

1 **Title:** Globalization of wild capture and farmed aquatic foods

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## 19 Abstract

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

## 33 Key words

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

## 35 1. Introduction

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

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

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

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

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

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

## 96 2. Results

### 97 2.1 Trends in aquatic food globalization

98 Globalization describes the degree of international connectedness, which can be  
99 characterized by increasing flows of input, intermediate and final products among  
100 countries. Aquatic food exports more than doubled from 1996-2019 (27.7 to 59.5 mil t;  
101 Fig 1a). Over that period, both farmed and wild exports increased, though aquaculture  
102 grew faster, more than tripling, whereas capture exports grew by 77%. Corresponding  
103 with the start of the COVID-19 pandemic, global aquatic food exports declined 4% in  
104 2020 relative to 2019, with a 4% decline in capture exports, but a 3.1% increase in  
105 aquaculture exports, highlighting differential impacts by sector (Fig 1a). Despite  
106 aquaculture comprising half of aquatic food production, capture fishery products still  
107 constitute 60% of exports.

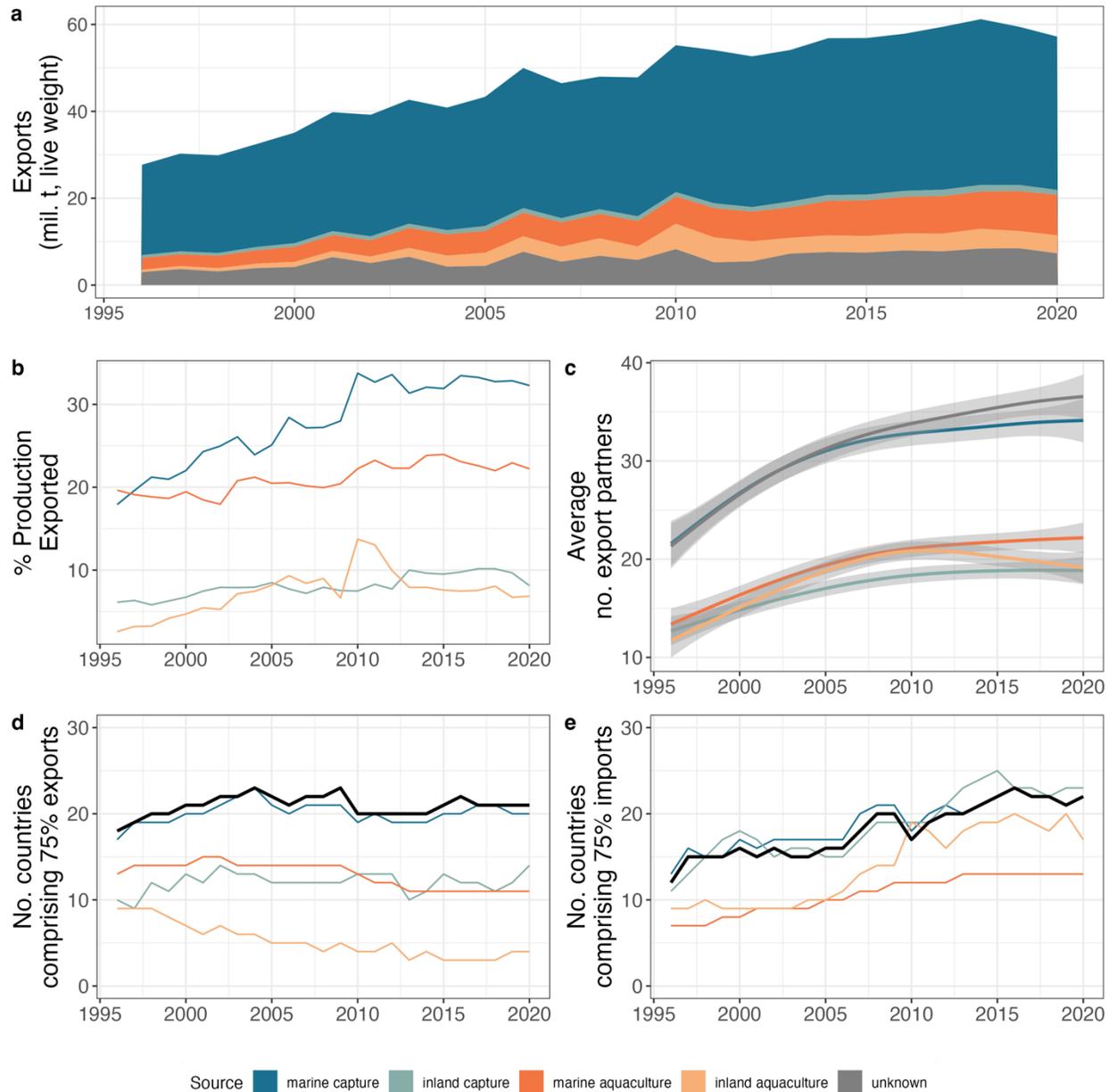
108 Another measure of the degree of globalization is the share of production  
109 exported. Domestic exports increased from 15% to 22% of production between 1996 and  
110 2019, while total exports, which include export of foreign-sourced products, reached

111 34% of all production in 2019. For comparison, the share of cereal production exported  
112 grew from around 10% in the late 1990s to 17% in the 2020s<sup>22</sup>. Increasing marine  
113 capture exports despite stagnating production resulted in marine capture products  
114 having the greatest share of production destined for export (33% of production) and the  
115 largest increases in the share exported (Fig 1b). Aquaculture production more than  
116 doubled from 1996 to 2019, but aquaculture exports grew even faster, increasing the  
117 share exported (Fig 1b). Despite increases, inland aquaculture still had the lowest share  
118 of production destined for export in 2019 (domestic exports represented only 6.7% of  
119 production) (Fig 1b). This finding clarifies standing debates about the orientation of  
120 aquaculture and export trends suggest a need to consider international markets when  
121 crafting nutrition-sensitive policies<sup>23–25</sup>.

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

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

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



153

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

## 161 2.2 Shifts in global flows of aquatic foods

162 Given the geographic patchiness of capture and aquaculture production, trade  
 163 helps meet aquatic food demand in many countries. Aquatic food imports are especially

164 important where per capita demand is rising, aquaculture is limited, wild fishery catch is  
165 stagnant, and where aquatic foods play an important nutritional role. Corresponding to  
166 the geographical variability, we find the top importers, exporters, and bilateral flows to  
167 differ by habitat and farmed versus wild source, underscoring the importance of  
168 disaggregating trade (Fig S1-3). For example, Asia and Europe, and to a lesser extent,  
169 North America recently dominated marine capture and aquaculture trade networks  
170 whereas Asia dominates all inland aquatic food trade (Fig S1).

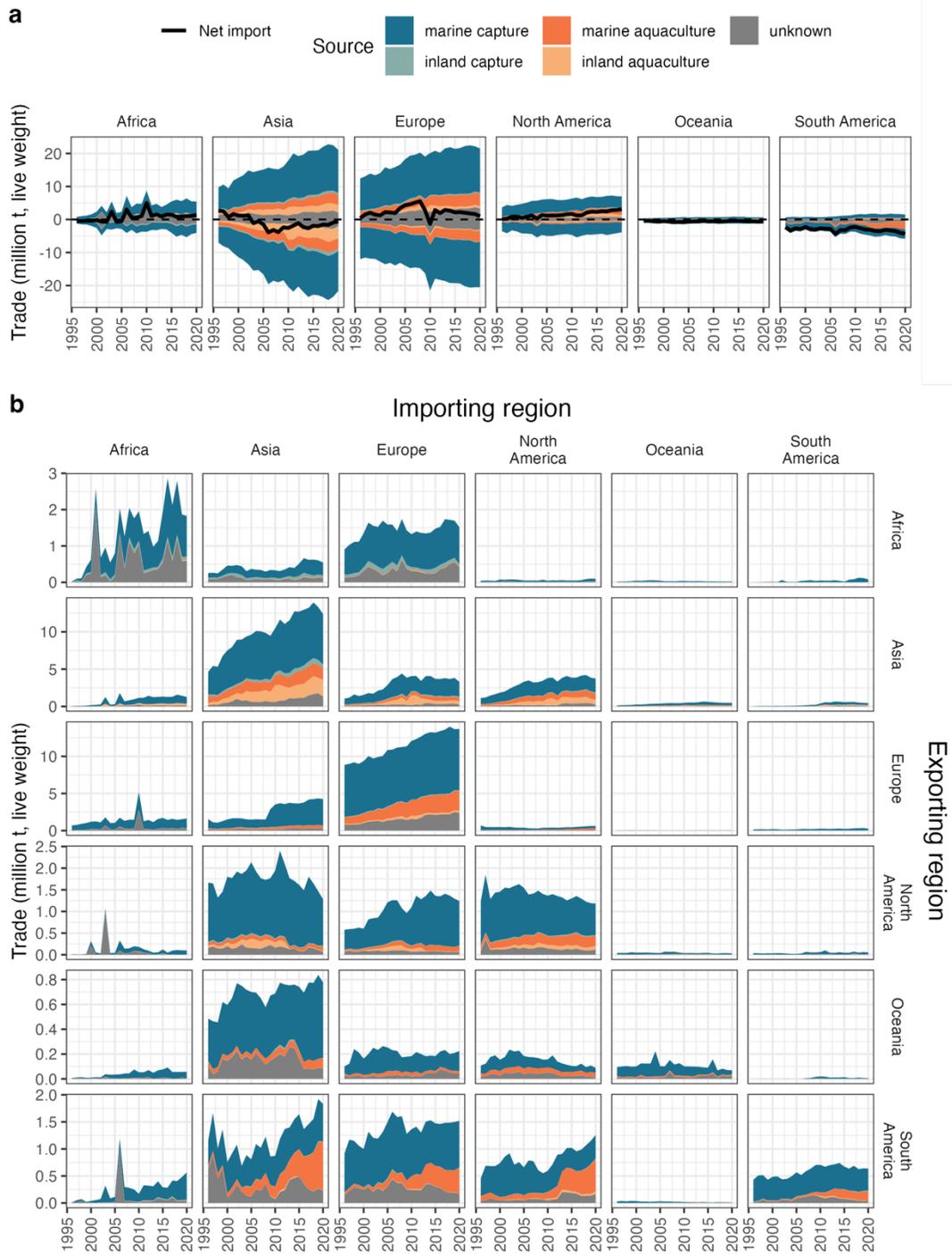
171 At the country level, although some countries rank among the top traders across  
172 all production methods, such as China for exports and China and the United States for  
173 imports, many countries are only top traders for one. China and Russia are the top  
174 marine capture aquatic food exporters,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

181 Intraregional trade is generally higher than interregional trade due to shorter  
182 transport distances, historical ties, patterns of aquatic food preferences and established  
183 regional trade agreements<sup>32</sup>. We find this pattern largely holds for aquatic food trade as  
184 intraregional trade is the highest for Asia, Africa, and Europe (Fig 2b). However,  
185 Oceania and North and South America all have the largest export to Asia (Fig 2b). Since  
186 1996, trade increased or remained approximately stable between nearly all regional  
187 trade pairs, other than within North America (Fig S4). At the country level, trade  
188 increased between two thirds of trade pairs. Despite trade increasing with partners  
189 across the globe, trade within Asia, Europe and Africa grew faster. The largest average  
190 annual growth increases occurred for trade within Asia and Europe, followed by trade  
191 between Europe and Asia (Fig 2b; Fig S4). Our trade estimates are ultimately from  
192 reported trade and therefore do not capture informal and unreported trade networks.  
193 Though estimated unreported trade is not globally available, it can be significant,  
194 especially for neighboring countries. For example, informal exports from Benin to  
195 Nigeria are estimated to be more than five times the formal exports<sup>33</sup>. Including  
196 informal trade would therefore likely strengthen intraregional trade patterns.

197 Increasing global trade, along with distant water fishing, drive an expanding  
198 divide between aquatic food production and consumption<sup>34</sup>. Complex international  
199 supply chains pose a challenge for traceability, raising sustainability concerns, including  
200 risk of mislabeled<sup>35</sup> and illegally sourced<sup>36</sup> products entering markets. We find  
201 increasing volumes of products moving through intermediate countries, either in transit  
202 or imported for processing and re-exported, which poses a traceability challenge (Fig  
203 S5). Certification and import monitoring schemes represent two tools aimed at  
204 improving traceability, and ultimately, sustainable sourcing. However, evidence of the  
205 effectiveness of aquatic food supply chain transparency initiatives is mixed<sup>37</sup>. Our

206 findings on increasing globalization across the aquatic food sector underscores the  
207 importance of evaluating the effectiveness and social impacts of these sustainability  
208 tools across a range of settings, while the ARTIS database enables future work on this  
209 topic.

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



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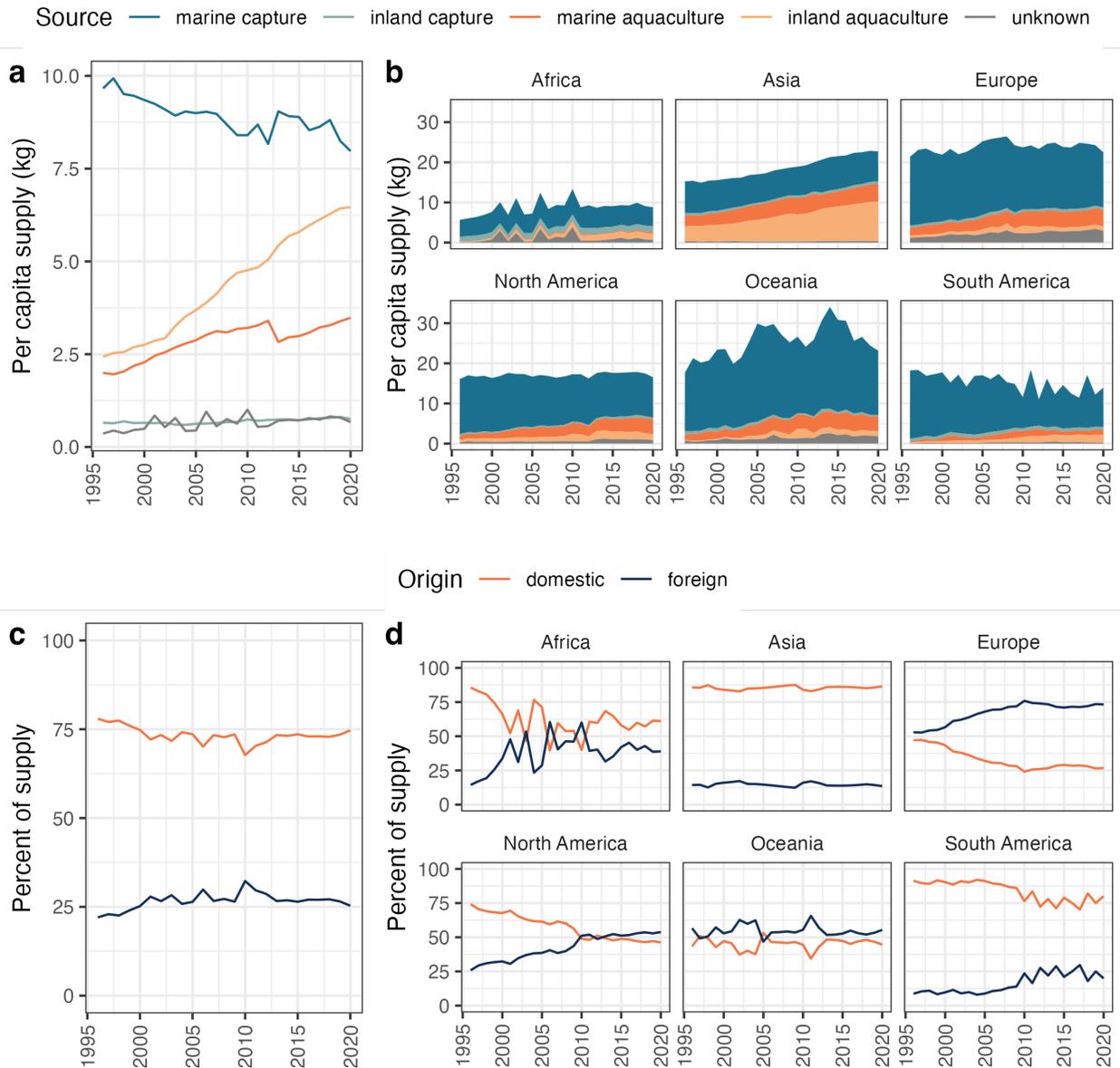
224 Figure 2: Regional trade flows by production source (habitat and method). a) Total  
 225 imports (positive) and exports (negative) colored by source, with net import trend in  
 226 black. b) Bilateral flows colored by production source with exporting region along the  
 227 rows and importing region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

## 229 2.3 Aquatic food consumption

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

237 Globally, annual aquatic food apparent consumption increased from 15.1 kg per  
238 capita in 1996 to 19.7 kg per capita in 2019 (Fig 3a). Our estimates are slightly lower  
239 than FAOSTAT<sup>41</sup>, which reports global aquatic food consumption at 15.6 kg/capita/year  
240 in 1996 and 20.7 kg/capita/year in 2019. We found aquatic food consumption increased  
241 across all regions outside of North America, which was relatively stable, and South  
242 America, where aquatic food consumption declined 33.1% (Fig 3b). Global increases  
243 were driven by inland and marine aquaculture, which increased by 164% (from 2.43  
244 kg/capita/year in 1996 to 6.43 kg/capita/year in 2019) and 69.7% (from 2  
245 kg/capita/year in 1996 to 3.39 kg/capita/year in 2019), respectively. Meanwhile, inland  
246 capture consumption grew from 0.65 kg/capita/year in 1996 to 0.81 kg/capita/year in  
247 2019, while marine capture consumption declined 14.7% (from 9.66 kg/capita/year in  
248 1996 to 8.25 kg/capita/year in 2019). Nevertheless, capture still makes up 45% of global  
249 aquatic food consumption, with its contribution to regional aquatic food consumption  
250 ranging from 71% in Oceania to 36% in Asia, where farmed consumption overtook wild  
251 consumption in 2003.

252 Estimating the foreign versus domestic source of consumption requires  
253 identifying the share of production retained in the country and tracking products that  
254 undergo foreign processing but are imported again. By estimating the source of traded  
255 aquatic foods, we can therefore track changes in reliance on foreign-sourced products.  
256 Globally the share of foreign-sourced consumption increased modestly, from 22% in  
257 1996 to 25% in 2019 (Fig 3c). However, patterns vary greatly across regions with  
258 countries in Asia and South America dominated by domestic supply (14% and 25%  
259 foreign in 2019, respectively), but countries in Europe dominated by foreign supply  
260 (73% foreign in 2019) in 2019 (Fig 3d). High reliance on foreign-sourced foods can pose  
261 a food security risk<sup>42,43</sup>, though it is not clear the extent to which these risks exist across  
262 aquatic foods. Nevertheless, countries have enacted policies to protect domestic  
263 supplies, including developing food stocks and subsidizing domestic food production<sup>44</sup>.  
264 The United States previously used foreign dependence on aquatic foods as motivation  
265 for a suite of policy changes to boost domestic production, including expanding  
266 aquaculture and opening marine protected areas to fishing<sup>2</sup>.



267

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

275

### 3. Conclusion

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

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

292 We showed that global per capita aquatic food consumption increased from 14  
293 kg/capita/year in 1996 to 17.7 kg/capita/year in 2019 despite declining consumption of  
294 marine capture aquatic foods. Globally, the percentage of foreign-sourced supply  
295 increased, though regions vary greatly in their foreign dependence, from 9% in Asia to  
296 65% in Europe.

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

303

## 304 Methods

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

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

## 325 Data

### 326 Production

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

339 According to the Coordinating Working Party on Fishery Statistics, catch and  
340 landings should be assigned to the country of the flag flown by the fishing vessel

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

## 352 Bilateral trade data

353 We use the CEPII BACI world trade database, which is a reconciled version of the  
354 UN Comtrade database<sup>45</sup>. Trade data are reported to the UN by both importers and  
355 exporters following the Harmonized System (HS) codes. The HS trade code system  
356 organizes traded goods into a hierarchy, with the highest level represented by two-digit  
357 codes (e.g., Chapter 03 covers "Fish and Crustaceans, Molluscs and Other Aquatic  
358 Invertebrates"), which are broken down into 4-digit headings (e.g., heading 0301 covers  
359 "Live fish"), which are then subdivided into 6-digit subheadings (e.g., subheading  
360 030111 covers "Live ornamental freshwater fish"). National statistics offices may further  
361 subdivide HS codes into 7- to 12-digit codes but since these are not standard across  
362 countries, the HS 6-digit codes are the most highly resolved trade codes available  
363 globally. HS codes are administered by the World Customs Organization, which updates  
364 the codes every five years. HS versions can be used from their introduction through the  
365 present, meaning that the HS 2002 version provides a time series of trade from 2002 to  
366 the present whereas the HS 2017 version only provides a time series back to 2017.  
367 Notably, HS version 2012 included major revisions to the HS codes relevant to fisheries  
368 and aquaculture products.

369 CEPII reconciles discrepancies in mirror trade records, which occur in around  
370 35% of observations (for all traded commodities), by first removing transportation costs  
371 and using a weighting scheme based on each country's reporting reliability to average  
372 discrepancies in reported mirror flows. BACI data focuses on trade flows between  
373 individual countries since 1994 and therefore drops flows within some groups of  
374 countries (e.g., Belgium-Luxembourg) to ensure consistent geographies. The resulting  
375 data set covers trade for over 200 countries and 5,000 products. Further details on the  
376 BACI data set are available in<sup>45</sup>. While BACI resolves many data issues contained in the  
377 raw UN Comtrade database, it does not correct for all implausible trade flows, which can  
378 especially arise if one country misreports a value and the partner country does not  
379 report a value<sup>46</sup>. Further, there are instances where one country reports on trade that is  
380 optional to report, and the partner country does not. Here, we do not identify and re-

381 estimate any values reported in BACI. Excessively large exports will generally result in  
382 high error terms, while high imports will result in high apparent consumption.

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

## 396 Live weight conversions

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

412 Live weight conversion factors applied to trade data introduce a source of  
413 uncertainty and error due to uncertainty in conversion factors is not reported and a  
414 single live weight conversion factor is often presented per code, regardless of the species  
415 or region of origin. This is a limitation given that there are geographical and temporal  
416 variation in live weight conversion factors due to differences in processing technology.  
417 Despite this limitation, EUMOFA data offers better documentation and alignment with  
418 HS commodity codes than other live weight conversion factor data sources<sup>2</sup> and is  
419 updated annually, providing documentation for changes in live weight conversion  
420 factors. Additionally, by supplementing the EUMOFA data with the other reported

421 values we can better capture specific species processing into various product forms and  
422 some regional variability.

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

## 432 Seafood production and commodity conversion

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

## 444 Taxonomic group to commodity assignment

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

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

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

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

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

## 480 Commodity to commodity processing assignment

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

## 494 Country standardization and regions

495 The FAO production and BACI trade datasets do not share the same set of  
496 countries and territories. For the production and trade data to balance, it is important

497 for the set of territories falling under a given name to align across the datasets. To avoid  
498 instances where, for example, production is reported under a territory, but trade is  
499 reported under the sovereign nation, we generally group all territories with the  
500 sovereign nation. As countries gain independence, they are added as a trade partner in  
501 the database.

## 502 Network Estimation

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

### 507 National mass-balance

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

$$515 \quad e = V_1 \circ X \cdot p + V_2 \circ W \cdot g - c + \epsilon$$

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

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

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

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

## 542 Converting the product trade network to a species trade network

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

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

$$563 \quad \text{max domestic exports} = \min(\text{domestic production}, \text{total exports})$$

$$564 \quad \text{max foreign exports} = \min(\text{imports}, \text{total exports})$$

$$565 \quad \text{min domestic exports}$$

$$566 \quad = \min(\text{domestic production}, \text{total exports} - \text{max foreign exports})$$

$$567 \quad \text{min foreign exports} = \min(\text{imports}, \text{total exports} - \text{max domestic exports})$$

$$568 \quad \text{midpoint domestic exports} = \frac{\text{max domestic exports} + \text{min domestic exports}}{2}$$

569 
$$\text{midpoint foreign exports} = \frac{\text{max foreign exports} + \text{min foreign exports}}{2}$$

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

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

## 591 Network post-estimation processing

592 Once the species trade flow network is built, we remove all volumes traded below  
593 0.1 tonnes, as the multiplication by small proportions generates overly specific, and  
594 likely unrealistic, small flows.

595 Next, to generate a complete time series, we need to compile estimates from  
596 across the HS versions. All HS versions are reported since they have been created, for  
597 example HS96 reports trade from 1996 until the present. However, the more recent HS  
598 versions generally include more specific trade codes and therefore are preferred over  
599 older versions. It takes a few years before an HS version is fully adopted, resulting in  
600 lower total trade volumes for the first few years an HS version is available compared to  
601 the previous HS versions (Fig S7). To provide the most accurate representation of trade,  
602 we create a continuous time series by adopting the most recent HS version available  
603 after its total trade has met up with the total trade reported under previous HS versions.  
604 This results in HS96 being used for 1996 - 2004, HS02 for 2004 - 2009, HS07 for 2010  
605 - 2012 and HS12 for 2013 - 2020.

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

## 616 Analysis

### 617 Calculation of apparent consumption (supply)

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

$$\begin{aligned} 634 & \\ 635 & \quad \textit{min remaining domestic production} \\ 636 & \quad \quad = \textit{domestic production} - \textit{max domestic exports} \\ 637 & \quad \textit{min remaining imports} = \textit{imports} - \textit{max foreign exports} \\ 638 & \\ 639 & \quad \textit{max remaining domestic production} \\ 640 & \quad \quad = \textit{domestic production} - \textit{min domestic exports} \\ 641 & \quad \textit{max remaining imports} = \textit{imports} - \textit{min foreign exports} \\ 642 & \end{aligned}$$

643 *midpoint remaining domestic production*  
644 *= domestic production – midpoint domestic exports*  
645 *midpoint remaining imports = imports – midpoint foreign exports*  
646

647 Midpoint estimate of domestic and foreign proportion:

648 *domestic consumption weight = midpoint remaining domestic / consumption*  
649 *foreign consumption weight = midpoint remaining imports / consumption*  
650

651 Maximum estimate of domestic and foreign proportion:

652 *domestic consumption weight = max remaining domestic / consumption*  
653 *foreign consumption weight = min remaining imports / consumption*  
654

655 Minimum estimate of domestic and foreign proportion:

656 *domestic consumption weight = min remaining domestic / consumption*  
657 *foreign consumption weight = max remaining imports / consumption*  
658

659 All domestic and foreign supply proportions were calculated by country and HS code.  
660

661 Domestic consumption weights were further resolved by multiplying them by the  
662 proportions found in our X matrix, which represents the estimated proportions of  
663 species by habitat and production method that go into each HS code by country. This  
664 gives the domestic supply proportions by country, HS code, species, habitat and  
665 production method. Domestic consumption was found by taking the total consumptions  
666 and multiplying them by the domestic weights.  
667

668 *Domestic Consumption =*  
669 *Consumption × domestic consumption weights*  
670 *× prop of species in HS code (by habitat method)*  
671

672 To resolve foreign consumption based on the species mix of the source country, we  
673 found the proportion of imports for each trade record by dividing the import volume by  
674 the total imports of each country by year. Foreign consumption was then calculated by  
675 multiplying consumption by foreign consumption weights and the proportion of  
676 imports. This provided a foreign consumption calculated by source country, exporter,  
677 importer, HS code, species, habitat, and production method.  
678

679 *Foreign consumption*  
680 *= consumption × foreign consumption weight × import proportion*  
681

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

## 684 Acknowledgements

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

## 691 Data and code availability

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

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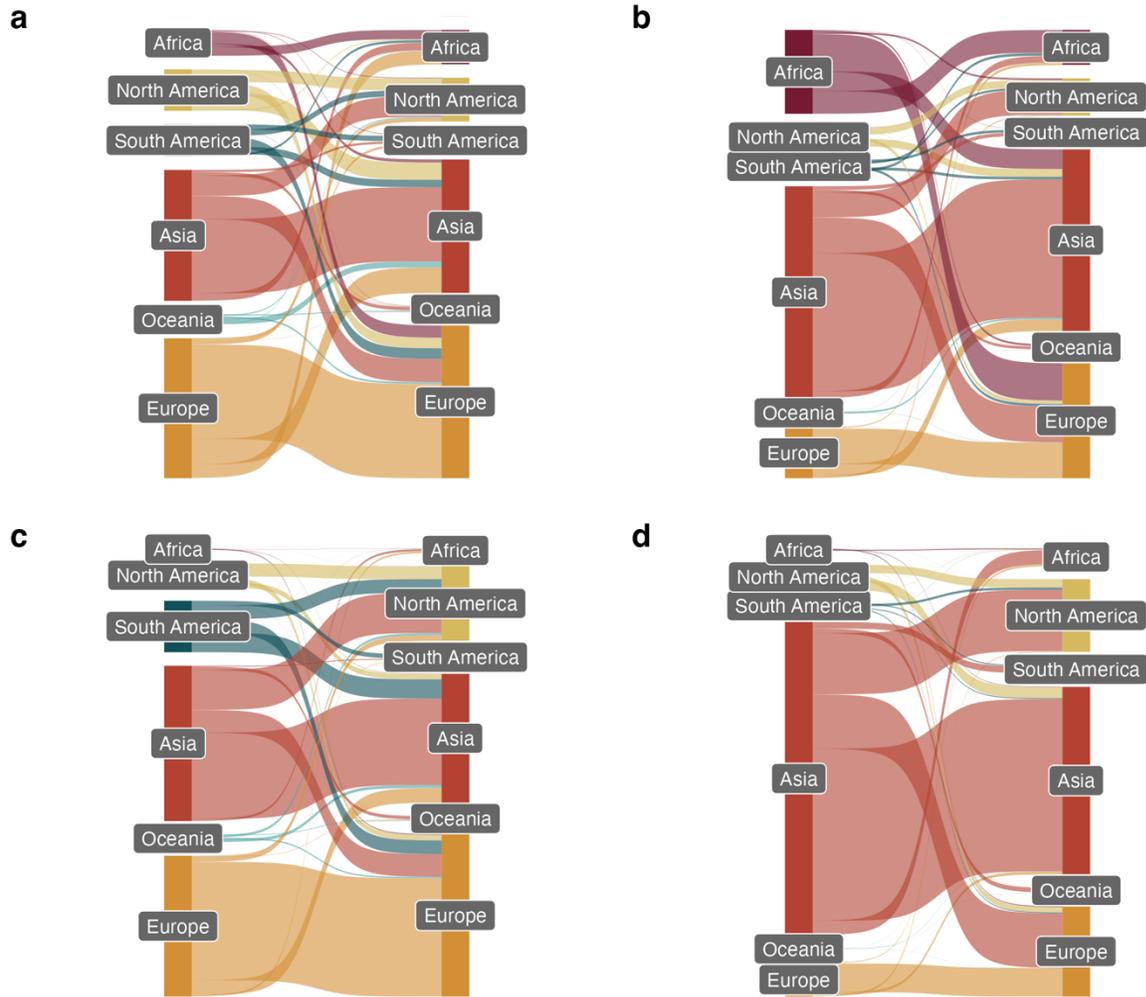
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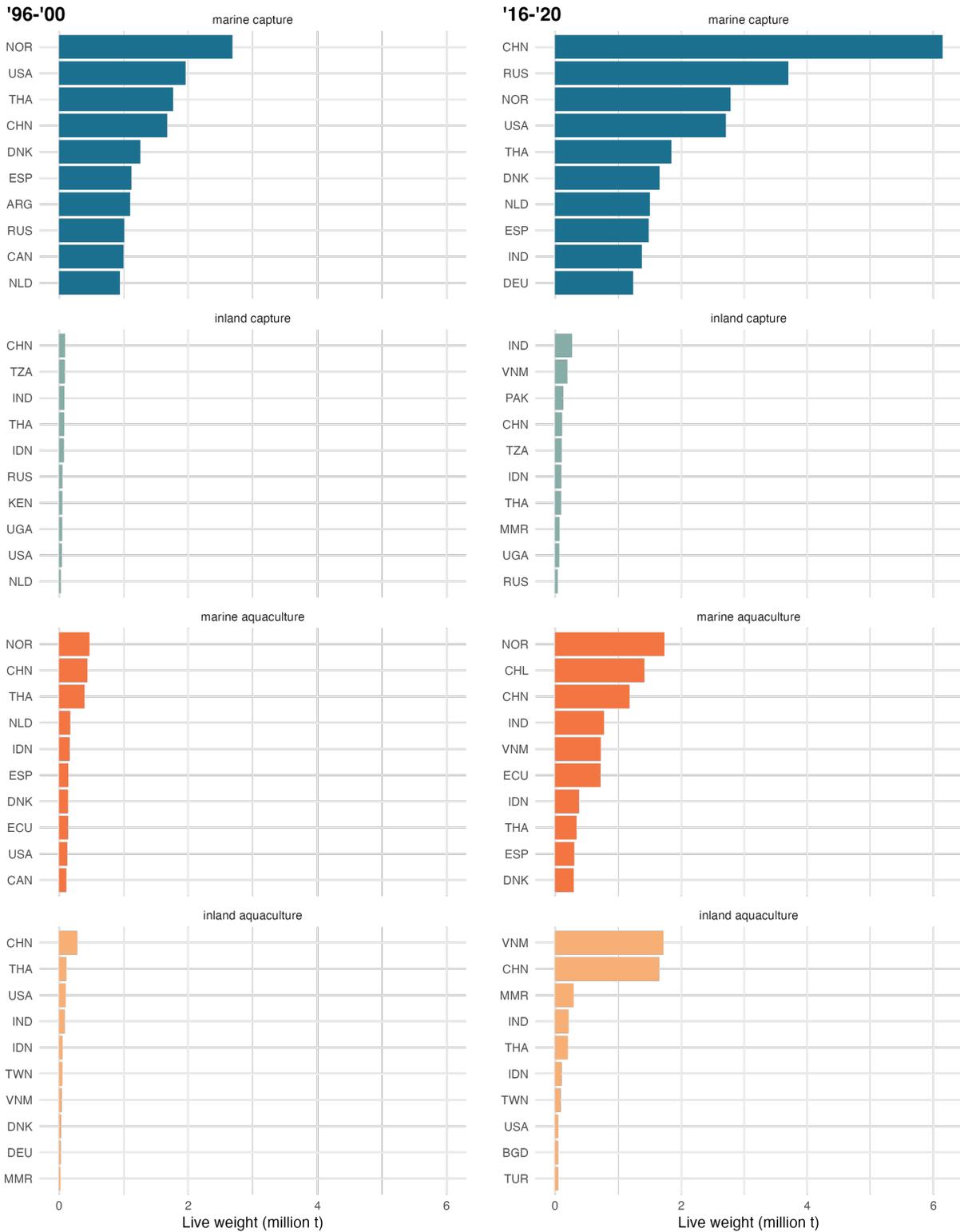
812 Supplementary Figures

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



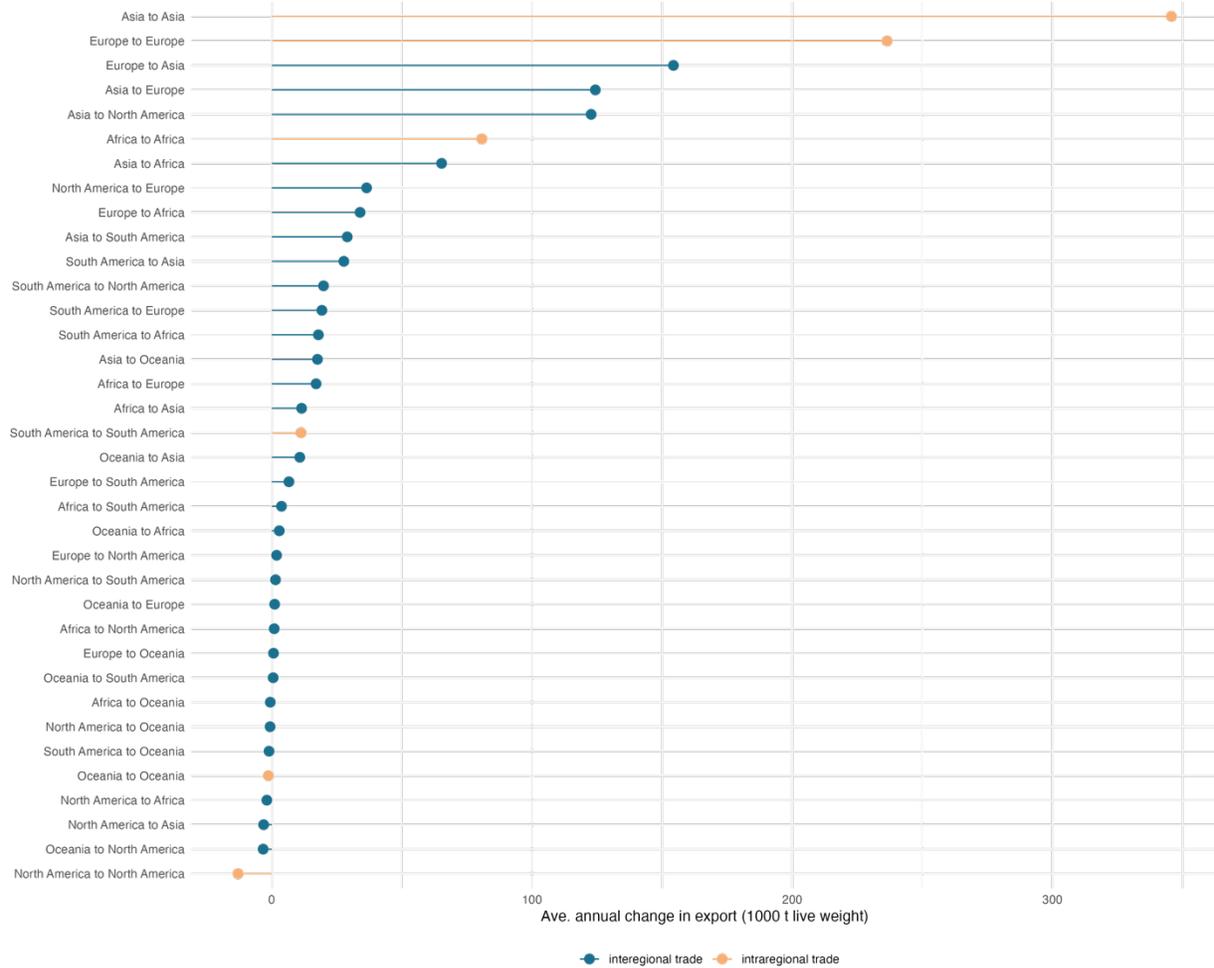
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820 Figure S2: Top exporters from 1996 - 2000 and 2016-2020 by habitat and production  
 821 method. Trade volumes represent the average annual trade volumes over that period in  
 822 live weight equivalent.



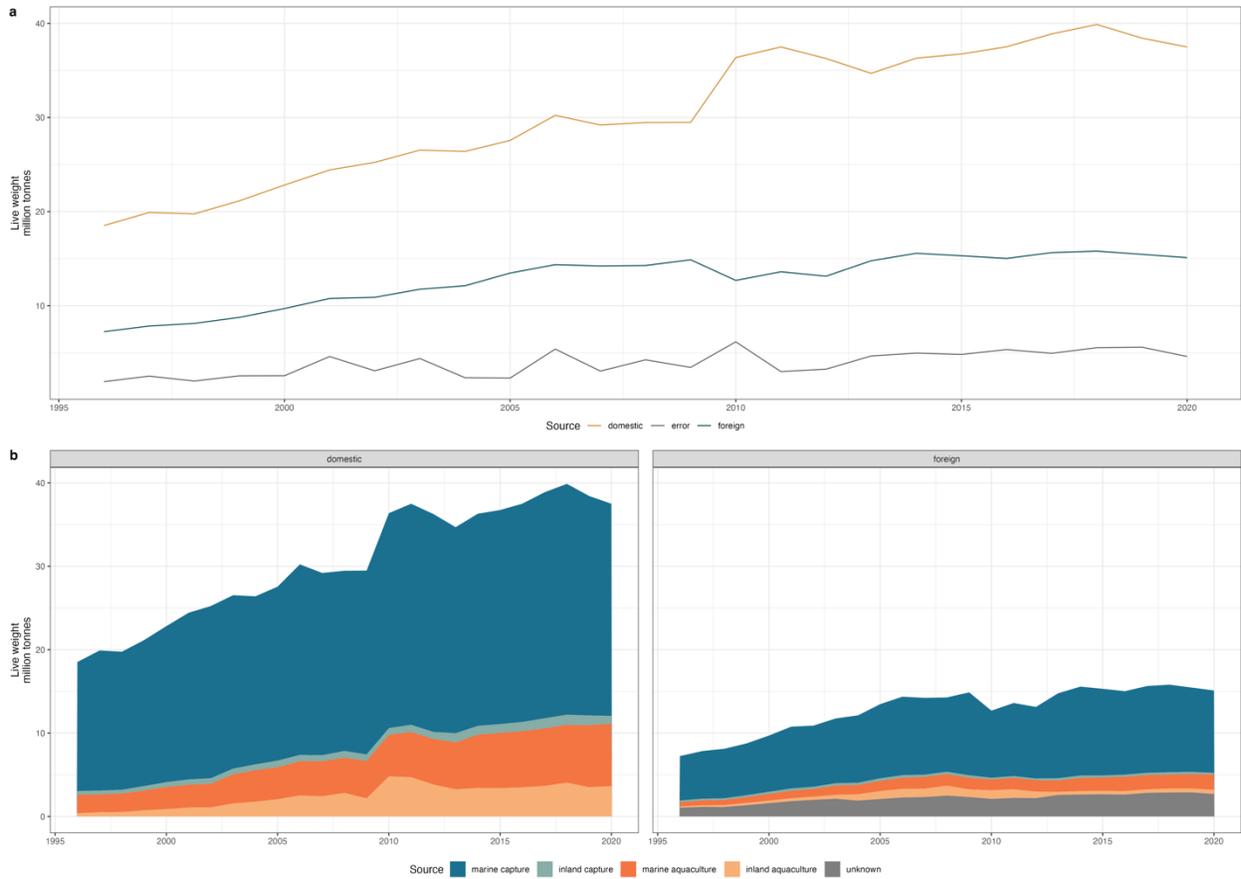
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824 Figure S3: Top importers from 1996 - 2000 and 2016-2020 by habitat and production  
 825 method. Trade volumes represent the average annual trade volumes over that period in  
 826 live weight equivalent.



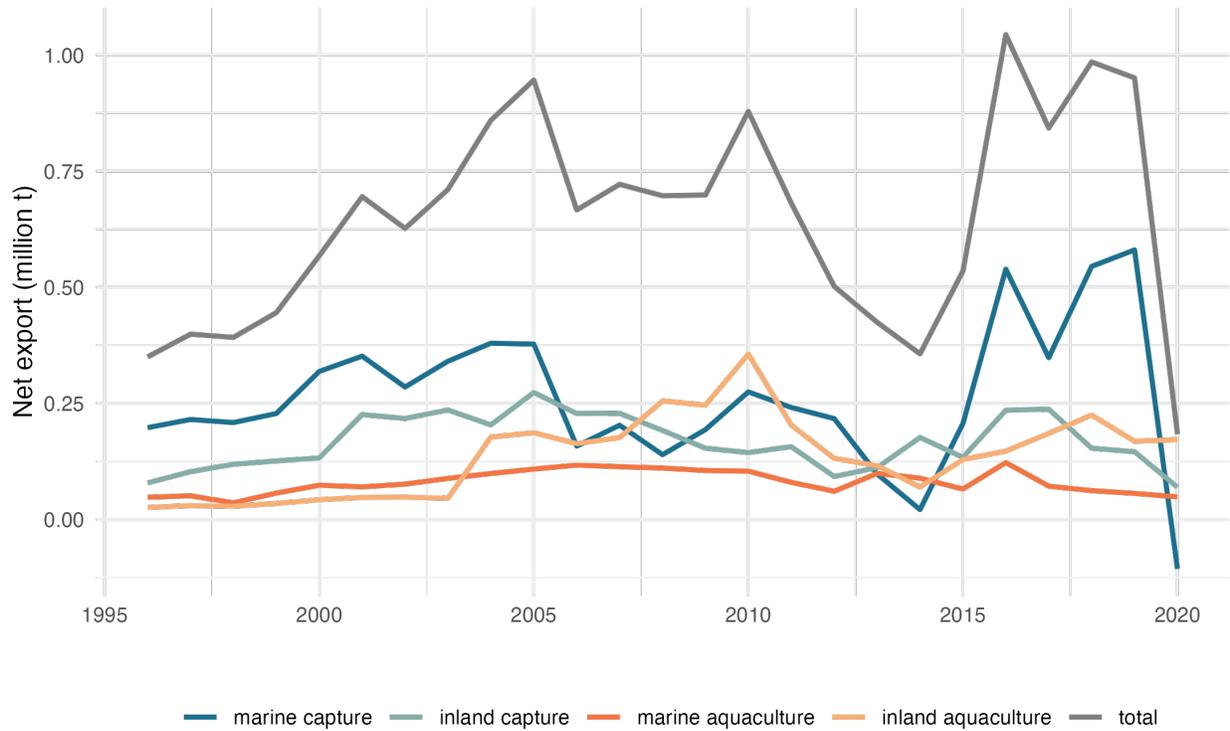
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828 Figure S4: Changes in interregional export (1000 live weight tonnes) flows.



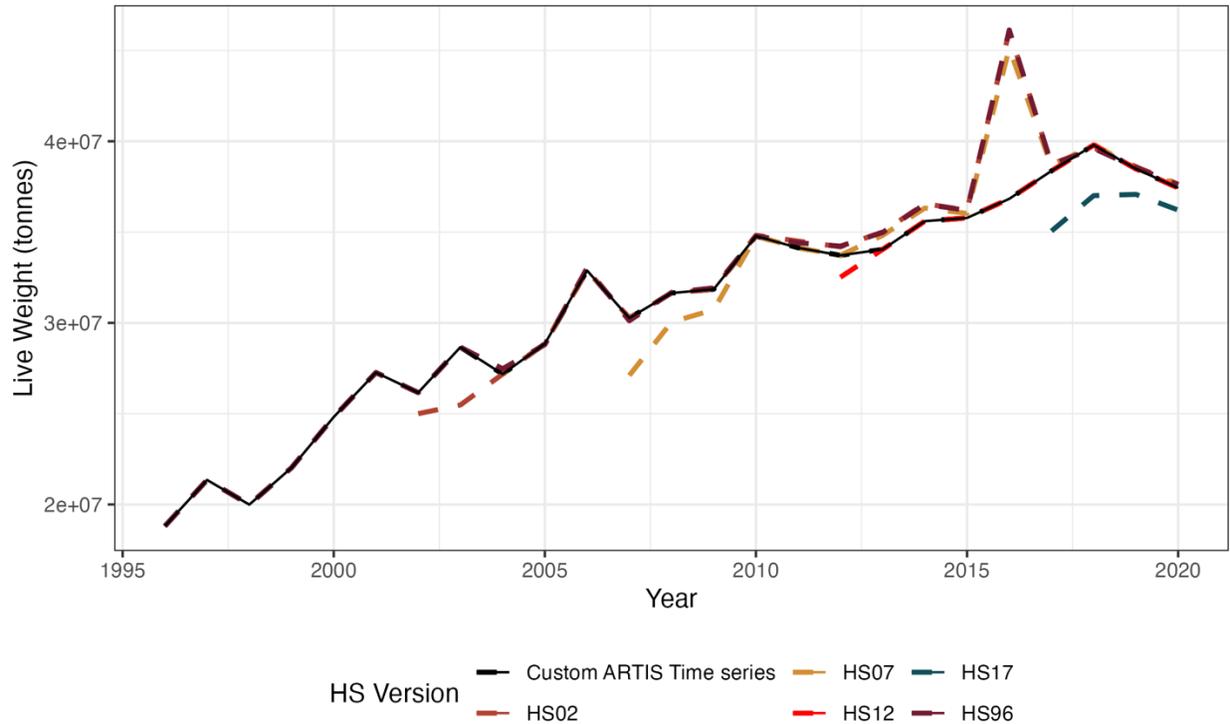
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830 Figure S5: Time series of blue food exports from 1996 - 2020 a) Blue food exports  
 831 disaggregated by domestic and foreign exports. b) Domestic and foreign exports are  
 832 disaggregated by habitat and production method.



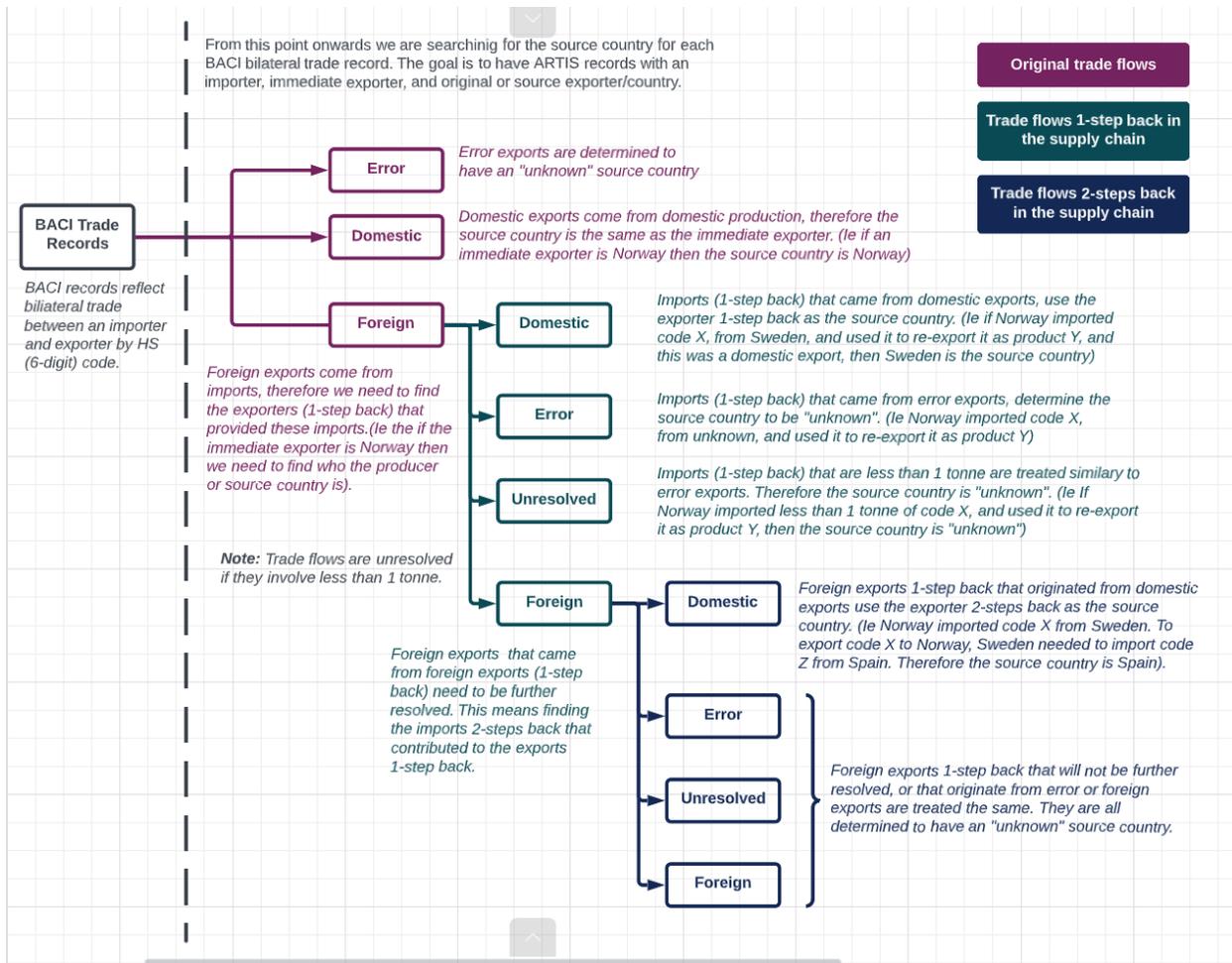
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834 Figure S6: Net exports from least developed countries, as defined by the United Nations.



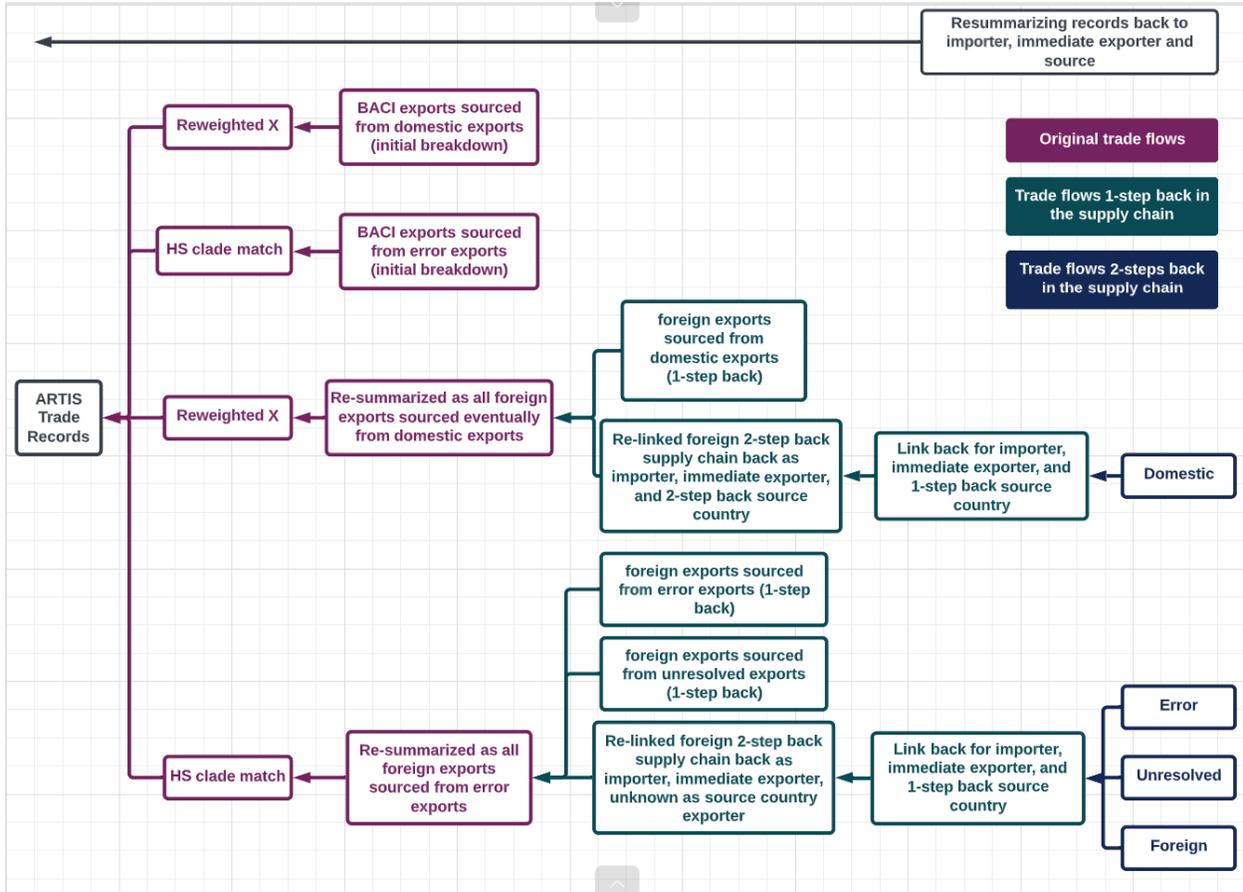
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836 Figure S7: Total live weight exports (tonnes) from 1996 - 2020, by HS Version, with the  
837 volumes for total ARTIS trade in black



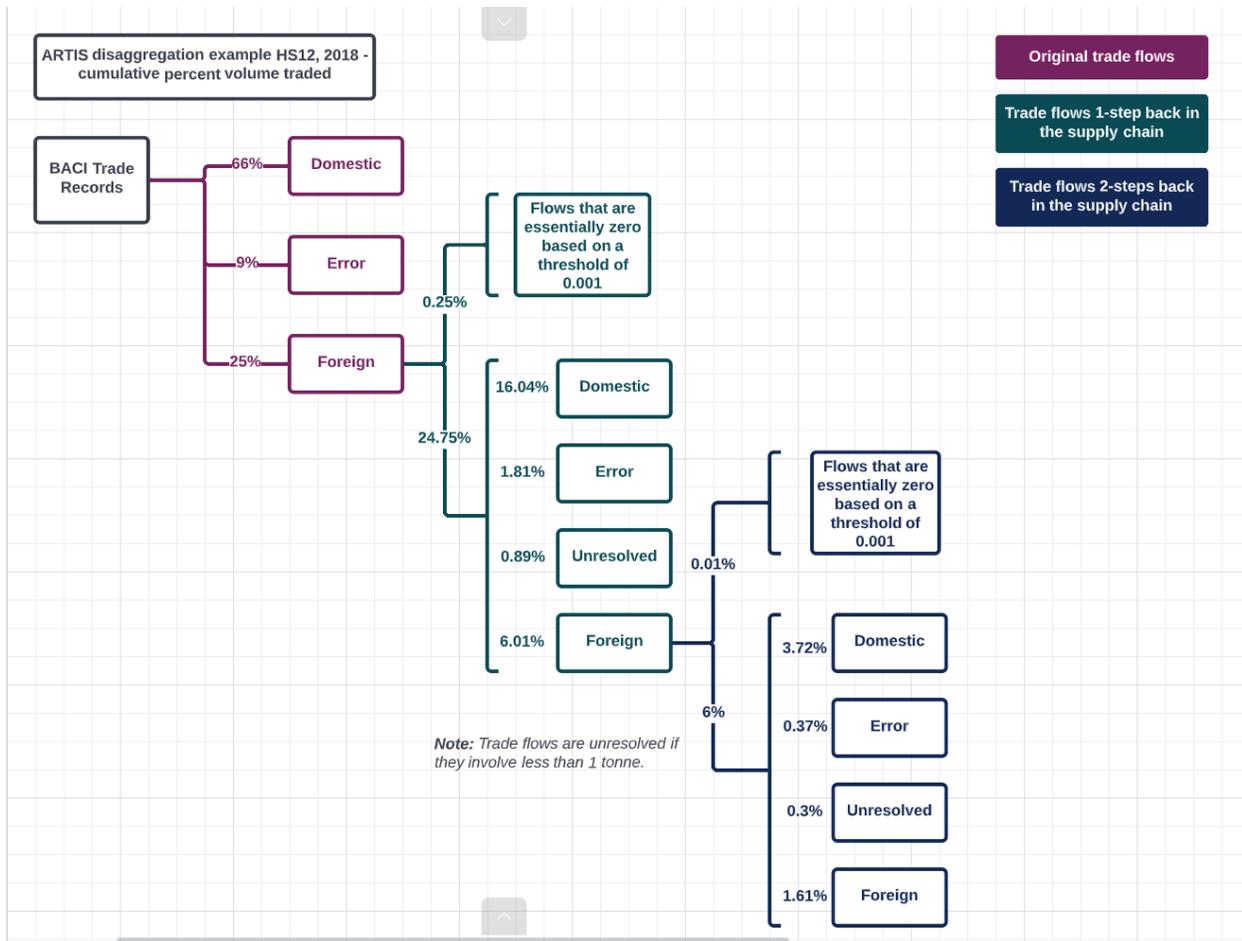
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Figure S8: Conceptual diagram of the disaggregation of BACI trade records to identify source countries of production.



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



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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.