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Recommendations for the Inclusion of Aquaculture Data in the Global Environmental Impacts of Consumption (GEIC) Indicator
Guidance Report

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Summary

Aquaculture is a rapidly growing sector with increasingly significant environmental impacts. Understanding the impacts of aquaculture production and trade is essential for informing policy relating to the sustainable consumption of commodities. This report synthesises recommendations for including aquaculture data in the Global Environmental Impacts of Consumption (GEIC) Indicator. Aquaculture production and trade data were assessed to determine the most suitable methods for inclusion in the indicator. A literature review was also conducted to identify key environmental impacts and potential datasets for linking to the production and trade data. The results from this report conclude that aquaculture production and bilateral trade data provided by the Food and Agriculture Organization (FAO) can be linked, and trade flows modelled in the indicator. Furthermore, environmental impacts datasets relating to eutrophication, greenhouse gas emissions, phosphorus use efficiency (PUE) and feed conversion ratios (FCR), were identified and can be matched to production data at either a species- or aggregated group-level. These results demonstrate that the inclusion of aquaculture data in the GEIC indicator is possible with the datasets currently identified, however further work would be required to identify additional species-level impact data. Including aquaculture data in the indicator would provide a more holistic assessment of the environmental impacts of consumption.

Contents

1 Introduction

This report aims to scope out the potential for the inclusion of aquaculture data in the Global Environmental Impacts of Consumption (GEIC) indicator. It begins by introducing the indicator, aquaculture and the aims and scope of this report (Section 1). It then explores the availability of production and trade data, uncertainties in the data and the key commodities, producers and consumers (Section 2). Next, it discusses the recommendations for linking production and trade data and methods for improving the accuracy of the datasets (Section 3). Finally, it describes the environmental impacts of aquaculture, assesses data availability for the environmental impacts of aquaculture and highlights the further work required for the potential inclusion of aquaculture data in the GEIC indicator (Section 4). Elements of this report are also relevant to the broader inclusion of capture fisheries data.

1.1 The Global Environmental Impacts of Consumption (GEIC) indicator

The Global Environmental Impacts of Consumption (GEIC) indicator provides estimates of global environmental impacts and risks driven by consumption and production activities. It links the production of over 160 agricultural commodities across 240 producer countries/territories ‘embedded’ within domestic and international supply chains to selected environmental impacts and risks associated with this production. The indicator is based on hybrid physical-financial multi-regional input-output (MRIO) modelling of global trade flows representing monetary inputs and outputs across different countries/territories and their commercial sectors and utilises physical data (tonnes of each commodity) from the Food and Agricultural Organization (FAO). The environmental impacts considered in the indicator include deforestation, biodiversity loss, carbon dioxide (CO_2) emissions related to deforestation, water consumption and scarcity-weighted water footprint, cropland area harvested and material consumption (tonnes of biomass production). The indicator can be used to inform the environmental impacts of consumption by 141 countries and territories. Data can be explored, visualised and downloaded using the interactive dashboard.

1.2 Why should aquaculture commodities be included in the indicator?

The GEIC indicator includes data for commodities produced from terrestrial agriculture, plus cattle pasture and industrial roundwood extraction. At the time of development, a primary driver was connection to deforestation-linked policy and this – combined with generally-more accessible data for terrestrial production and its impacts – determined an initial terrestrial focus. Data for commodities produced in aquatic systems, through capture fisheries or aquaculture, are currently not included and their environmental impacts cannot be assessed as a result. Aquaculture is the controlled cultivation of aquatic organisms such as fish, crustaceans, molluscs and aquatic plants in freshwater, brackish or saltwater farming systems. It involves production under controlled or semi-natural conditions, in contrast to the harvesting of wild fish through capture fisheries. Total fisheries and aquaculture production has significantly expanded since 1950, with the main driver of growth in recent years coming from aquaculture. In 2020, global aquaculture production totalled 122.6 million tonnes, valued at US$ 281.5 billion, and now accounts for more than half of the total production of aquatic commodities (FAO 2022b). The demand for aquaculture products continues to grow (FAO 2021). The environmental impacts and risks associated with aquaculture include eutrophication from feed inputs, side effects from antibiotics, the introduction of invasive species or foreign pathogens, habitat destruction (particularly mangrove forests), water pollution and the salinization/acidification of soils (De Lacerda *et al.* 2021; Ju *et al.* 2019; Peñuelas *et al.* 2013; Rasul & Majundar 2017; Schindler *et al.* 2008). With the expansion of the aquaculture sector and the associated environmental impacts, inclusion of aquaculture data in the GEIC indicator would provide a more holistic assessment of the environmental impacts of consumption.

1.3 Aims and scope

This report is based on a review of both scientific and grey literature, as well as the analysis of aquaculture and capture fisheries production and trade data provided by the FAO. The overall aims were to describe production and trade data for easier use in future work, assess the possibility of linking trade flows with the production of aquatic species, identify datasets for linking production quantities with environmental impacts, and provide recommendations for the inclusion of aquaculture data in the GEIC indicator.

The scope of this report largely focuses on describing the production and trade data and providing recommendations for combining the datasets in the GEIC indicator. It identifies gaps and uncertainties in both datasets, discusses methods for improving the accuracy of the trade data when linking to production and environmental impacts, and highlights the future work that would be required to incorporate aquaculture data in the indicator.

For the environmental impacts, this project builds on recommendations provided in the PRINCE phase 2 report by the Swedish Environmental Protection Agency. Datasets identified as potentially useful for inclusion in an aquaculture consumption indicator were assessed in greater depth, and other potential datasets were explored through a review of academic literature. However, this work was time-restricted as part of a three-month UKRI policy internship placement and so further work is needed to comprehensively assess the availability of data for linking aquaculture production to environmental impacts.

2 Production and trade data

To maintain consistency with the commodity data already used in the GEIC indicator, the focus of this report was FAO production and trade data. Fisheries and aquaculture datasets are provided for 1950–2021 through the FAO's FishStatJ software. Data can be filtered and aggregated using multiple columns (described in Section 2.1.1) and exported as csv files for further analysis. This section describes the datasets available, identifies the key commodities, producing countries and consuming countries, and highlights the uncertainties with the datasets and assumptions that would need to be made when including aquaculture data in the GEIC indicator. For this report, only the most recently available data for 2021 were used as a case study.

2.1 Production data

The FishStatJ software provides a workspace for Global Fishery and Aquaculture Production Statistics. Within the workspace there are separate datasets specific to global aquaculture production (quantity in live weight for 1950–2021 and value for 1984–2021), global capture production (quantity for 1950–2021) and combined global production by production source (quantity for 1950–2021). Regional capture fisheries statistics (1976–2021) are also provided separately from the global capture production. The Global Fishery and Aquaculture Production Statistics workspace also provides a dataset for global aquatic processed production statistics (quantity in weight for 1976–2021). This dataset is useful for assessing the production of derived products, such as fishmeal or fish oil, and determining the trade flows and processing steps associated with the aquaculture sector. The rest of this section focuses on the global aquaculture production (quantity in live weight for 1950–2021) dataset.

2.1.1 Description of the global aquaculture production dataset

The data columns provided, and their grouping classifications are summarised in Table 1. The FishStatJ software allows filtering, sorting and aggregating the data by one or more columns. For linking commodity production with consumption and environmental impacts in the GEIC indicator, the country level location data and Aquatic Sciences and Fisheries Information System (ASFIS) species level commodity data are the most suitable aggregations. These aggregations provide the finest resolution data, allowing the consumption of specific species and the environmental impacts of production to be linked to the relevant production country, thereby more accurately informing policy and trade.

Table 1. The data columns (bold) provided in the Global Aquaculture Production – Quantity (1950–2021) dataset. Each line below indicates a different "concept" used for aggregating the data within each column, for example Location can be any of Country, Continent, Geographical region, etc. Environment and Unit only have the one option indicated in bold. ASFIS is the Aquatic Sciences and Fisheries Information System, ISSCAAP is the International Standard Statistical Classification of Aquatic Animals and Plants, CPC is the Central Product Classification, FAOSTAT is the Food and Agricultural Organization Statistics.

Location	**Commodity**	**FAO Major Fishing Area**	**Environment**	**Unit**
Country Continent Geographical Region World Bank Income Classification Economic Group Fishery Commission Other Country Groups FAO Regional Groups	ASFIS Species (e.g. Common carp) ISSCAAP Division (e.g. Freshwater fishes) ISSCAAP Group (e.g. Carps, barbels & other cyprinids) Main Species Grouping (e.g. Pisces) Order (e.g. Cypriniformes) Family (e.g. Cyprinidae) FAOSTAT Group of Species (e.g. Freshwater & Diadromous fish) CPC Division (e.g. Fish & other fishing products) CPC Group (e.g. Fish, live, fresh or chilled for human consumption) CPC Class (e.g. Freshwater fish, live, fresh or chilled)	FAO Major Fishing Area Inland/ Marine areas Ocean Oceanic Area Fishing Area Region	**Freshwater, marine or brackish water**	**Tonnes – live weight**

2.1.2 Key aquaculture commodities

There are 710 species included in the FishStatJ Aquaculture production dataset for 2021. Of these species, 25 account for 77.94% of total global aquaculture production by weight. Including only species that contribute greater than 0.1% towards total global production weight leaves 84 species that account for 97% of live weight produced (potentially useful for simplifying the production data prior to combining with trade data and impacts). The most produced species globally was Japanese Kelp (10.38% of total weight), accounting for almost twice as much as the second most produced species, Eucheuma seaweeds nei (5.62%) [nei = not elsewhere included]. Whiteleg shrimp, Grass carp and Cupped oysters nei are the next most produced species (Figure 1).

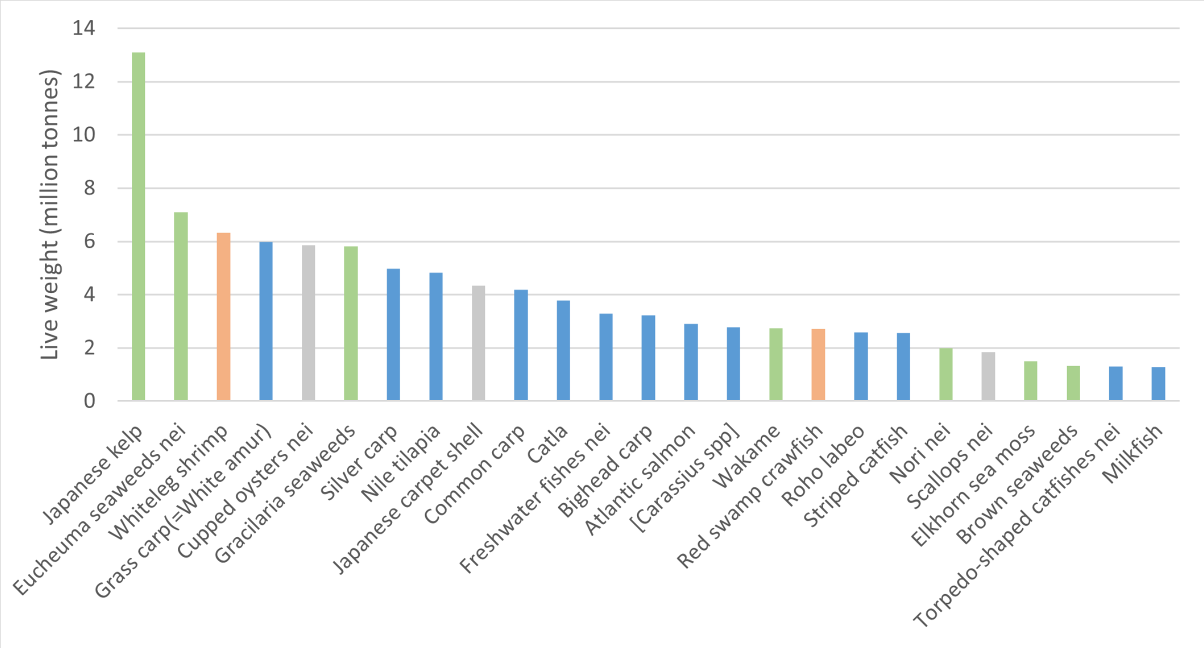

Figure 1. The top 25 most produced aquaculture species globally in 2021. Only species that contributed more than 1% of total global production are included. Green bars are seaweed, blue are fish, orange are crustaceans and grey are molluscs.

2.1.3 Major producing countries

Asia is the largest producer of aquaculture commodities, contributing ~92% towards global production in 2021. China dominates production within Asia (54% of global production in 2019), with Indonesia (13%), India (6.4%) and Vietnam (3.7%) the next biggest producers. Together these four countries made up 77% of total aquaculture production in 2019 (European Commission 2019). The contribution of each continent, and the main producing countries within each continent, are summarised in Table 2.

Table 2. World aquaculture production by region and selected major producers. Table from (FAO, 2022b), reproduced under Creative Commons license.

Regions and selected countries	2010 Animals (thousand tonnes, live weight)	2010 Algae (thousand tonnes, live weight)	2010 All species (thousand tonnes, live weight)	2020 Animals (thousand tonnes, live weight)	2020 Algae (thousand tonnes, live weight)	2020 All species (thousand tonnes, live weight)
Africa (% in world)	1286.1 (2.23)	138.3 (0.69)	1424.4 (1.83)	2250.2 (2.57)	104.1 (0.30)	2354.3 (1.92)
Egypt (% in Africa)	919.6 (71.50)		919.6 (64.56)	1591.9 (70.74)		1591.9 (67.62)
Northern Africa, excluding Egypt (% in Africa)	10.1 (0.78)		10.1 (0.71)	40.1 (1.78)	0.3 (0.27)	40.4 (1.72)
Nigeria (% in Africa)	200.5 (15.59)		200.5 (14.08)	261.7 (11.63)		261.7 (11.12)

Regions and selected countries	2010 Animals (thousand tonnes, live weight)	2010 Algae (thousand tonnes, live weight)	2010 All species (thousand tonnes, live weight)	2020 Animals (thousand tonnes, live weight)	2020 Algae (thousand tonnes, live weight)	2020 All species (thousand tonnes, live weight)
Sub-Saharan Africa, excluding Nigeria (% in Africa)	155.9 (12.12)	138.3 (100.00)	294.2 (20.66)	356.5 (15.84)	103.8 (99.73)	460.3 (19.55)
Americas (% in world)	2514.6 (4.35)	12.9 (0.06)	2527.6 (3.24)	4375.2 (5.00)	25.3 (0.07)	4400.5 (3.59)
Chile (% in Americas)	701.1 (27.88)	12.2 (94.17)	713.2 (28.22)	1485.9 (33.96)	19.6 (77.39)	1505.5 (34.21)
Rest of Latin America and the Caribbean (% in Americas)	1154.5 (45.91)	0.8 (5.83)	1155.3 (45.71)	2270.1 (51.89)	5.4 (21.43)	2275.5 (51.71)
North America (% in Americas)	659.0 (26.21)		659.0 (26.07)	619.2 (14.15)	0.3 (1.19)	619.5 (14.08)
Asia, excluding Cyprus (% in world)	51228.8 (88.70)	20008.2 (99.18)	71237.0 (91.41)	77377.0 (88.43)	34916.3 (99.54)	112293.3 (91.61)
China, mainland (% in Asia)	35513.4 (69.32)	12273.3 (61.34)	47786.7 (67.08)	49620.1 (64.13)	20862.9 (59.75)	70483.1 (62.77)
India (% in Asia)	3785.8 (7.39)	4.2 (0.02)	3790.0 (5.32)	8636.0 (11.16)	5.3 (0.02)	8614.3 (7.70)
Indonesia (% in Asia)	2304.8 (4.50)	3915.0 (19.57)	6219.8 (8.73)	5226.6 (6.75)	9618.4 (27.55)	14845.0 (13.22)
Viet Nam (% in Asia)	2683.1 (5.24)	18.2 (0.09)	2701.3 (3.79)	4600.8 (5.95)	13.9 (0.04)	4614.7 (4.11)
Bangladesh (% in Asia)	1308.5 (2.55)		1308.5 (1.84)	2583.9 (3.34)		2583.9 (2.30)
Rest of Asia (% in Asia)	5633.1 (11.00)	3797.4 (18.98)	9430.5 (13.24)	6709.6 (8.67)	4415.8 (12.65)	11125.4 (9.91)
Europe, including Cyprus (% in world)	2537.3 (4.39)	2.1 (0.01)	2539.4 (3.26)	3270.0 (3.74)	21.8 (0.06)	3291.7 (2.69)
Norway (% in Europe)	1019.8 (40.19)		1019.8 (40.16)	1490.1 (45.57)	0.3 (1.54)	1490.4 (45.28)

Regions and selected countries	2010 Animals (thousand tonnes, live weight)	2010 Algae (thousand tonnes, live weight)	2010 All species (thousand tonnes, live weight)	2020 Animals (thousand tonnes, live weight)	2020 Algae (thousand tonnes, live weight)	2020 All species (thousand tonnes, live weight)
European Union 27 (% in Europe)	1072.1 (45.25)	1.4 (70.17)	1073.5 (42.27)	1093.8 (33.45)	0.5 (2.38)	1094.3 (33.24)
Rest of Europe (% in Europe)	445.5 (17.56)	0.6 (29.83)	446.1 (17.57)	686.1 (20.98)	20.9 (96.08)	707.0 (21.48)
Oceania (% in world)	189.7 (0.33)	12.8 (0.06)	202.5 (0.26)	228.5 (0.26)	10.1 (0.03)	238.6 (0.19)
WORLD	**57756.4**	**20174.3**	**77930.7**	**87500.9**	**35077.6**	**122578.5**

The production of the main farmed aquaculture species differs by region and country. For example, Norway and Chile, countries with large areas of fjords protected from rough seas, as well as China, dominate marine aquaculture of finfish species using sea cages. However, countries like Norway produce cold-water species such as Atlantic Salmon, whereas China produces a more diverse composition of warm-water finfish species (FAO 2022b). Asian countries, notably China, Indonesia and the Philippines, are the largest producers of seaweeds, accounting for 99% of total production in 2020 (Table 2). In 2021, the United Kingdom almost only produced Atlantic Salmon (89% of production), as well as Rainbow trout (5.7%) and Sea mussels nei (4%) from aquaculture.

2.1.4 Data gaps and uncertainties

Only data for 2021 (the most recent year with data) were explored for this report; Covid19 may have affected production quantities, or some species or production systems more than others (FAO 2022b). There are also uncertainties for certain commodities in the production data. The production of some commodities can be reported in aggregations such as “Brown seaweeds” or “freshwater fishes nei” and not at the species level. These commodities contribute significantly to their larger aggregated groups for example the ISSCAAP group (see section 3.2 for more on classifications) and would be more difficult to link to species-specific environmental impacts. Other limitations of the production data include over or under-reporting. For example, some countries incentivise increasing economic output, which may lead to overreporting. Over or under-reporting would make linking production to environmental impacts, and identifying regions at risk of over-consumption, less accurate in the GEIC indicator.

2.2 Trade data

The FAO FishStatJ software provides global aquatic trade statistics by quantity (weight in tonnes) and value (USD) from 1976 to 2021 (all partner countries aggregated) and from 2019 to 2021 (by partner country). The trade data combine all aquatic products from both aquaculture and capture fisheries, and there is no distinguishing between the production source within the dataset. A dataset for border rejections is also provided monthly for 2016-2022, detailing the exporter country, importer country and reason for rejection, for example poor temperature, labelling issues or mercury. However, data are described as “fish”, “carp” or “shrimp” and do not match the production or trade commodity descriptions. Additionally, the number of border rejections are insignificant and will not be discussed further.

Trade data provided by UN Comtrade were also assessed to determine their suitability for linking to aquaculture production data. However, UN Comtrade data had similar uncertainties and difficulties with linking to production data as the FAO trade data (as discussed in section 2.2.5). Products were aggregated for multiple species and have long, complex product names, for example “Fish; fresh or chilled, Pacific salmon (*Oncorhynchus nerka, Oncorhynchus gorbuscha, Oncorhynchus keta, Oncorhynchus tschawytscha, Oncorhynchus kisutch, Oncorhynchus masou, Oncorhynchus rhodurus*), not fillets, meat of 0304, and edible fish offal of 0302.9”. Commodities can be downloaded in three levels of classification: Harmonised System (HS) which provides complicated product names similar to the example above, Standard International Trade Classification (SITC) which provides broader aggregated groups, for example “Salmonidae, fresh or chilled (excluding livers and roes)”, and Broad Economic Categories (BEC) which is too aggregated to link to production data, for example “Food and beverages”. Bilateral trade data can be obtained from UN Comtrade for a longer time period than from the FAO, however data for each commodity need to be downloaded manually without a license to the API and not all goods are reported in quantities (only value). Conversions would need to be made from values to quantities using the FishStatJ data (Gephart & Pace 2015) before production could be linked to environmental impacts using the Comtrade data. Therefore, the rest of this section focuses on the FAO aquatic trade statistics data.

2.2.1 Description of the aquatic trade statistics data

The data columns provided, and their grouping classifications are summarised in Table 3. The FishStatJ software allows filtering, sorting and aggregating the data by one of more columns. For inclusion in the GEIC indicator, the reporting and partner country level data and the Commodity level commodity data are the most suitable aggregations. Using the finest resolution aggregations will allow the production country (and associated environmental impacts) of consumed products to be modelled.

Table 3. The data columns (bold) provided in the Global aquatic trade by partner country (2019–2021) dataset. Each line below indicates a different "concept" used for aggregating the data within each column, for example "Reporting country" can be any of Reporting country, Reporters by Continent, etc. Trade flow and Unit only have the one option described in bold. SOFIA is The State of World Fisheries and Aquaculture, SITC4 is the 4-digit Standard International Trade Classification. Nei means 'not elsewhere included'.

Reporting Country	**Partner Country**	**Commodity**	**Trade flow**	**Unit**
Reporting Country	Partner Country	Commodity (e.g. Fish fillets, dried, salted or in brine, nei)	**Imports, exports or reexports**	**Tonnes – net product weight**
Reporters by Continent	Partners by Continent	Yearbook/SOFIA selection of commodities (e.g. Fish, crustaceans & molluscs)		
Reporters by Geographical Region	Partners by Geographical Region	FAO Major Group (e.g. Fish, dried, salted or smoked)		
Reporters by Economic Class	Partners by Economic Class	Harmonized Group (HS 2017) (e.g. Herrings, prepared or preserved)		
Reporters by Economic Group	Partners by Economic Group	FAO Yearbook Table (e.g. Herrings, prepared or preserved)		
Other Reporter Country Groups	Other Partner Country Groups	SITC 4 (e.g. Herrings, sardines, sardinella & brislings or sprats, whole or in pieces, but not minced)		
		ISSCAAP Division (e.g. Marine fishes)		
		ISSCAAP Group (e.g. Herrings, sardines, anchovies)		
		FAOSTAT Group (e.g. Pelagic, frozen, whole)		
		CPC Division (e.g. Fish & other fishing products)		
		CPC Group (e.g. Prepared & preserved fish, crustaceans, molluscs & other aquatic invertebrates)		
		CPC Class (e.g. Fish fillets, dried, salted or in brine, but not smoked)		

2.2.2 Key products traded

Commodities in the global aquatic trade statistics data include both raw products (e.g. whole fish) and processed products (e.g. fish fillets, fish waste). In 2021, 19 products accounted for 47.2% of total trade (Figure 2). The most traded product was fishmeal, accounting for 8.7% of total trade (including all imports, exports and reexports). Some of the other most traded products are non-specific "fish body oils", "fish waste" and "fish, frozen". Shrimps and prawns are the second most traded product, likely because all shrimp and prawn species are aggregated in the trade data, whereas fish products are often reported to the species level.

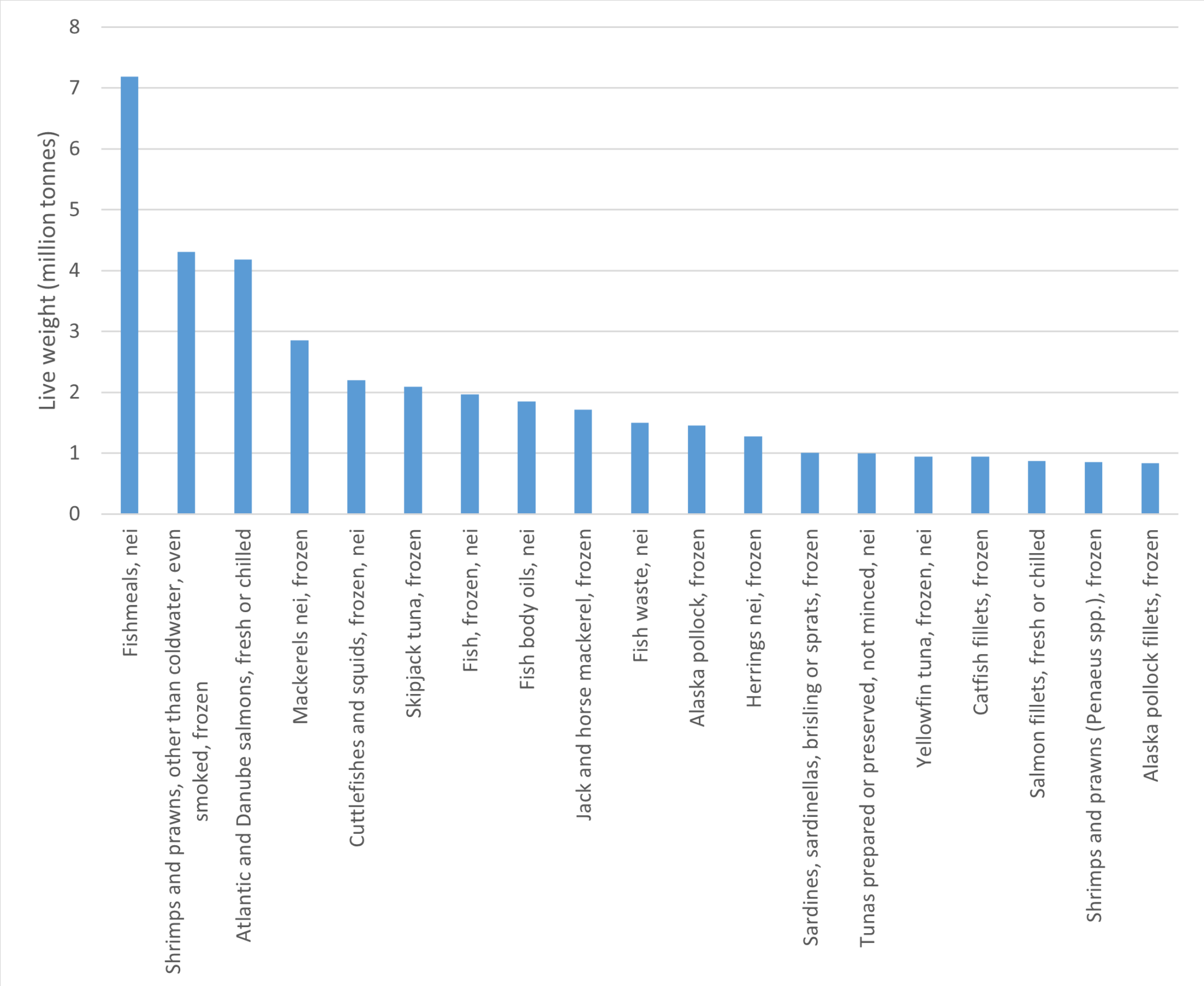

Figure 2. The 19 most traded aquatic products in 2021 including all imports, exports and reexports. Only products that contributed more than 1% towards total global trade are included.

To determine which of the most traded products could be linked to aquaculture production, a literature review was conducted, and the production data were explored further. Products not related to specific species, such as fish meal, fish oil and fish waste, are some of the most traded products. Fish meal is a high-protein powder used in livestock feed, mostly in aquaculture, and is the final product for around one-third of the annual world catch of fish (Barlow 2003). Around 90% of fish meal is produced from oily fish species, such as sardine, anchovy, capelin and menhaden, with less than 10% coming from white offal (frames) of cod and haddock (Barlow 2003). Therefore, fishmeal mostly comes from pelagic species fisheries and its production would not be directly linked to the environmental impacts of aquaculture; however, fish meal is often used in aquaculture feed. In the FishStatJ trade data, Peru dominates fish meal exports, exporting five times more fish meal than the second largest exporter Chile. China imports eight times more fish meal than any other country, highlighting its importance as feed in aquaculture. Fish body oil is largely a byproduct of fish meal production and therefore also comes mostly from pelagic species, with Peru also being the largest exporter of fish body oils. Fish waste is produced during fish processing and represents 20–80% of the fish. It is often then used to produce fish meal and fish oil, fish sauce, biodiesel and fish leather (Islam *et al.* 2021). Fish waste is produced through both aquaculture and capture fisheries.

To identify the main production source for species specific products, the top 25 aquaculture production species (77.9% of aquaculture production), the top 25 capture fisheries production species (50.3% of capture production) and the top 25 most exported products in 2021 (14% of total exports) were compared. Some traded products, for example "Salmon fillets" are aggregated and could come from mostly farmed species such as Atlantic salmon or mostly captured species such as Pacific salmon species; production data were explored to determine this. The production source of exported products that could not be easily assigned to either capture fisheries or aquaculture, specifically Shrimps and prawns, Salmon, Catfish and Tilapia, are visualised in Figure 3. These results were used to assign products to either aquaculture, capture fisheries or both for linking to environmental impacts. The allocations to aquaculture and capture fisheries for the top 25 most exported products are described in Table 4.

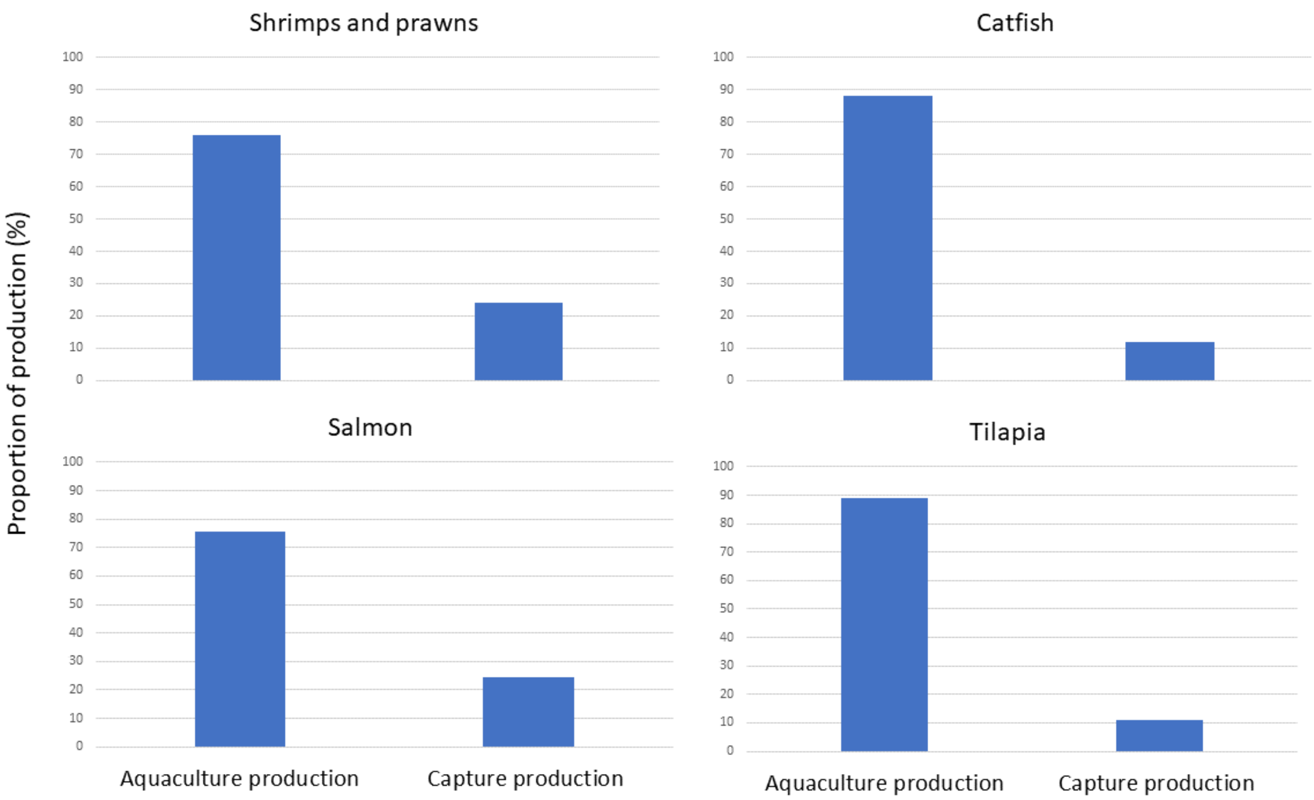

Figure 3. Proportion of production from each production source (Aquaculture or Capture fisheries) for four species groups that contribute towards some of the most exported products in 2021. As trade data are aggregated for these species, for example "Salmon fillets", all related species were combined in each production source for comparison, so for example Salmon included Atlantic salmon, Pink Salmon, Sockeye Salmon, *etc*.

Table 4. The top 25 aquaculture commodities (green [1]) and capture fisheries commodities (blue [2]) and the most likely production source of the top 25 most traded products. Products described in Figure 3 (i.e. Salmon, Shrimps and prawns, Catfish and Tilapia), were assigned to a production source if it contributed more than 75% of production. Products that have significant contributions from both aquaculture and capture fisheries are highlighted in yellow [3].

Top 25 fisheries capture species	Top 25 aquaculture species	Top 25 traded aquatic products
Marine fishes nei [2]	Japanese kelp [1]	Fishmeals, nei [2]
Anchoveta (= Peruvian anchovy) [2]	Eucheuma seaweeds nei [1]	Shrimps & prawns, other than coldwater, even smoked, frozen [1]
Freshwater fishes nei [2]	Whiteleg shrimp [1]	Atlantic & Danube salmons, fresh or chilled [1]
Alaska pollock (= Walleye poll.) [2]	Grass carp (= White amur) [1]	Mackerels nei, frozen [2]
Skipjack tuna [2]	Cupped oysters nei [1]	Cuttlefishes & squids, frozen, nei [2]
Pacific chub mackerel [2]	Gracilaria seaweeds [1]	Fish, frozen, nei [3]
Yellowfin tuna [2]	Silver carp [1]	Skipjack tuna, frozen [2]
Atlantic herring [2]	Nile tilapia [1]	Fish body oils, nei [2]
European pilchard (= Sardine) [2]	Japanese carpet shell [1]	Jack & horse mackerel, frozen [2]
Scads nei [2]	Common carp [1]	Alaska pollock, frozen [2]
Blue whiting (= Poutassou) [2]	Catla [1]	Fish waste, nei [3]
Pacific sardine [2]	Freshwater fishes nei [1]	Herrings nei, frozen [2]
Atlantic cod [2]	Bighead carp [1]	Atlantic mackerel, frozen [2]
Largehead hairtail [2]	Atlantic salmon [1]	Tunas prepared or preserved, not minced, nei [2]
Atlantic mackerel [2]	[*Carassius* spp] [1]	Skipjack prepared or preserved, not minced, nei [2]
Jumbo flying squid [2]	Wakame [1]	Salmon fillets, fresh or chilled [1]
Cyprinids nei [2]	Red swamp crawfish [1]	Alaska pollock fillets, frozen [2]
Japanese anchovy [2]	Roho labeo [1]	Yellowfin tuna, frozen, nei [2]
Chilean jack mackerel [2]	Striped catfish [1]	Catfish fillets, frozen [1]
Sardinellas nei [2]	Nori nei [1]	Tilapias prepared or preserved, not minced [1]
Natantian decapods nei [2]	Scallops nei [1]	Fish meat, minced or not, frozen, nei [3]
Indian oil sardine [2]	Elkhorn sea moss [1]	Salmon fillets, frozen [1]
Pink (= Humpback) salmon [2]	Brown seaweeds [1]	Sardines, sardinellas, brisling or sprats, frozen [2]

Top 25 fisheries capture species	Top 25 aquaculture species	Top 25 traded aquatic products
Clupeoids nei [2]	Torpedo-shaped catfishes nei [1]	Shrimps & prawns (*Penaeus* spp.), frozen [1]
Tuna-like fishes nei [2]	Milkfish [1]	Pacific salmons, frozen, nei [2]

2.2.3 Trade flows and processing steps

The production and trade datasets, as well as academic and grey literature, were used to better understand the processing steps in aquaculture supply chains, determine if products are processed within producing countries and elucidate the trade flows of commodities. From the FishStatJ trade data for Alaska Pollock, Tilapia, Salmon and Shrimp, raw products tend to be produced in one country, exported as raw or processed products elsewhere, or exported as raw products to Asia (mostly China) for processing to fillets then exported elsewhere. Tilapia was produced mostly in Indonesia, China and Egypt (similar levels of production). However, China dominated the export of raw and processed products. This indicates that China either imports raw Tilapia products for reexport or processing, or that Indonesia and Egypt consume more Tilapia within the country. For Salmon, the biggest producers are Norway and Chile, whereas the biggest exporters of raw products are Norway, Sweden and Chile. Sweden must import and reexport Salmon. Similarly, the biggest exporters of processed salmon products are Chile, Norway, Poland and China, indicating that processing of raw salmon products occurs away from the production country in Poland and China. The Atlantic salmon aquaculture supply chain is visualised in Figure 4.

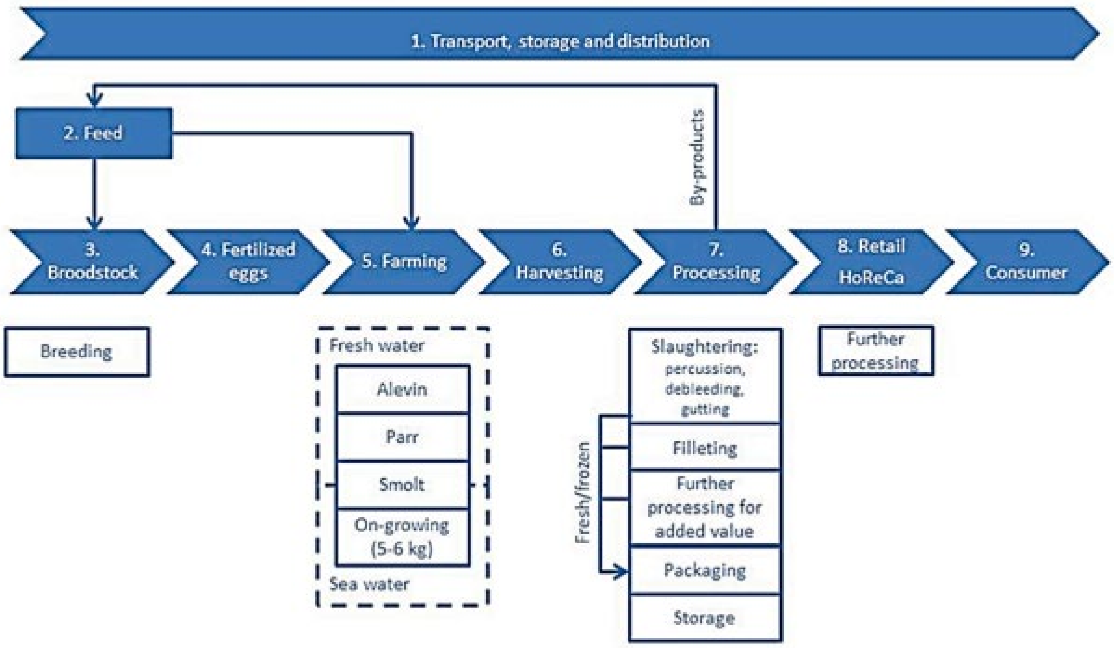

Figure 4. The Atlantic salmon aquaculture supply chain. From Marvin *et al.* (2020), reproduced under Creative Commons license.

2.2.4 Data gaps and uncertainties

The key limitation when linking aquaculture production and trade data is that the trade data combine aquaculture and capture fisheries commodities. Work towards disentangling aquaculture and fisheries products is described in section 2.2.2. Other uncertainties arise due to the aggregations used in the trade data. Production data are species specific, for example Atlantic salmon or Pink salmon, whereas trade data aggregates species into processed products, for example Salmon fillets. A surface level count of species vs. larger aggregations in the trade data identified 114 species products compared to 80 aggregated products (multiple species combined), highlighting the proportion of aggregations in the dataset. Similar products also have numerous names, for example salmon fillets, salmons, Salmonidae, etc. making linking to production species more technically challenging. Some of the most traded products are fish meal, fish body oils and fish waste, accounting for 12.7% of total trade in 2021. Furthermore, three of the five most traded ISSCAAP groups by weight (including imports, exports and reexports) are “Marine fishes not identified”, “Miscellaneous pelagic fish” and “Miscellaneous freshwater fish”. The uncertainty in origin for these products makes linking traded products to specific production systems within aquaculture and their environmental impacts difficult. There are also reexports within the trade data, mostly for fish species, making trade flows more complicated, however reported reexports do not account for a substantial amount of trade and could be ignored for inclusion in the indicator.

3 Linking production and trade

3.1 Classification schemes for species and products

Due to the uncertainties in traded products and the numerous reporting names for similar products, production and trade data could be matched using higher-level classifications. The ISSCAAP groups classification is the most suitable option as it is present in both production and trade datasets, and it provides enough resolution for linking production and consumption with environmental impacts. The other classification levels are described for production data in Table 2 and trade data in Table 3. There are 39 ISSCAAP groups, however 14 groups accounted for 95.5% of the total global production in 2021 (Table 5). These 14 groups are largely determined by between 1 to 7 key species, meaning that environmental impacts associated with the key species could be averaged or weighted to provide a single value for the environmental impacts of each ISSCAAP group.

Table 5. The 14 ISSCAAP groups that account for 95.5% of the total global aquaculture production in 2021. The key species within each group, and the proportion of the production in that group that the key species covers, are provided. This information would allow the ISSCAAP group classification to be used for linking production and trade data, whilst accounting for the environmental impacts of the key species within each group using weights or averages.

ISSCAAP group	Proportion of total weight produced globally in 2021	Key species within the group	Proportion the key species contribute to the total weight produced for the group
Carps, barbels & other cyprinids	24.68	Grass carp (=White amur) Silver carp Common carp Catla Bighead carp Roho labeo	6 species, 87.5%
Brown seaweeds	13.94	Japanese kelp Wakame Brown seaweeds	3 species, 98.1% Top two species, 90.5%
Red seaweeds	13.86	Eucheuma seaweeds nei Gracilaria seaweeds Nori nei Elkhorn sea moss Laver (Nori)	5 species, 98.3%

ISSCAAP group	Proportion of total weight produced globally in 2021	Key species within the group	Proportion the key species contribute to the total weight produced for the group
Miscellaneous freshwater fishes	9.66	Freshwater fishes nei Striped catfish Torpedo-shaped catfishes nei Largemouth black bass Yellow catfish Snakehead Channel catfish	8 species, 77.9%
Shrimps, prawns	5.83	Whiteleg shrimp Giant tiger prawn Penaeus shrimps nei Metapenaeus shrimps nei	4 species, 98.7% Whiteleg shrimp is 86.1% on its own
Oysters	5.30	Cupped oysters nei Pacific cupped oyster American cupped oyster	2 species, 97.0% 3 species, 99.0%
Tilapias & other cichlids	5.00	Nile tilapia Tilapias nei Blue-Nile tilapia, hybrid	3 species, 98.6%
Clams, cockles, arkshells	4.58	Japanese carpet shell Constricted tagelus Blood cockle	3 species, 97.2%
Salmons, trouts, smelts	3.37	Atlantic salmon Rainbow trout Coho (= Silver) salmon	3 species, 96.2%
Freshwater crustaceans	3.26	Red swamp crawfish Chinese mitten crab Giant river prawn Oriental river prawn	4 species, 98.7% 2 species, 85.6%

ISSCAAP group	Proportion of total weight produced globally in 2021	Key species within the group	Proportion the key species contribute to the total weight produced for the group
Miscellaneous coastal fishes	1.66	Mullets nei Gilthead seabream European seabass Large yellow croaker Groupers nei Japanese seabass Porgies, seabreams nei	7 species, 86.0%
Scallops, pectens	1.66	Scallops nei Yesso scallop Peruvian calico scallop	3 species, 99.4% 1 species, 87.6%
Mussels	1.60	Sea mussels nei Chilean mussel Blue mussel Green mussel New Zealand mussel Mediterranean mussel Korean mussel	7 species, 99.3% 2 species, 73.1%
Miscellaneous diadromous fishes	1.12	Milkfish Barramundi (=Giant seaperch)	2 species - 99.9% 1 species - 90.5%

3.2 Conversion factors

For linking production and trade to environmental impacts it is important to know the proportion of products traded as the raw product (e.g. whole fish) compared to the processed product (e.g. fish fillet). If processed products account for a large proportion of trade for certain species, the products will need to be converted to the live production weight equivalent to link to the impacts of producing that quantity of the product. Trade for three case study species (or aggregations of species) were explored further to determine the importance of processed products: Alaska Pollock, Salmon and Carps. For Alaska Pollock, the raw frozen product accounted for 52% of trade, whereas fillets and meat were ~40%. For Salmon species, frozen or chilled fillets accounted for ~>70% of trade. For Carp species, 74% of trade comes from the raw product either live, chilled or frozen. However, for Carps, processed products such as fillets and meat are often aggregated with Tilapia, Eels, Catfish and Nile Perch and may not be as accurate. Thus, the trade of processed products is species specific yet contributes a significant proportion and must be accounted for.

Conversion factors for aquatic trade products are provided by the FAO. Conversion factors are values (e.g. 1.63) that are used to multiply the weight of a processed product e.g. 1

tonne of fish fillets, to get the live production weight equivalent for the weight of that processed product (e.g. 1.63 tonnes of whole fish). Converting to live weight equivalent allows the trade of processed products to be more accurately linked to the environmental impacts of production. The conversion factors provided by the FAO cover a number of fish species, crustaceans and molluscs, and a range of processed products for each taxonomic group. However, some key aquaculture species, such as Carps, are not included, so averages or proxy species would need to be used to cover all species.

The use of conversion factors was tested for Alaska pollock, Salmon species and Shrimps and prawns. The ease of assigning conversion factors to the correct product differs significantly for different species. For example, Alaska pollock has eight traded products whereas Salmon species have 34 traded products. Additionally, for salmon products, only the raw whole fish is species specific e.g. Atlantic salmon. The processed products are not species specific, for example salmon fillets, so converting the processed products could not be linked to a specific species or production system for live weight equivalent. Converted processed products could be assigned to production species based on their relative production weights (e.g. 69% of total Salmon production in 2021 was Atlantic salmon). Furthermore, if products are exported multiple times or different processed products from the same raw fish are converted to live weight equivalent (this does not look common as the rest of the fish usually becomes fish meal or fish waste), then the converted values may be overestimated.

Despite their limitations, conversion factors do make a considerable difference in the total live weight equivalent of the commodity. Alaska pollock live weight equivalent was more than twice the non-converted processed products weight (Figure 5). For all Salmon species combined, using the conversion factors increased the live weight equivalent by 982,583 tonnes (Figure 5). This was also tested for just Atlantic salmon (69% of Salmon produced), however as described above only the raw traded products are species specific and the converted values were equal to the non-converted values. Shrimps and prawns were also difficult to convert due to the large number of processed products (e.g. canned, in brine, smoked, peeled, tails, meat, etc.), however conversion increased the traded weight by 419,158 tonnes (Figure 5). These values are not insignificant when linking to environmental impacts and conversion factors should be considered for use in the GEIC indicator.

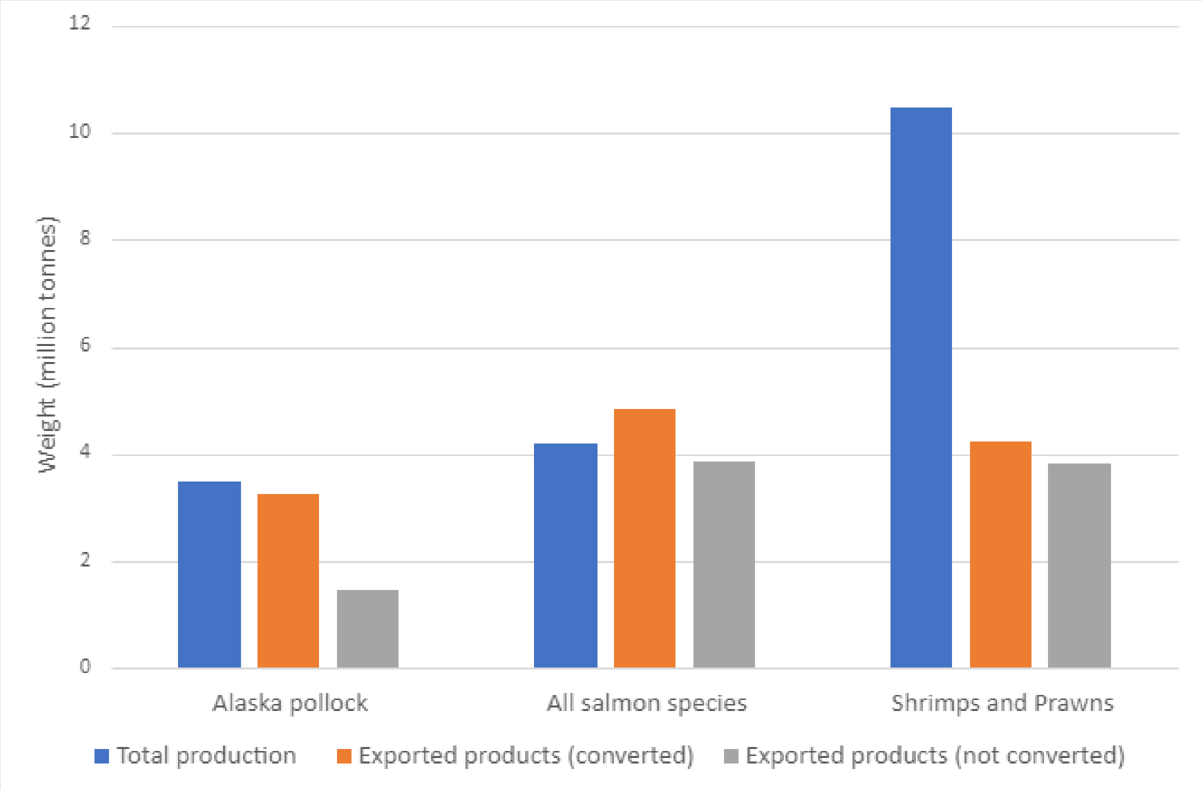

Figure 5. Converted weights, non-converted weights and the total production weight for Alaska Pollock, all Salmon species and Shrimp and prawns.

The availability of conversion factors for the top 25 most produced aquaculture species is described in Table 6. Only five species have a good match for some or most of their products, however most species have at least an indirect match or some of their products covered. Assumptions or averages would need to be used for the species or products not covered by the conversion factors.

Table 6. The top 25 most produced aquaculture species and their coverage of conversion factors provided by the FAO. Green [1] indicates a good match between processed products in the trade data and conversion factors data and yellow [2] indicates an indirect match or some product coverage. Seaweeds (grey [3]) are ignored due to their relatively benign environmental impact.

25 most produced aquaculture species	Conversion factors available
Japanese kelp [3]	NA
Eucheuma seaweeds nei [3]	NA
Whiteleg shrimp [2]	Shrimp & prawns - tails (shell on), tailed (peeled), meat. Shrimps canned. Shrimp & prawn paste
Grass carp (= White amur) [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Cupped oysters nei [2]	"Oysters" canned
Gracilaria seaweeds [3]	NA

25 most produced aquaculture species	Conversion factors available
Silver carp [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Nile tilapia [2]	Tilapia dried gutted, "freshwater fish" for other products
Japanese carpet shell [2]	Molluscs in containers - molluscs fermented, no specific matches for other products
Common carp [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Catla [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Freshwater fishes nei [1]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Bighead carp [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Atlantic salmon [1]	For some products, also non-specified salmon fillets
[*Carassius* spp] [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Wakame [3]	NA
Red swamp crawfish [2]	Not directly - could use lobsters or shrimps & prawn
Roho labeo [2]	No fillets (could convert from dried fillets for freshwater fish - 1.62 conversion for dried), "freshwater fish" for other products
Striped catfish [1]	Catfish fillets & steaks, "freshwater fish" for other products
Nori nei [3]	NA
Scallops nei [1]	Scallop meat/meat (dried), scallops canned
Elkhorn sea moss [3]	NA
Brown seaweeds [3]	NA
Torpedo-shaped catfishes nei [1]	Catfish fillets & steaks. "freshwater fish" for other products
Milkfish [2]	No direct matches, could use "other" fish dried fillet, "other pelagic" fish salted, "other small pelagic" smoked fish

3.3 Recommendations for linking production and trade

The following are recommendations for linking production and trade data in the GEIC indicator:

- Trade data mostly use the common names of species, whereas production data have both common and scientific names. Common names should be used for matching between the datasets.
- Some commodities have numerous reporting names for the same products, for example Salmon fillets, Salmonidae fillets, etc. Data cleaning would be required to

simplify matching. These complicated groups, such as Salmon or Shrimps and prawns, tend to be dominated by two to three products, usually the raw whole product (chilled, frozen) or fillets. It would be useful to identify the key products within these groups and only include these or set a minimum weight threshold for traded products (e.g. 500 tonnes) to remove the less important processed products.

- Consider using higher-level classifications of commodities such as ISSCAAP group. This would simplify linking production and trade; however, it may be less accurate as conversion factors could not be applied to the trade data as accurately. Environmental impacts studies often use these higher classifications (see section 4.4) so it could make linking to impacts or production systems easier. The key species within these groups (Table 5) could also be used to link to impacts.
- Use conversion factors for processed products in the trade data to convert to live weight equivalent. This will allow more accurate estimates of production mass and therefore associated environmental impacts. The limitations and assumptions that would need to be made are discussed in section 3.2.
- For linking to aquaculture impacts, use the combined aquaculture and capture production data to determine the main production source for different species in the trade data. The main production source for each species within each country could also be determined for more accurate linking to production systems.
- The exploratory work for this report was conducted manually or in Excel. Automating matching between production, trade and conversion factors would allow more useful assessments of their accuracy. It would also be useful for identifying the main production source for each species.

4 Environmental impacts of aquaculture

Aquaculture production can have a number of environmental impacts depending on the species produced, the production system, production technologies used and the environment. For the inclusion of aquaculture data in the GEIC indicator, the impacts of production need to be identified and linked to specific species or groups. This section discusses the impacts of aquaculture, differences between production systems, the options for linking impacts to species in the indicator, and the availability of datasets for environmental impacts.

4.1 Overview of impacts

Environmental impacts associated with aquaculture production include:

- Nutrient pollution, particularly from nitrogen and phosphorus, from feed input and fish waste. The feed conversion ratio (FCR) reflects the amount of feed needed per unit of animal weight gain, with nitrogen and phosphorus emissions from uneaten feed, and fish faeces, entering the surrounding environment. This can lead to eutrophication and harmful algal blooms (Fry *et al*. 2018; Peñuelas *et al*. 2013; Schindler *et al*. 2008).
- Habitat destruction, for example Mangrove forests in Southeast Asia and Brazil for shrimp farming (De Lacerda *et al*. 2021)
- Greenhouse gas emissions from commodity and feed production and the aquaculture supply chain. See Figure 6 for Salmon example.
- Increased demand for wild forage fish (from capture fisheries) to feed farmed piscivorous species, for example Salmon. The majority of fishmeal (greater than 80%) and fish oil (>90%) is used for aquaculture feeds (FAO 2022a; Huss 2003). Impacts are influenced by feed conversion ratios (FCR).
- Salinization and acidification of soils caused by various chemical treatments, such as adding lime. Sediment from abandoned aquaculture farms can remain hypersaline, acidic and eroded for long periods (Rajarshi 2011).
- Introduction of invasive plant and animal species when commodities are produced outside of their native range, particularly in open production systems such as cages (Ju *et al*. 2019).
- Introduction of pathogens and parasites to wild populations when production occurs in open systems or when unprocessed fish are used to feed more marketable carnivorous fish (Ju *et al*. 2019).
- Side effects of antibiotics, including the development of antibiotic-resistant bacteria and inducing oxidative stress (Limbu *et al*. 2020; Rasul & Majundar 2017).
- Competition between farmed and wild animals when aquaculture commodities escape from open systems such as cages and pens (WWF 2023).
- Input of fish waste into the environment, damaging benthic habitats, releasing antibiotics and pesticides, and decreasing dissolved oxygen (Costa-Pierce 2002).
- Plastic pollution, for example expanded polystyrene from floats and sea cage collars (FAO 2022b).

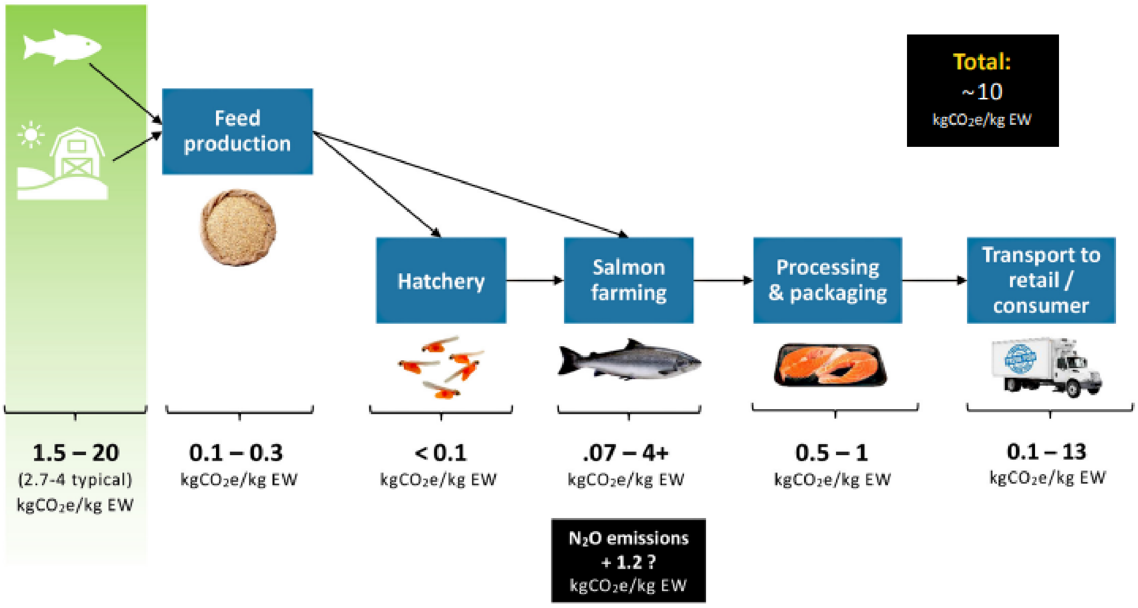

Figure 6. Range of Greenhouse Gas Emissions from aquaculture Salmon supply chains. Figure from Moberg *et al.* "Measuring and Mitigating GHGs: Salmon," WWF Markets Institute, 2022. Reproduced with permission.

The impacts described above refer to the production of fish, crustaceans and molluscs in aquaculture systems. Seaweeds constitute the top two and seven of the 25, most produced aquaculture species (Figure 1). However, seaweed farming does not require large supplementary phosphorus input and seaweeds have been shown to remove less than 0.01 Tg P yr^{-1} from aquatic ecosystems (Huang *et al*. 2020). Furthermore, seaweeds reduce ocean acidification by removing carbon dioxide and provide habitat for fish (Wilding *et al*. 2021). Seaweed farming can, however, increase the introduction of parasites and disease, entangle larger species when produced using lines, shade sea beds and facilitate the settlement of sediments on benthic habitats (Wilding *et al*. 2021). Despite the potential impacts of seaweed aquaculture, production is generally considered to be relatively environmentally benign in marine ecosystems (Wilding *et al*. 2021). Thus, the inclusion of seaweed in the GEIC indicator would add less value in the immediate term and the rest of this section will focus on fish, crustaceans and molluscs.

4.2 Production systems

The environmental impacts resulting from aquaculture production depend on the production system and technologies used (Bohnes *et al*. 2019). Aquaculture farming occurs in both marine ecosystems (mariculture) and inland freshwaters. In both environments, aquaculture can be conducted inshore, in well-sheltered shallow waters nearshore of a body of water using pens, or offshore, using enclosed sections of open water away from the shore such as cages. These productions systems are exposed to natural conditions including climate, water currents and nutrient cycles. Aquaculture can also be conducted onshore using artificial facilities built on land, such as fish tanks, ponds and raceways. Artificial systems allow greater control over the water quality and environmental conditions.

The production method used determines the risk to the environment (Bohnes *et al*. 2019). High-risk systems, including open-net pens or cages, allow free exchange between the farm and the environment. Waste, chemicals, parasites, disease and farmed fish can enter the surrounding environment from the cages. Salmon are often farmed using these methods. Ponds, either semi or fully enclosed, can also be high-risk depending on the management practices. Untreated waste can be discharged into the environment and pollute nearby waterways, however sufficient treatment of discharge can lower the risk. Ponds are often associated with habitat destruction, for example the removal of mangroves for shrimp farming (SeaChoice 2023). Low risk systems include closed systems, raceways, re-circulation systems and suspended aquaculture. Closed systems, raceways and re-circulation systems often treat effluent before it is discharged to natural water bodies and minimise the risk of fish escapes though barriers. Suspended aquaculture uses ropes, plastic trays or mesh bags and is used to produce filter feeding molluscs; there is a low risk if the species cultured are native and there is sufficient water flow to prevent waste accumulation (SeaChoice 2023). Similar to seaweeds, aquaculture production of filter feeding molluscs such as mussels and oysters can be considered environmentally benign in open, marine, passive-feeding production systems (Olaniyi 2022).

To accurately link production to environmental impacts, the production system should be accounted for where possible. The FishStatJ aquaculture production data include the FAO Major fishing area, for example “Asia – Inland waters” or “Indian Ocean, Eastern” and the production environment, for example “Marine”, “Freshwater” or “Brackishwater” (Table 1). In combination with the “Country” location data, aquaculture production could be linked to freshwater, brackish water or marine production systems at a country level. In terms of marine aquaculture, the FAO states that it is relatively easy to separate marine aquaculture (open water) and coastal aquaculture of crustaceans and molluscs based on the biological characteristics of these species and the culture methods adopted to rear them (FAO, 2022b). Crustaceans are almost only produced from coastal aquaculture, whereas 99.5% of molluscs are produced using marine aquaculture. However, it is more challenging to separate finfish for countries that produce different finfish species in both systems, due to the aggregation in the production data. Using data from alternative sources, the FAO determined that 37.4% of marine finfish production came from coastal aquaculture and 62.6% from marine aquaculture. The contribution of inland aquaculture and marine and coastal aquaculture to the production of five major groups by region are described in Table 7.

Table 7. Inland aquaculture and marine and coastal aquaculture production (tonnes, live weight) by region and by main species group in 2020. Table from (FAO 2022b), reproduced under Creative Commons license.

	Africa	**Americas**	**Asia**	**Europe**	**Oceania**	**World**	**Share in world total (%)**
Inland aquaculture	**1,857,361**	**1,253,959**	**50,776,437**	**555,472**	**5,301**	**54,448,530**	**100**
Finfish	1,857,209	1,179,727	45,526,599	551,802	5,124	49,120,461	90.2
Crustaceans	2	72,541	4,401,336	3,145	177	4,477,201	8.2
Molluscs	…	…	192,671	…	…	192,671	0.4
Other aquatic animals	…	370	593,161	176	…	593,707	1.1
(Aquatic animals subtotal)	*(1,857,211)*	*(1,252,638)*	*(50,713,767)*	*(555,123)*	*(5,301)*	*(54,384,040)*	*(99.9)*
Algae	150	1,321	62,670	349	…	64,490	0.1
Marine and coastal aquaculture	**496,934**	**3,146,589**	**61,524,239**	**2,728,935**	**233,279**	**68,129,976**	**100**
Finfish	379,322	1,240,969	4,502,888	2,121,867	95,587	8,340,633	12.2
Crustaceans	7,617	1,193,549	5,549,811	418	8,420	6,759,815	9.9
Molluscs	5,994	688,077	16,158,709	578,712	116,363	17,547,855	25.8
Other aquatic animals	60	…	459,185	6,495	2,844	468,584	0.7
(Aquatic animals subtotal)	*(392,993)*	*(3,122,595)*	*(2,667,0593)*	*(2,707,492)*	*(223,214)*	*(33,116,887)*	*(48.6)*
Algae	103,941	23,994	34,853,646	21,443	10,065	35,013,089	51.4

	Africa	**Americas**	**Asia**	**Europe**	**Oceania**	**World**	**Share in world total (%)**
Total aquaculture	**2354295**	**4400548**	**112300676**	**3284407**	**238580**	**122578506**	**100**
Finfish	2,236,531	2,420,696	50,029,487	2,673,669	100,711	57,461,094	46.9
Crustaceans	7,619	1,266,090	9,951,147	3,563	8,597	11,237,016	9.2
Molluscs	5,994	688,077	16,351,380	578,712	116,363	17,740,526	14.5
Other aquatic animals	60	370	1,052,346	6,671	2,844	1,062,291	0.9
(Aquatic animals subtotal)	*(2,250,204)*	*(4,375,233)*	*(77,384,360)*	*(3,262,615)*	*(228,515)*	*(87,500,927)*	*(71.5)*
Algae	104,091	25,315	34,916,316	21,792	10,065	35,077,579	28.6

Aggregations in the production data create similar challenges when assigning aquaculture species to inland production systems. Inland aquaculture employs diverse culture methods and facilities. Constructed earthen ponds are by far the most widespread culture method, particularly for finfish (finfish contribute 90.2% to total inland aquaculture production (FAO 2022b). Cage culture and, to a lesser extent, pen culture are also widely used, but their relative importance varies by country (Table 8). However, the contribution of cage and pen culture in inland aquaculture are relatively insignificant.

Table 8. Contribution of cage and pen culture to inland finfish aquaculture production (tonnes, live weight) in selected countries. Table from (FAO 2022b), reproduced under Creative Commons license.

Cage culture	Total production 2010	Cage production 2010	Contribution 2010 (%)	Total production 2015	Cage production 2015	Contribution 2015 (%)	Total production 2020	Cage production 2020	Contribution 2020 (%)
China (mainland)	19913	1131	5.7	24642	1379	5.6	25864	321	1.2
Indonesia	1332	121	9.1	2955	191	6.5	3390	650	19.2
Bangladesh	1147	…	…	1831	2	0.1	2294	5	0.2
Egypt	920	160	17.4	1175	173	14.7	1592	201	12.6
Thailand	404	40	9.9	391	33	8.4	369	32	8.7
Philippines	308	103	33.3	303	95	31.2	285	74	26.0
Russian Federation	115	25	21.6	138	30	21.6	189	59	31.2
Colombia	68	23	33.5	93	19	20.8	173	30	17.5
Türkiye	79			101	70	69.0	128	100	78.0

Pen culture	Total production 2010	Cage production 2010	Contribution 2010 (%)	Total production 2015	Cage production 2015	Contribution 2015 (%)	Total production 2020	Cage production 2020	Contribution 2020 (%)
China (mainland)	19913	523	2.6	24642	481	2.0	25864	37	0.1
Indonesia	1332	309	23.2	2955	577	19.5	3390	24	0.7
Bangladesh	1147	…	…	1831	13	0.7	2294	13	0.6
Philippines	308	63	20.3	303	61	20.1	285	40	14.0
Russian Federation	115	5	4.7	138	3	2.4	189	10	5.2

For linking production quantities to more specific production systems, for example earthen ponds, cage culture or pen culture, coastal aquaculture or marine aquaculture, a detailed review of species level production by country would be required. Alternatively, standardised impacts data should be used for each commodity and production systems disregarded, or assumptions should be made in the GEIC indicator:

- Production systems would need to be assigned to broader groups such as molluscs, crustaceans or finfish, rather than to species level.
- Molluscs are produced using open water marine aquaculture.
- The 60% of total crustacean production in marine and coastal aquaculture should be assigned to coastal aquaculture production systems. The remaining 40% from inland aquaculture should be assigned to earthen ponds.
- The 85% of finfish production from inland aquaculture should be assigned to constructed earthen ponds. For the remaining 15% in marine aquaculture, 62.6% should be assigned to open water marine aquaculture and 37.4% to coastal aquaculture systems.
- Ignore the relatively insignificant impacts of seaweeds and filter feeding molluscs, such as oysters and mussels, when produced in open water aquaculture systems.

4.3 Options for linking impacts to production and trade data

Environmental impacts can be linked to aquaculture production either quantitatively or qualitatively in the GEIC indicator. Impacts with a quantitative value can be linked to live production weight in tonnes by species; examples include greenhouse gas emissions, feed conversion ratios (FCR), area of habitat destruction and nutrient inputs. Impacts without such values, such as the introduction of disease, parasites or invasive species, could be linked to production using qualitative flags, for instance low risk, medium risk or high risk. Disease and invasive species risk would require information on the production system used. Quantitative values would be more useful when assessing the impacts of consumption on the environment by species and production region. However, the methods used for including impacts in the indicator would depend on the availability of data and its coverage of aquaculture species and production systems.

4.4 Data availability

This section explores the availability of datasets on the environmental impacts of production for aquaculture species. The work presented here builds on the preliminary work conducted for the PRINCE phase 2 report by the Swedish Environmental Protection Agency. The report identified two key studies with potential for providing data on the impacts of production, Huang *et al*. (2020) and Lucas *et al* (2021) but stated that more work needed to be done to determine their suitability for linking to FAO production data. These datasets have been explored further and their suitability for inclusion in the indicator are discussed in sections 4.4.1 and 4.4.2 below. Other potential datasets have also been identified and described, including greenhouse gas emissions and Feed conversion ratios (FCR).

4.4.1 Phosphorus use efficiency (PUE) – Huang *et al*. (2020)

Phosphorus (P) is an essential element in all forms of life and is a required input in aquaculture for increasing food production. Phosphorus input in aquaculture occurs directly through feeds or through fertilisers that increase primary productivity for herbivores and omnivores (Huang *et al*. 2020). Excessive P input that is not used up by the farmed species can enter the environment and lead to eutrophication (the accumulation of nutrients) in inland and coastal waters. Impacts of eutrophication in aquatic systems include the degradation of water quality, increases in harmful algal blooms, decreases in dissolved oxygen and a decline in biodiversity (Peñuelas *et al*. 2013; Schindler *et al*. 2008). The input of excessive P to an aquaculture system, and therefore the associated risk to the environment, can be quantified using the phosphorus use efficiency (PUE). PUE is defined as the proportion of supplementary P applied to feed fish and fertilise the system that is recovered in harvested fish, or the ratio of harvested to input P. Lower values indicate less efficient use of P, higher quantities of P input into the aquatic environment and a higher risk of eutrophication.

Huang *et al*. (2020) compiled a dataset detailing the phosphorus use efficiency of different farmed and captured aquaculture and fisheries species from 96 peer-reviewed publications. The data covers 21 individual species, several aggregations of species farmed together and a large number of nondescript “fish”, “crab” or “shrimp” data entries. Columns are included to distinguish between those farmed in ponds vs not in ponds, marine or freshwater, and fish, mollusc or crustacean (or a combination for the aggregations). These data flags would match up with the production system assumptions suggested in section 4.2 i.e. assigning production systems to broader groups and using averages (finfish, molluscs, crustaceans), obtaining average PUE estimates for pond and non-pond farming of finfish in inland aquaculture, and comparing PUE between marine and freshwater production systems for similar species. PUE data are not provided for all of the important aquaculture species, however, ignoring seaweeds, all of the top 25 most produced aquaculture species have either a direct match or a related species match (Table 8). Table 9 provides the average PUE values for broader group aggregations i.e. crustaceans, molluscs and fish by freshwater or marine production. These values could be assigned to aquaculture species without direct or indirect matches in the PUE dataset.

Table 9. The top 25 most produced aquaculture species and their species matches with the phosphorus use efficiency (PUE) data in the Huang *et al*. (2020) dataset. Direct (green [1]) and related (yellow [2]) matches are provided. Seaweeds (grey [3]) are ignored for matching as they are not included in the PUE dataset and are considered relatively environmentally benign. The average PUE values for each match are provided for both pond and non-pond production and marine or freshwater production systems (if available).

25 most produced aquaculture species (FishStatJ)	PUE data match	Average PUE value for match (%)
Japanese kelp	[3]	-
Eucheuma seaweeds nei	[3]	-
Whiteleg shrimp	White shrimp [1]	21.8 (pond, marine)
Grass carp (= White amur)	Common carp [2]	75.5 (Pond, freshwater)
Cupped oysters nei	Abalone [2]	14.3 (Pond, marine)
Gracilaria seaweeds	[3]	-
Silver carp	Common carp [2]	75.5 (Pond, freshwater)
Nile tilapia	Nile tilapia [1]	16.0 (Pond, freshwater)
Japanese carpet shell	Abalone [2]	14.3 (Pond, marine)
Common carp	Common carp [1]	75.5 (Pond, freshwater)
Catla	Common carp [2]	75.5 (Pond, freshwater)

25 most produced aquaculture species (FishStatJ)	PUE data match	Average PUE value for match (%)
Freshwater fishes nei	Fish (several specified and non-specified freshwater fish) [1]	28.3 (All fish, freshwater) 16.6 (Not pond, freshwater) 30.0 (Pond, freshwater)
Bighead carp	Common carp [2]	75.5 (Pond, freshwater)
Atlantic salmon	Rainbow Trout [2]	13.2 (Pond, freshwater) 14.0 (Not pond, marine)
[*Carassius* spp]	Crucian carp [1]	24.1 (Pond, freshwater)
Wakame	[3]	-
Red swamp crawfish	Giant freshwater Prawn [2]	9.9 (Pond, freshwater)
Roho labeo	Common carp [2]	75.5 (Pond, freshwater)
Striped catfish	Striped catfish [1]	15.7 (Pond, freshwater)
Nori nei	[3]	-
Scallops nei	Abalone [2]	14.3 (Pond, marine)
Elkhorn sea moss	[3]	-
Brown seaweeds	[3]	-
Torpedo-shaped catfishes nei	Hybrid catfish, Striped catfish, Channel catfish [2]	22.4 (Pond, freshwater)
Milkfish	Fish (several specified and non-specified marine fish) [2]	31.2 (All fish, marine) 26.9 (Not pond, marine) 32.8 (Pond, marine)

Table 10. The average phosphorus use efficiency (PUE) values for broader species aggregations by marine or freshwater production systems. Values can be used for commodities without species-level data. Data are averaged from species values provided by Huang *et al*. (2020).

Species group	Freshwater or marine	PUE average
Crustaceans	Marine	15.1
	Freshwater	12.0
Molluscs	Marine	14.3
	Freshwater	NA
Fish	Marine	31.2
	Freshwater	28.3

4.4.2 Climate change, eutrophication and energy demand – Lucas *et al.* (2021)

The second study identified as having potential for providing environmental impacts data in the Prince2 report was Lucas *et al.* (2021). This LCA-inspired study quantifies the impacts of aquaculture with a focus on French production and trade, however mean impacts at the global level are provided for broad species groups, for instance Salmonidae, Shrimps and prawns and freshwater fish (Table 11). The three impacts included are climate change (kg CO_2/tonne), eutrophication (kg PO_4^{-3}/tonne) and energy demand (MJ/tonne). The eutrophication potential considers the emissions of reactive nitrogen and phosphorus in the production system.

Table 11. Estimates of climate-, eutrophication- and energy-linked indicators per tonne of live weight, at global level, for different aquaculture production systems. The most closely related ISSCAAP group has been added for linking to the FAO production data. From Lucas *et al.* (2021).

Species group	ISSCAAP group match up	Climate (kg CO_2 eq.)	Eutrophication (kg PO_4^{-3} eq.)	Energy demand (MJ)
Demersal & benthic	Miscellaneous demersal fishes	2,368	8	27,961
Shellfish	Clams, cockles, arkshells	545	1	10,414
Pelagic	Miscellaneous pelagic fishes	1,155	3	17,917
Salmonidae	Salmons, trouts, smelts	2,143	48	33,283
Shrimps & prawns	Shrimps, Prawns	10,344	78	34,446
Crustaceans (excl. S&P)	Freshwater crustaceans, Miscellaneous marine crustaceans	10,315	34	132,906
Freshwater fish	Miscellaneous freshwater fishes	5,370	33	19,731
Cephalopods	Squids, cuttlefishes, octopuses	6,094	14	47,953
Seabass & seabream	Marine fishes not identified	2,909	65	45,147
Overall	NA	2,622	18	26,599

The data provided here have a low resolution and would not allow species-specific impacts to be included in the indicator, however it would enable the inclusion of three different environmental impacts for broader species groups. The species groups included are similar aggregations to the ISSCAAP groups provided in the FAO production and trade data. Table 5 in section 3.1 demonstrates that 14 ISSCAAP groups accounted for 95.5% of total aquaculture production in 2021, with most groups consisting of 2 to 3 key species. Thus, the impacts data provided in Table 11 would cover the majority of aquaculture production and more detailed species-specific data may not be essential for a useful indication of the impacts of consumption of aquaculture commodities in the GEIC indicator.

4.4.3 Greenhouse gas emissions and feed conversion ratios (FCRs) – FAO tool

The FAO developed an interactive tool, FISH-emissions (*FAO: FISH-e*, 2017) for quantifying the greenhouse gas emissions arising from aquaculture. Only emissions generated from production are quantified and post-farm processes such as transport, product processing and distribution are excluded. The tool was released as a test version in 2017 and an updated version is not available. The interactive excel spreadsheet requires inputs for production country, commodity (Catfish, Cyprinids, Freshwater fish - General, Indian Major Carps, Marine fish – General, Salmonids, Shrimp, Tilapia) and production system (Cages, Ponds: Extensive, Ponds: semi-intensive, Ponds: intensive, Recirculating aquaculture systems, Tanks: flow-through). More specific information can then be provided for production (e.g. fish weight at harvest, growing time, total feed consumption, feed conversion ratios), feed composition (commercial and farm-made), on-farm energy use (grid electricity and fuel use) and pond fertilisation (synthetic, organic and lime). Default feed compositions (or rations) are provided for the most common commodity/location combinations. The results provided include fish production (feed conversion ratios, liveweight gain), total annual emissions, emissions by production input (e.g. fuel use, feed input, fertiliser production), emission intensity and the related comparisons with other seafood and livestock commodities. The emissions quantified are described in Table 12. Bar graphs are also generated to visualise the contribution of different production methods towards total annual emissions, the contribution of different feed compositions towards emissions and comparisons of emission estimates by liveweight with other studies.

Table 12. Summary of the GHG categories included in FISH-e v1. Table from FISH-e user guide (MacLeod 2017).

Name	Description
Feed: fertilizer production	Emissions arising from the production of synthetic fertilisers applied to crops
Feed: crop N_2O	Direct and indirect nitrous oxide from the application of (synthetic and manure) N to crops and crop residues management
Feed: crop energy use	CO_2 from energy use in field operations, feed transport and processing, and fertiliser production.
Feed: crop LUC	CO_2 from land use change arising from soybean cultivation.
Feed: rice CH_4	Methane arising from flooded rice cultivation
Feed: fishmeal	CO_2 from energy use in the production of fishmeal
Feed: animal by-products	CO_2 from energy use in the production of animal by-product feeds
Feed: blending & transport	CO_2 from energy use in the production and distribution of compound feed

Name	Description
Feed: other	Emissions from the production of a small number of "other" feeds (including lime and synthetic amino acids)
Juvenile fish production	Emissions arising in hatcheries during the production of fingerlings
Pond fertilizer production	Emissions arising from the production of synthetic fertilisers applied to increase aquatic primary productivity
Grid electricity	Emissions arising from the production of electricity used on the fish farm
On-farm fuel use	Emissions arising from the use of fuels on the fish farm

The tool is in its initial stages and data are contained within a password-protected excel spreadsheet. For use in the GEIC indicator, the impacts data, either greenhouse gas emissions or feed conversion ratios, would need to be collated from the source material. The user guide describes the data sources used for FISH-E as a combination of data tools such as AFFRIS (FAO 2017a) and GLEAM (FAO 2017b), journal articles, technical reports, grey literature and expert opinion. Sources are separated into four key categories for easier use: default rations (food inputs) and feed conversion ratios, emission factors for feed, emission factors for fuels and grid electricity, and emission factors for fertilisers. Based on the FishStatJ production and trade data and the limited information on feed compositions or production inputs, the feed conversion ratios (FCRs) have the most potential for inclusion in the indicator. FCRs could act as a proxy for waste, greenhouse gas emissions and eutrophication risk (Brown *et al*. 2022) and provide a broader indication of the environmental impacts linked to the consumption of aquaculture commodities. Further data for FCRs could be obtained from the Fry *et al*. (2018) study identified in the Prince2 report (Table 13). To include greenhouse gas emissions directly, default rations (or feed composition), fuel and electricity use and fertiliser inputs would need to be assumed, and standardised emission factors applied across production systems.

Table 13. Feed conversion ratios (FCR) for species and broader species groups collated from multiple sources. FCRs obtained from Tacon and Metian (2015) were the predicted values for 2025. For some species, values are provided both for the individual species and separately for broader aggregations, for instance Common carp and Chinese fed carps.

Aquaculture species	Feed Conversion Ratio (FCR)	Source
Common carp	1.7	Fry *et al*. 2018
Grass carp	1.7	Fry *et al*. 2018
Channel catfish	1.4	Fry *et al*. 2018
Pangas catfish	1.4	Fry *et al*. 2018
Atlantic salmon	1.3	Fry *et al*. 2018
Rainbow trout	1.3	Fry *et al*. 2018
Giant tiger prawn	1.7	Fry *et al*. 2018
Whiteleg shrimp	1.7	Fry *et al*. 2018
Nile Tilapia	1.7 1.43	Fry *et al*. 2018 Robb *et al*. 2017
Rohu	1.32	Robb *et al*. 2017

Aquaculture species	Feed Conversion Ratio (FCR)	Source
Catla	1.32	Robb *et al*. 2017
Striped catfish	1.52	Robb *et al*. 2017
Chinese fed carps (includes Grass carp, Common carp, Crucian carp, etc.)	1.6	Tacon & Metian 2015
Tilapia (includes Nile Tilapia, Tilapia nei, Blue-nile Tilapia, etc.)	1.6	Tacon & Metian 2015
Catfishes (includes Pangas catfishes, torpedo-shaped catfishes, channel catfishes, etc.)	1.3	Tacon & Metian 2015
Other freshwater and diadromous fishes	1.7	Tacon & Metian 2015
Salmon (includes Atlantic salmon, Coho salmon, Chinook salmon, etc.)	1.3	Tacon & Metian 2015
Trout (includes Rainbow trout, Sea trout, etc.)	1.3	Tacon & Metian 2015
Milkfish	1.5	Tacon & Metian 2015
Eel (includes all family Anguillidae)	1.5	Tacon & Metian 2015
Marine fish (includes all ISSCAAP division)	1.5	Tacon & Metian 2015
Shrimp (includes all FAO ISSCAAP group for shrimp)	1.5	Tacon & Metian 2015
Freshwater crustaceans (includes all ISSCAAP group for freshwater crustaceans)	1.7	Tacon & Metian 2015
Aquaculture weighted average	1.6	Fry *et al*. 2018

4.4.4 Other potential datasets

The scope of the datasets identified for this report is limited due to the time-restricted nature of this project. Further work could be conducted to identify other suitable environmental impact datasets. Specifically, it would be useful to determine the area of land required to produce different aquaculture species to link to habitat destruction, improve estimates of nutrient loss and eutrophication, quantify medicinal and chemical inputs, and categorise the risks of disease and invasive species introduction by commodity. A report by Hall *et al.* (2011) was identified as having potential for use in the GEIC indicator. The report provides visualisations for six environmental impacts by live production weight: eutrophication, acidification, climate change, land occupation, energy demand and biotic depletion. These impacts are then broken down by inland and coastal production systems, by species groups, and by production system and species group (Figure 7 and 8). The impacts data are from 2008 and the raw data could not be located; further work would be required to obtain the data presented or an updated version of the data. The breakdown by species group and by inland and coastal production systems would match with data columns provided in the FishStatJ production data. Another direction for future work would be to explore the digital tools and databases provided by WorldFish. FishBase, the WorldFish Dataverse and the WorldFish Dspace repository are collections of potentially useful aquaculture studies and datasets that require further exploration (*WorldFish: Digital Innovations*, 2024).

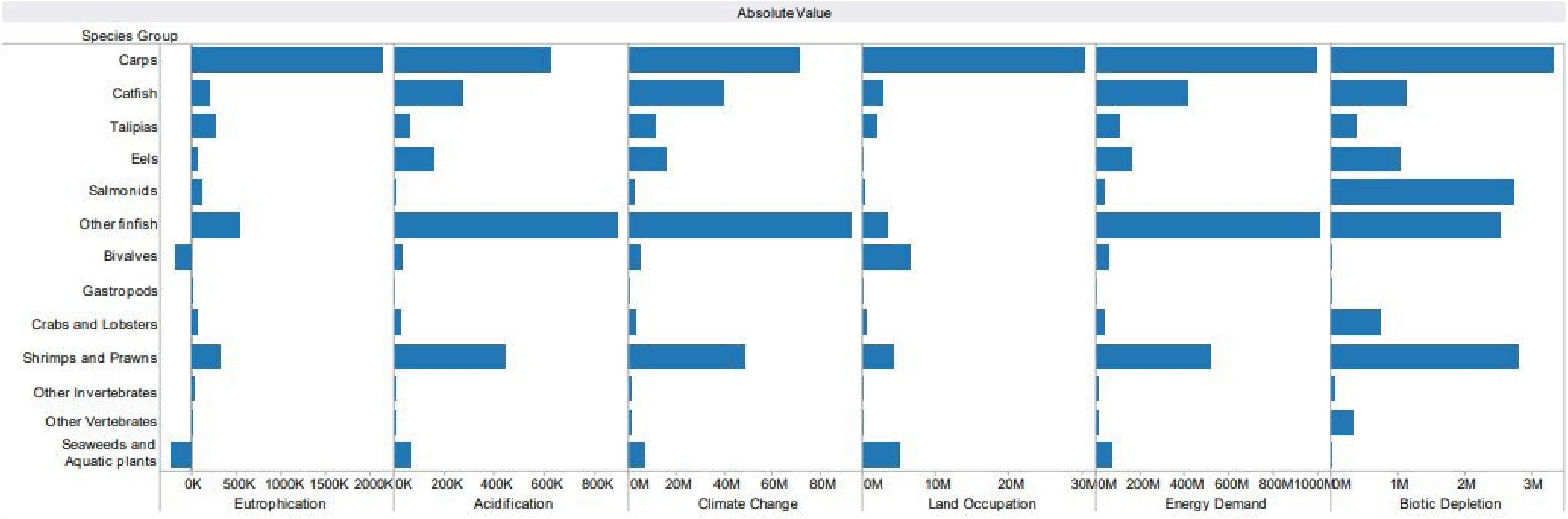

Figure 7. The environmental impacts of production of major aquaculture species groups per tonne of live weight. Figure adapted from Hall *et al*. (2011), reproduced under Creative Commons license.

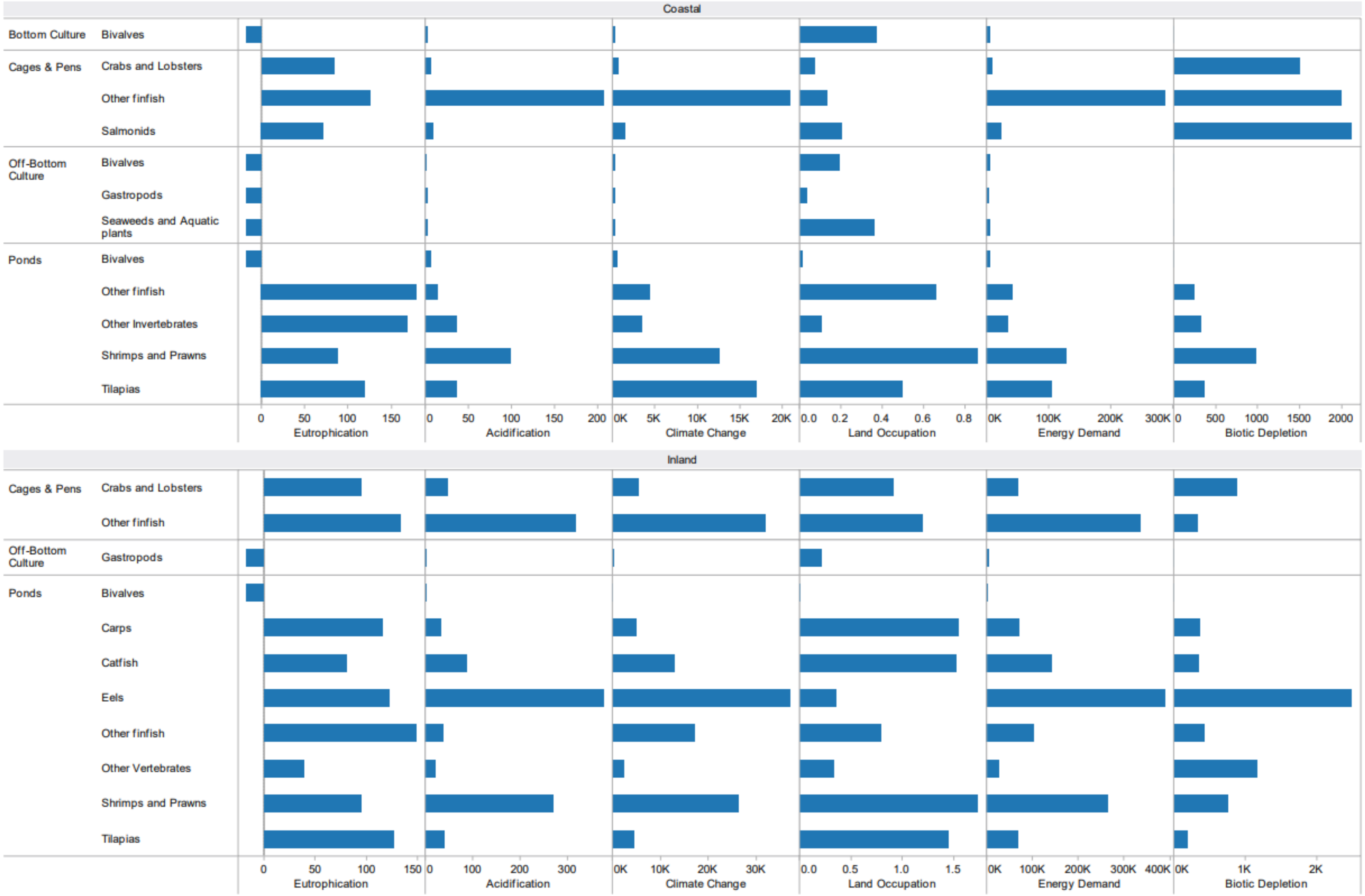

Figure 8. Impacts by species group by production system in inland or coastal waters. Figure adapted from Hall *et al*. (2011), reproduced under Creative Commons license.

4.5 Recommendations for the inclusion of environmental impacts

The following are recommendations for including environmental impact data associated with aquaculture production in the GEIC indicator:

- Based on the datasets explored for this report, eutrophication, phosphorus use efficiency, feed conversion ratios and greenhouse gas emissions are the most suitable environmental impacts to include in the GEIC indicator. The data available are often for species groupings such as Salmonidae or Shrimps and prawns, and species-specific data are unavailable. Phosphorus use efficiency has species-specific data and could be combined with phosphorus input values for higher resolution impact data, however further work is required to identify phosphorus input values. Similarly, feed conversion ratios have both species- and ISSCAAP group-level data and could be used as a proxy for eutrophication, greenhouse gas emissions and waste.
- There is very limited information in the FishStat database about the technologies employed for production. To link production system-specific impacts to production quantities, assumptions would need to be made based on the broader species group, location and the environment (freshwater, marine or brackish water). For example, molluscs are produced using open water marine aquaculture and fin fish produced inland are most likely cultured using constructed earthen ponds. Furthermore, mollusc and seaweed production is relatively environmentally benign and should be excluded when quantifying the impacts of nutrient loads, however it might be necessary to include both groups when considering disease or invasive species risk. The full list of recommended assumptions regarding production systems is provided at the end of section 4.2.
- Impacts such as disease risk or invasive species introductions could be included in the indicator as qualitative flags rather than quantitative values per tonne of live weight produced. For example, invasive species introduction risk could be classified and assigned weights. Weights could also be influenced by the production system, as open systems are higher risk than closed systems. Production quantities could then be multiplied by the relevant class weight to identify regions in which the introduction of invasive species is a key threat. Further work is required to determine the disease risk or invasive species risk associated with the major aquaculture commodities grown in different production systems.
- The datasets discussed in this report provide sufficient information for inclusion in the GEIC indicator to improve understanding of the impacts of consumption of aquaculture commodities. However, further work should be undertaken to identify other environmental impacts datasets, particularly at a species level, and to explore the other potential datasets discussed in section 4.4.4.

5 Conclusions

In summary, the aquaculture production and trade data provided by the FAO can be matched and used, with appropriate assumptions and matches between classification schemes, in the GEIC indicator. Commodity production can then be linked to various environmental impacts, notably eutrophication, greenhouse gas emissions and feed conversion ratios, using the datasets described in section 4.4. It is possible to include species-specific data, however it may be easiest to include higher-level groupings yz Salmonidae or Shrimps and Prawns. The ISSCAAP groups classification would be the most suitable aggregation for simplifying the linkages between production and trade data. Similarly, impact data is often provided for higher-level species aggregations, and the ISSCAAP groups provided in the production data would allow easier matches with the impact data. Species-level trade and production could still be modelled, but the impacts data would be standardised across the ISSCAAP groups. The inclusion of broader-level standardised impact data in the indicator would provide invaluable information about the impacts of consumption of aquatic products and identify regions most threatened by aquaculture production. At present, only phosphorous use efficiency or feed conversion ratios could be linked at a species level, and thus standardised impacts data across broader species groups is not essential. Further work is required to identify additional species-level impacts datasets. Including aquaculture commodities in the GEIC indicator would improve understanding of the environmental impacts of consumption and provide invaluable information to support trade and policy decisions in the future.

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