**, 12852 (2017).

20. Guillen, J. *et al.* Global seafood consumption footprint. *Ambio* **48**, 111–122 (2019).

21. Watson, R. A., Nichols, R., Lam, V. W. Y. & Sumaila, U. R. Global seafood trade flows and developing economies: Insights from linking trade and production. *Mar. Policy* **82**, 41–49 (2017).

22. Clapp, J. Concentration and crises: exploring the deep roots of vulnerability in the global industrial food system. *J. Peasant Stud.* **50**, 1–25 (2023).

23. Golden, C. D. *et al.* Does Aquaculture Support the Needs of Nutritionally Vulnerable Nations? *Front. Mar. Sci.* **4**, (2017).

24. Belton, B., Bush, S. R. & Little, D. C. Not just for the wealthy: Rethinking farmed fish consumption in the Global South. *Glob. Food Secur.* **16**, 85–92 (2018).

25. Gephart, J. A. *et al.* Scenarios for Global Aquaculture and Its Role in Human Nutrition. *Rev. Fish. Sci. Aquac.* **29**, 122–138 (2021).

26. Gephart, J. A., Rovenskaya, E., Dieckmann, U., Pace, M. L. & Brännström, Å. Vulnerability to shocks in the global seafood trade network. *Environ. Res. Lett.* **11**, 035008 (2016).

27. Marchand, P. *et al.* Reserves and trade jointly determine exposure to food supply shocks. *Environ. Res. Lett.* **11**, 095009 (2016).

28. Bren d'Amour, C., Wenz, L., Kalkuhl, M., Christoph Steckel, J. & Creutzig, F. Teleconnected food supply shocks. *Environ. Res. Lett.* **11**, 035007 (2016).

29. Love, D. C. *et al.* Emerging COVID-19 impacts, responses, and lessons for building resilience in the seafood system. *Glob. Food Secur.* **28**, 100494 (2021).

30. Hicks, C. C. *et al.* Rights and representation support justice across aquatic food systems. *Nat. Food* **3**, 851–861 (2022).

31. Naylor, R. L. *et al.* Blue Food Demand Across Geographic and Temporal Scales. *Nature* (In Revision).

32. Natale, F., Borrello, A. & Motova, A. Analysis of the determinants of international seafood trade using a gravity model. *Mar. Policy* **60**, 98–106 (2015).

33. Bensassi, S., Jarreau, J. & Mitaritonna, C. Regional Integration and Informal Trade in Africa: Evidence from Benin's Borders. *J. Afr. Econ.* **28**, 89–118 (2019).

34. Watson, R. A. *et al.* Marine foods sourced from farther as their use of global ocean primary production increases. *Nat. Commun.* **6**, 7365 (2015).

35. Kroetz, K. *et al.* Consequences of seafood mislabeling for marine populations and fisheries management. *Proc. Natl. Acad. Sci.* **117**, 30318–30323 (2020).

36. Roheim, C. A. Seafood supply chain management: Methods to prevent illegally-caught product entry into the marketplace. *IUCN World Conserv. Union-US Proj. PROFISH Law Enforc. Corrupt. Fish. Work* 1–23 (2008).

37. Virdin, J. *et al.* Combatting illegal fishing through transparency initiatives : Lessons learned from comparative analysis of transparency initiatives in seafood, apparel, extractive, and timber supply chains. *Mar. Policy* **138**, 104984 (2022).

38. Asche, F., Bellemare, M. F., Roheim, C., Smith, M. D. & Tveteras, S. Fair Enough? Food Security and the International Trade of Seafood. *World Dev.* **67**, 151–160 (2015).

39. Brugere, C., Troell, M. & Eriksson, H. More than fish: Policy coherence and benefit sharing as necessary conditions for equitable aquaculture development. *Mar. Policy* **123**, 104271 (2021).

40. Nash, K. L. *et al.* Trade and foreign fishing mediate global marine nutrient supply. *Proc. Natl. Acad. Sci.* **119**, e2120817119 (2022).

41. FAO. FAOSTAT. (2020).

42. Baer-Nawrocka, A. & Sadowski, A. Food security and food self-sufficiency around the world: A typology of countries. *PLOS ONE* **14**, e0213448 (2019).

43. Kummu, M. *et al.* Interplay of trade and food system resilience: Gains on supply diversity over time at the cost of trade independency. *Glob. Food Secur.* **24**, 100360 (2020).

44. Wood, A. *et al.* Reframing the local–global food systems debate through a resilience lens. *Nat. Food* **4**, 22–29 (2023).

45. Gaulier, G. & Zignago, S. BACI: International Trade Database at the Product-Level (the 1994-2007 Version). SSRN Scholarly Paper at https://doi.org/10.2139/ssrn.1994500 (2010).

46. Brewer, T. D. *et al. A method for cleaning trade data for regional analysis: The Pacific Food Trade Database (version 2, 1995-2018)*. (2020).

47. United Nations Statistical Division. *International Merchandise Trade Statistics: Concepts and Definitions 2010*. (UN, 2011).

48. EUMOFA. *Annex 7 - Conversion factors by CN-8 code, from 2001-2021*. (2021).

49. Jackson, A. Fish in-Fish out. *Ratios Explain.* **34**, (2009).

50. Froese, R. FishBase. world wide web electronic publication. *Httpwww Fishbase Org* (2005).

51. Pauly, D., Zeller, D. & Palomares, M. L. D. *Sea Around Us Concepts, Design and Data*. (2020).

52. Asche, F. *et al.* China's seafood imports—Not for domestic consumption? *Science* **375**, 386–388 (2022).

Supplementary Figures

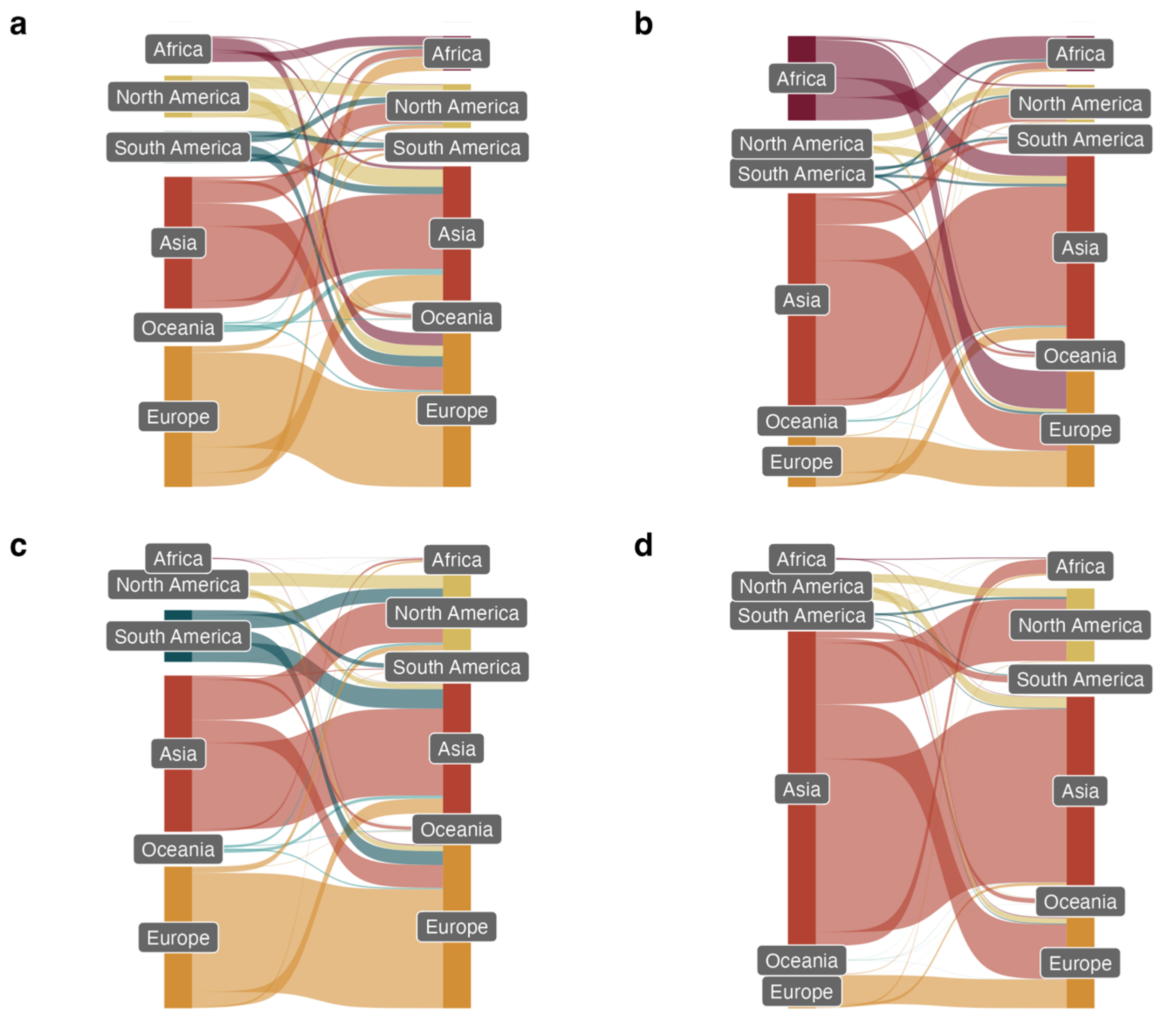

Figure S1: Regional trade networks for 2019. a) Sankey diagram showing regional trade of marine capture. b) Sankey diagram showing regional trade of inland capture. c) Sankey diagram showing regional trade of marine aquaculture. d) Sankey diagram showing regional trade of inland aquaculture.

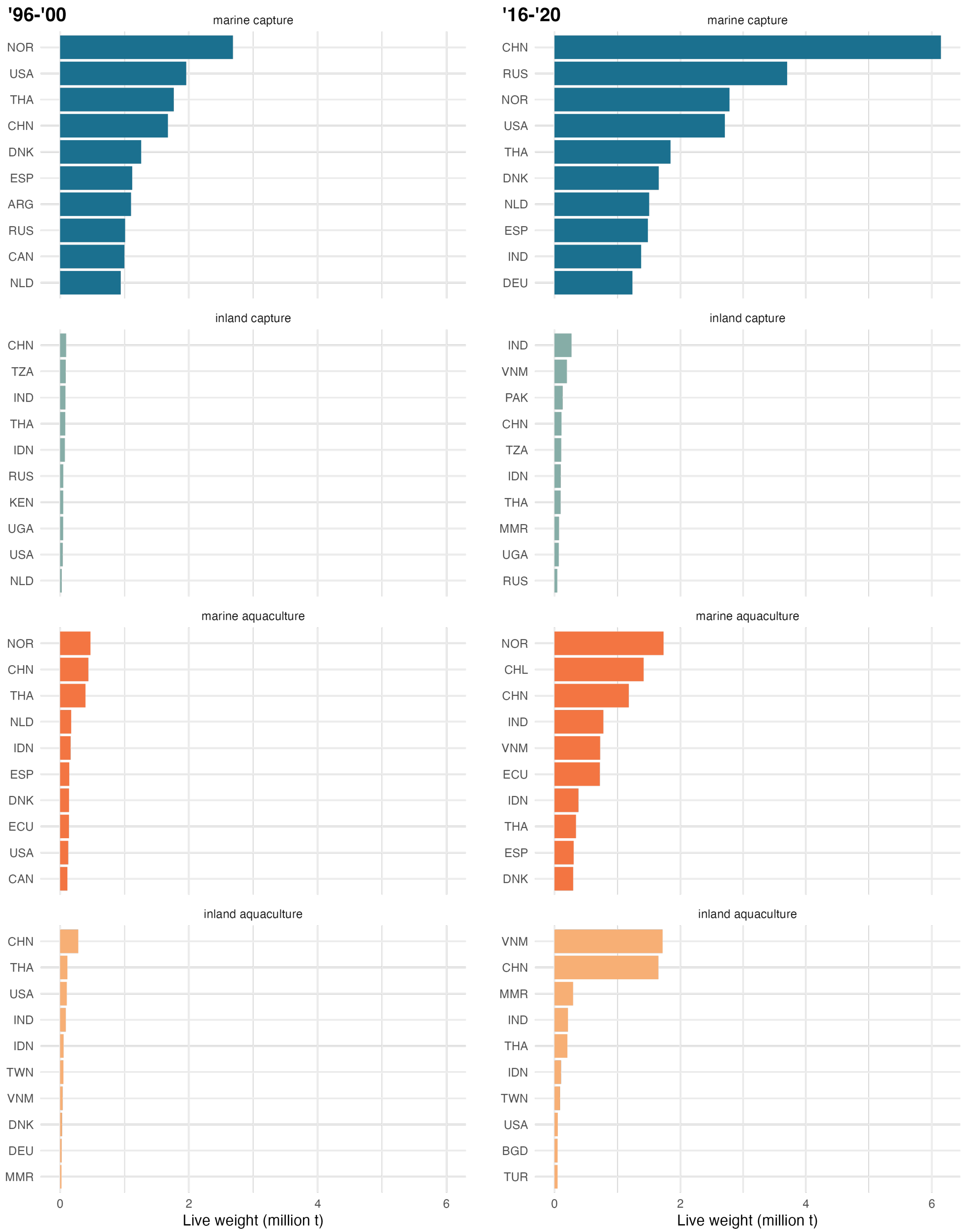

Figure S2: Top exporters from 1996 - 2000 and 2016-2020 by habitat and production method. Trade volumes represent the average annual trade volumes over that period in live weight equivalent.

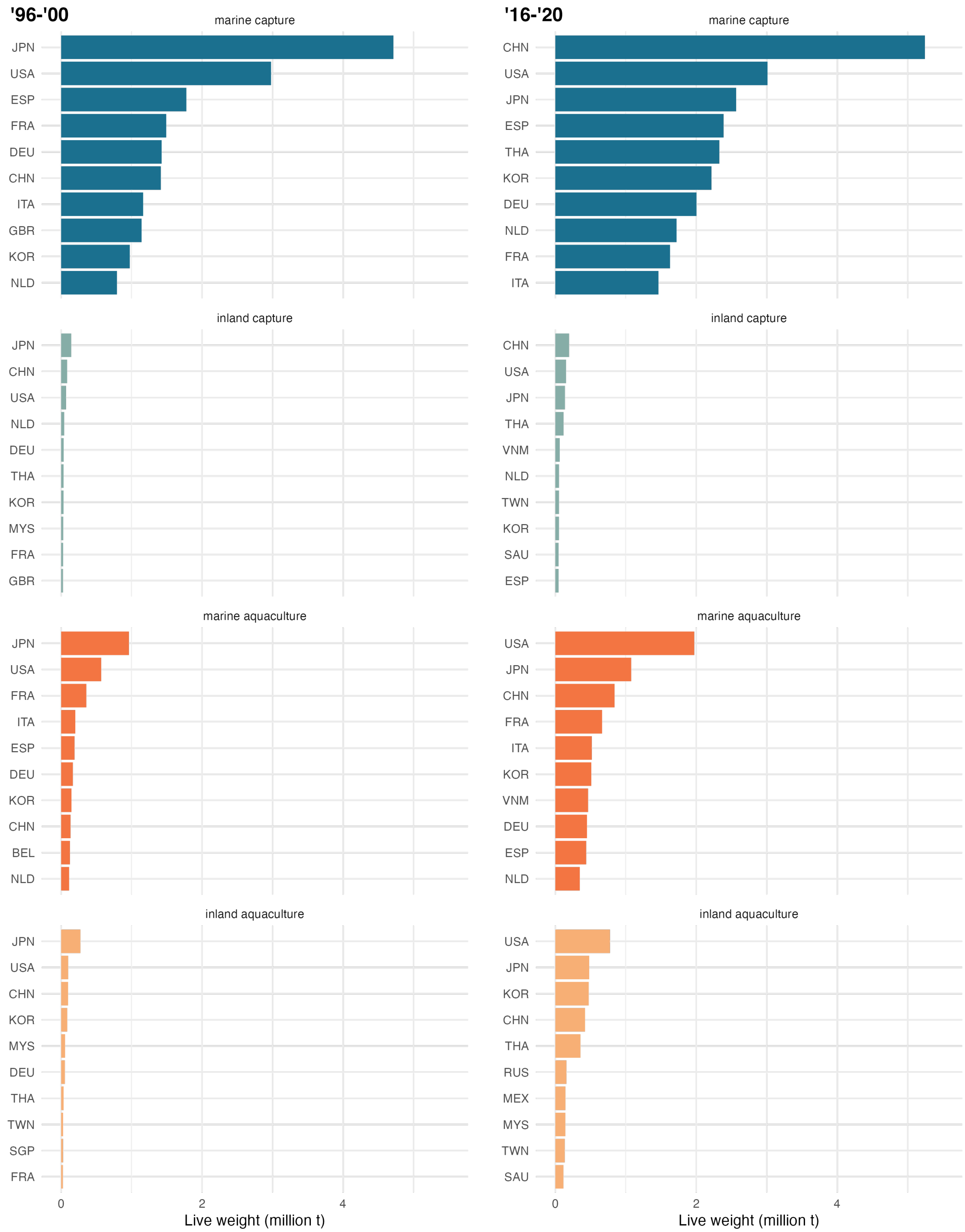

Figure S3: Top importers from 1996 - 2000 and 2016-2020 by habitat and production method. Trade volumes represent the average annual trade volumes over that period in live weight equivalent.

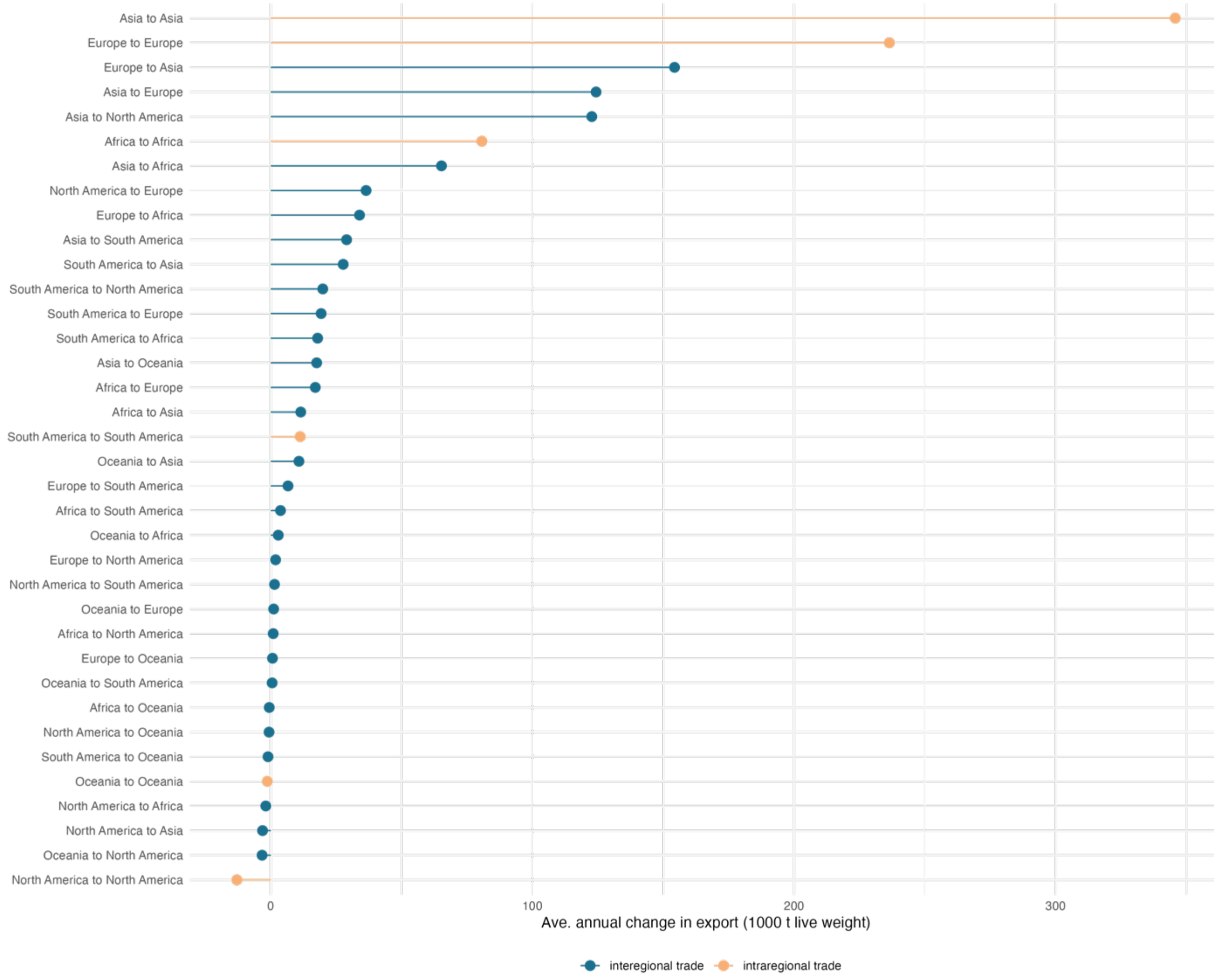

Figure S4: Changes in interregional export (1000 live weight tonnes) flows.

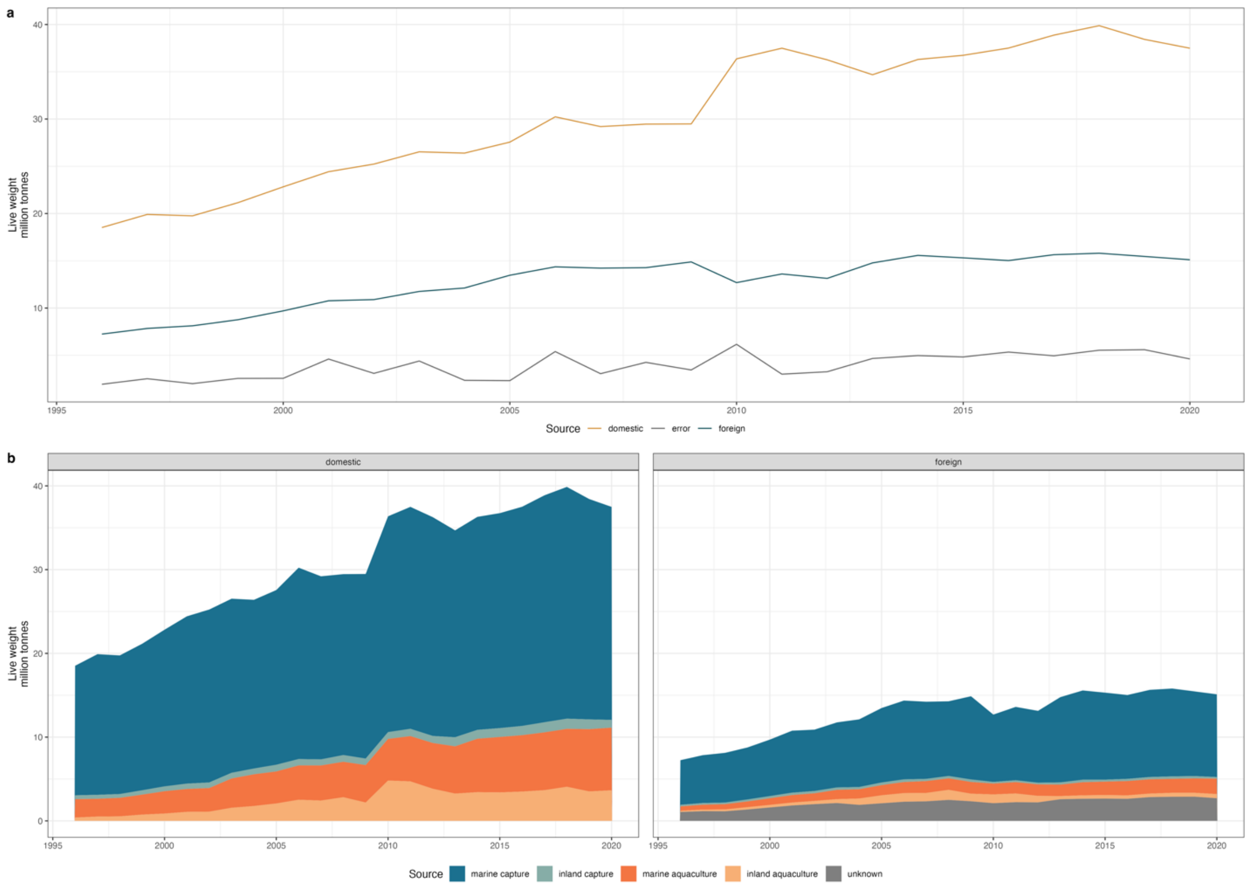

Figure S5: Time series of blue food exports from 1996 - 2020 a) Blue food exports disaggregated by domestic and foreign exports. b) Domestic and foreign exports are disaggregated by habitat and production method.

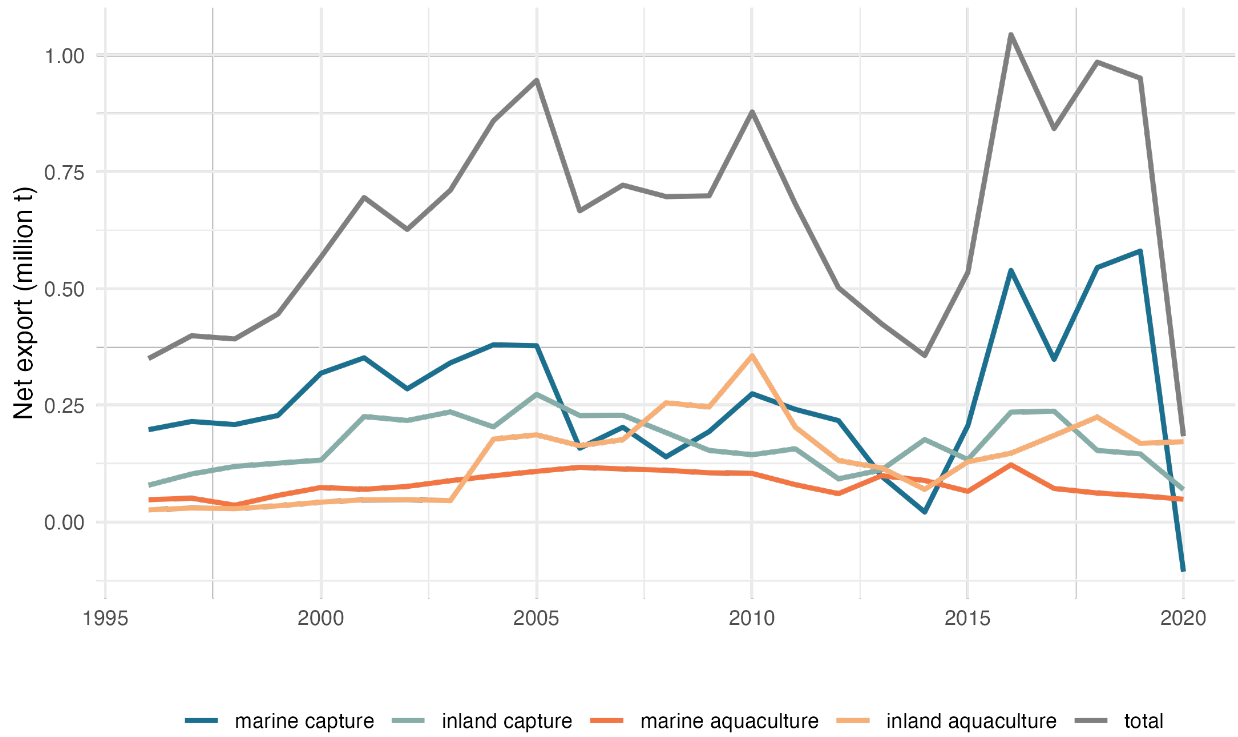

Figure S6: Net exports from least developed countries, as defined by the United Nations.

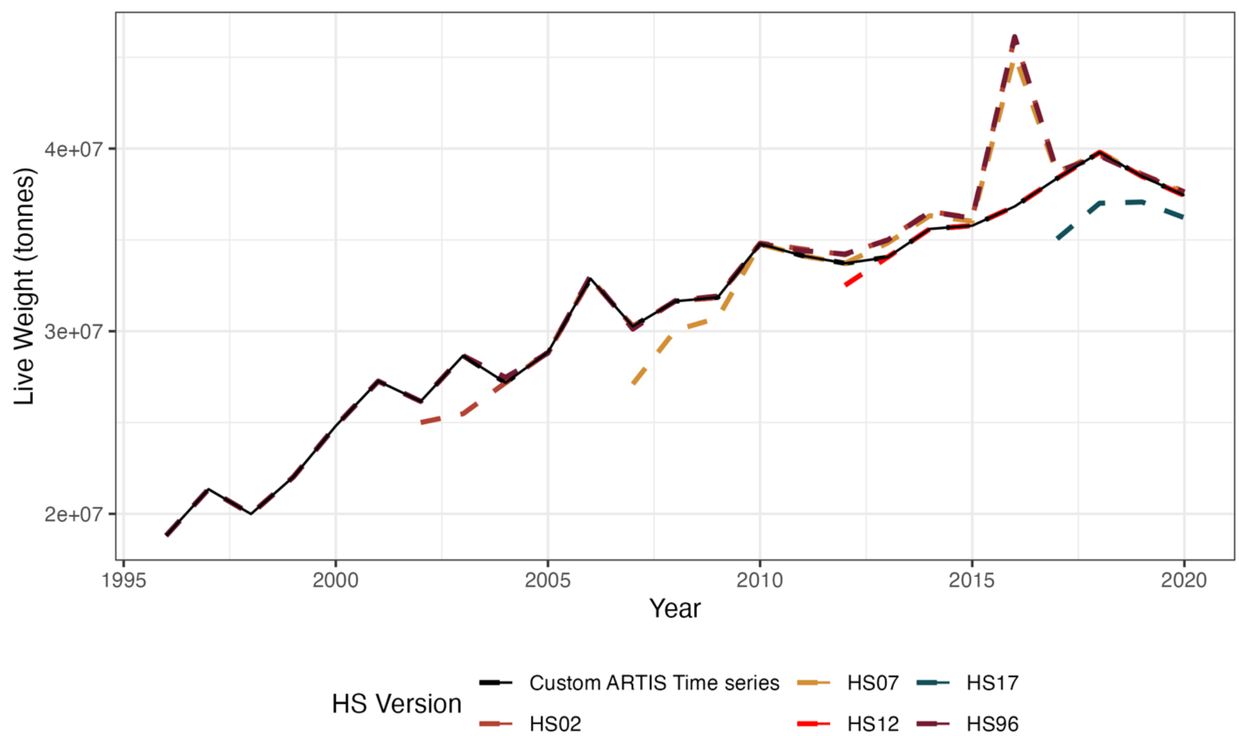

Figure S7: Total live weight exports (tonnes) from 1996 - 2020, by HS Version, with the volumes for total ARTIS trade in black

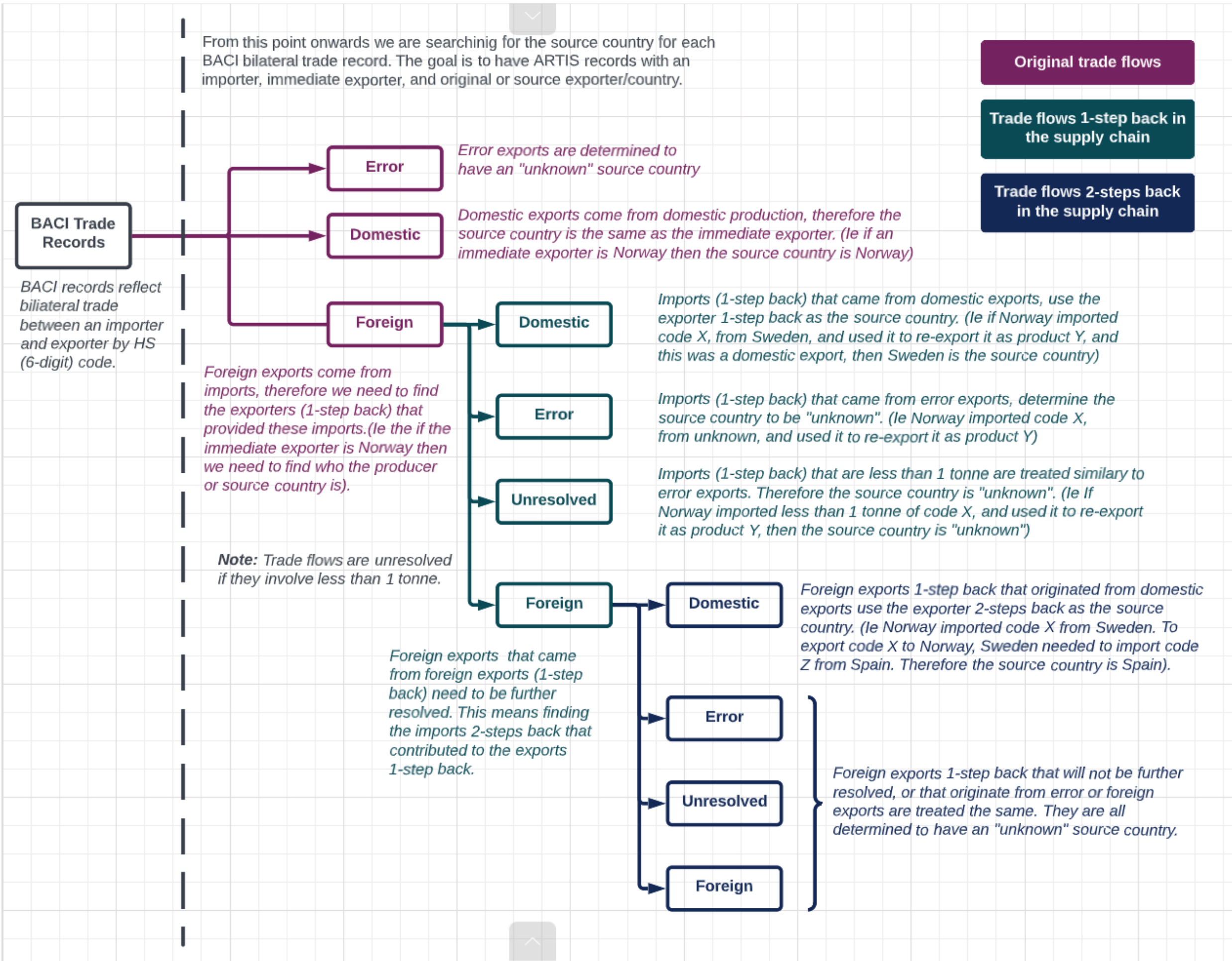

Figure S8: Conceptual diagram of the disaggregation of BACI trade records to identify source countries of production.

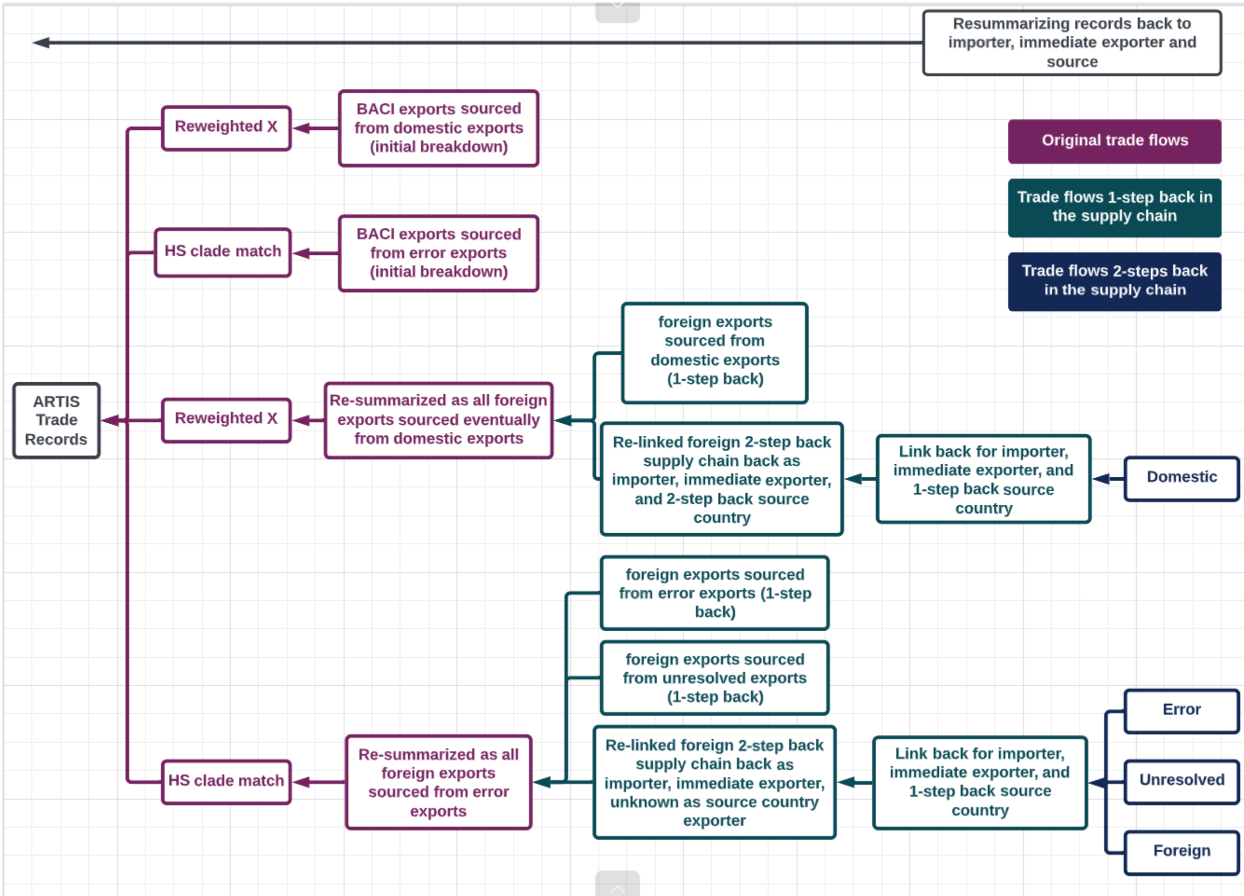

Figure S9: Conceptual diagram linking trade data by source country to appropriate species mix estimates.

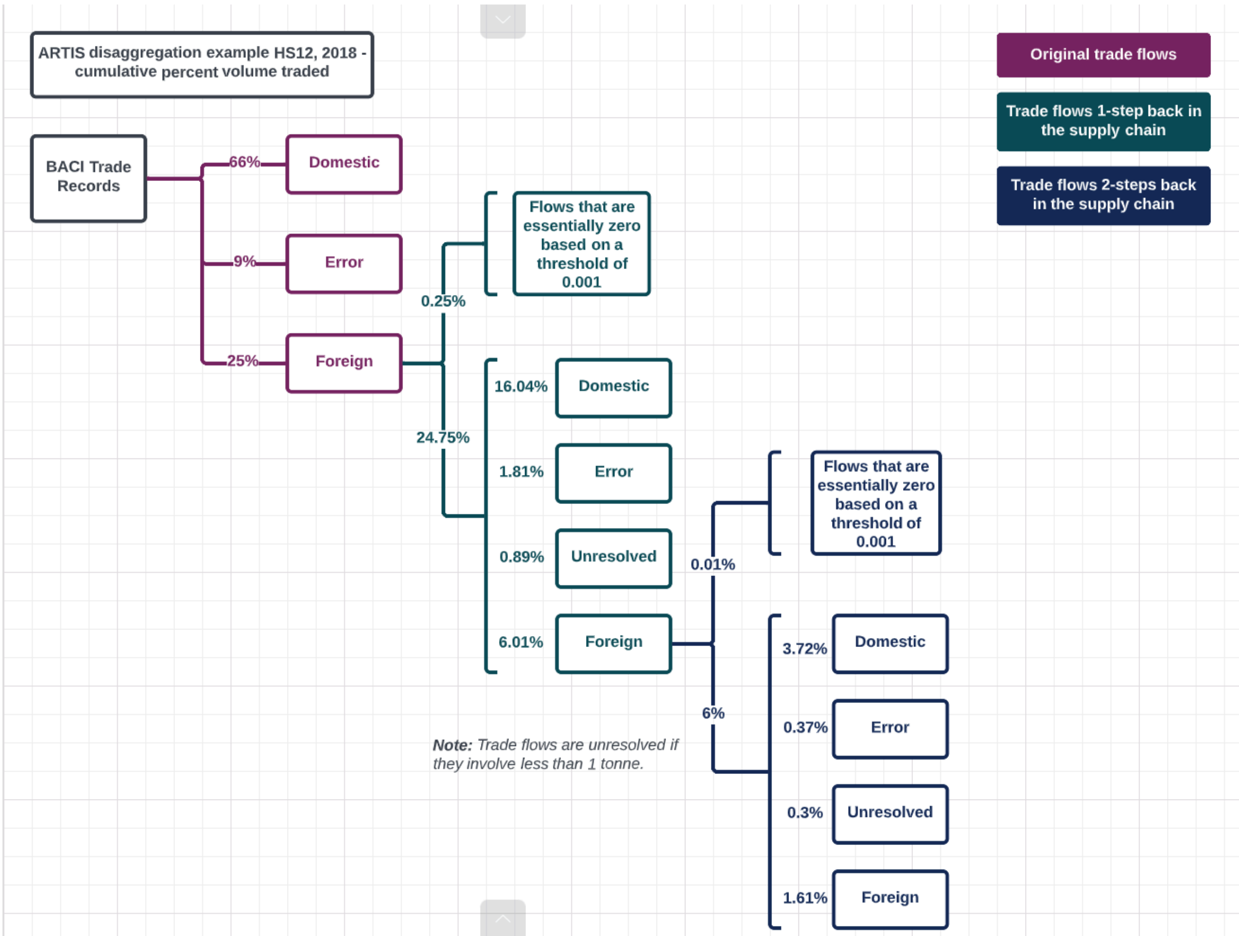

Figure S10: Flow chart illustrating the percent of the total traded volume attributed to each component of the disaggregated trade flows. Data is for 2018, using HS version 2012.