Systems approach to quantify the global omega-3 fatty acid cycle

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Abstract

Long-chain omega-3 fatty acids, eicospeantaenoic and docosahexaenoic acids, are essential components of human diets and some aqua/animal feeds – but are sourced from finite marine fisheries, in short supply and deficient in large parts of the world. We use quantitative systems analysis to model the current global EPA/DHA cycle and identify options for increasing supply. Opportunities lie in increased by-product utilization and food waste prevention. Economic, resource, cultural and technical challenges need, however, to be overcome.

Main Text

Long-chain omega-3 fatty acids (FA), in particular eicosapentaenoic (EPA) and docosahexaenoic (DHA) acid, are essential components of human diets due to their role in visual and neurological development in infants and the vast range of cognitive, cardiovascular and psychological benefits for adults.[1] The daily recommended intake of EPA/DHA ranges between 250 and 1000 mg for healthy adults, with higher DHA requirements for pregnant and lactating women.[1] The primary dietary source for EPA/DHA is fish; however, fish themselves are inefficient at producing EPA/DHA and instead accumulate them through the food chain from primary producers.[2]

First estimates show that aquaculture, fisheries and other marine sources supply 0.8 million tonnes of EPA/DHA per year for human consumption.[2] This is below the human nutritional demand of 1.4 million tonnes required to supply the global population with 500 mg EPA+DHA daily and will be further exacerbated by population growth. EPA/DHA deficiencies have been observed worldwide and particularly affect populations located in North America, central Europe, the Middle East, India, Brazil and the U.K., with regional and socio-economic differences seen within the countries.[3] Filling the EPA/DHA supply gap is unlikely to occur through capture fisheries, due to 63% of fish stocks being considered exploited and in need of rebuilding.[4] Aquaculture can increase the supply of EPA/DHA, however, many farmed species require the input of fish meal (FM) and fish oil (FO) sourced from capture fisheries and seafood byproducts to meet their nutritional needs and maintain the FA profile of the fish.[5] Due to the scarcity and increasing price of marine oils, the aquafeed industry has reduced FM and FO inclusion by partial substitution with plant ingredients.[6] Thus, aquaculture production has grown at 5.8% per annum, without considerably increasing FM and FO consumption.[7] However, reduced FM and FO inclusion has affected the FA profile of certain fed species (e.g. salmonids), with lowered EPA/DHA contents.[6]

The growing EPA/DHA supply gap, related potential human health consequences and the need to protect marine ecosystems makes it essential to optimize the management of long-chain omega-3 FA, considering all relevant intervention options and evaluating their combined effects. Here, we use a systems approach and quantify the global EPA and DHA cycle to i) provide a comprehensive problem description to improve overall resource efficiency and ii) identify system-wide opportunities and challenges for meeting the human EPA/DHA demand. We, thereafter, aim to inform decision makers on the current EPA/DHA status, its drivers and the most effective intervention options at a global level.

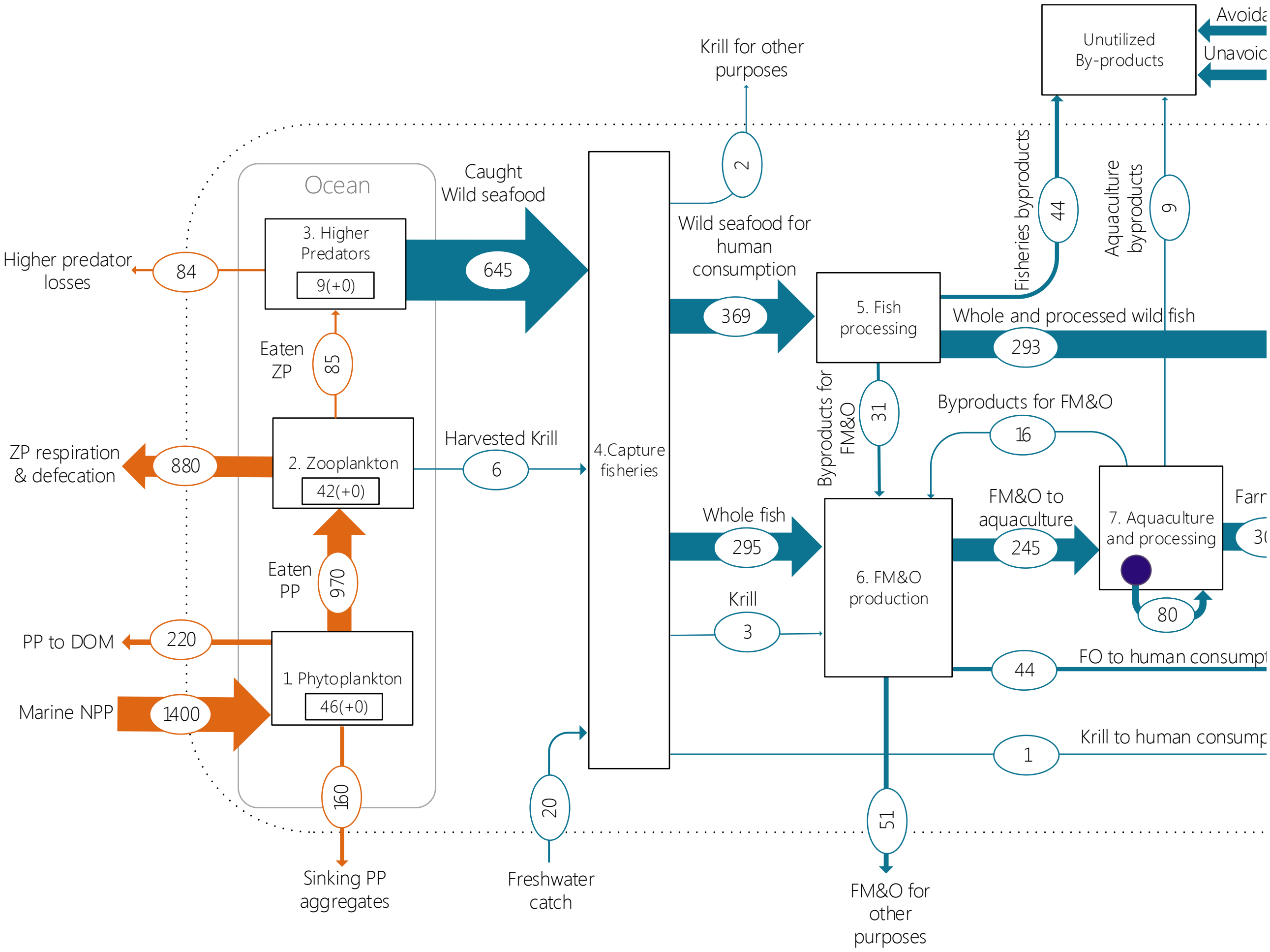

Figure 1. Global EPA and DHA balance; Orange arrows in Mt, Blue arrows in kt EPA+DHA/yr; Purple dot denotes net endogenous EPA/DHA production by fish; NPP = Net primary production; PP = Phytoplankton; DOM = Dissolved organic matter; ZP = zooplankton; FM&O = fish meal and oil. Mass balance inconsistencies due to i) rounding errors and ii) uncertainty All flows in process 6 were independently calculated and the remaining mass balance inconsistency is less than 1% of total flows in this process. Net endogenous production in the ocean system is not visualized.

We find that between net primary production (NPP) and higher predators, approximately 90% of EPA/DHA is lost via respiration, defecation and deaths, indicating large trophic losses up the food chain (figure 1). The zooplankton and phytoplankton stocks are of comparable sizes (approximately 40 Mt EPA+DHA), with no net yearly addition to stock. Caught wild seafood accounts for 0.04% of the EPA/DHA produced via NPP. Approximately half of harvested marine EPA/DHA is managed through FM and FO production (primarily for aquaculture consumption, figure 2 top) and half for direct human consumption.

Despite aquaculture being a major consumer of EPA/DHA, it is also a major producer via non-fed species, such as molluscs and carp, accumulating EPA/DHA from their environment and/or endogenous production through the elongation of shorter-chained FA. Freshwater fish are better at elongation compared to marine fish due to unique enzymes and desaturase genes that allow for EPA/DHA synthesis.[8] In contrast, fed high-trophic salmonid species i) consume a high proportion of aquaculture's use of FM and FO (58% and 22%, respectively, in 2015), ii) have EPA/DHA retention rates varying from 30 to 75% and iii) are inefficient at FA elongation[9], but also supply EPA/DHA through a farmed product based on an otherwise under-utilized wild fish resource.

We find the supply of EPA/DHA for human consumption is 420 kt/year or 149 mg EPA+DHA/capita daily, representing 30% of global demand. We, therefore, confirm the supply gap identified by Tocher et al.[2] but find it to be twice as large as previous estimates. Significant losses occur due to unavoidable and avoidable food waste (114 and 105 kt EPA+DHA/yr, respectively) and unutilized fish processing byproducts (53 kt EPA+DHA/yr), with the largest losses in Asia (figure 2, bottom).

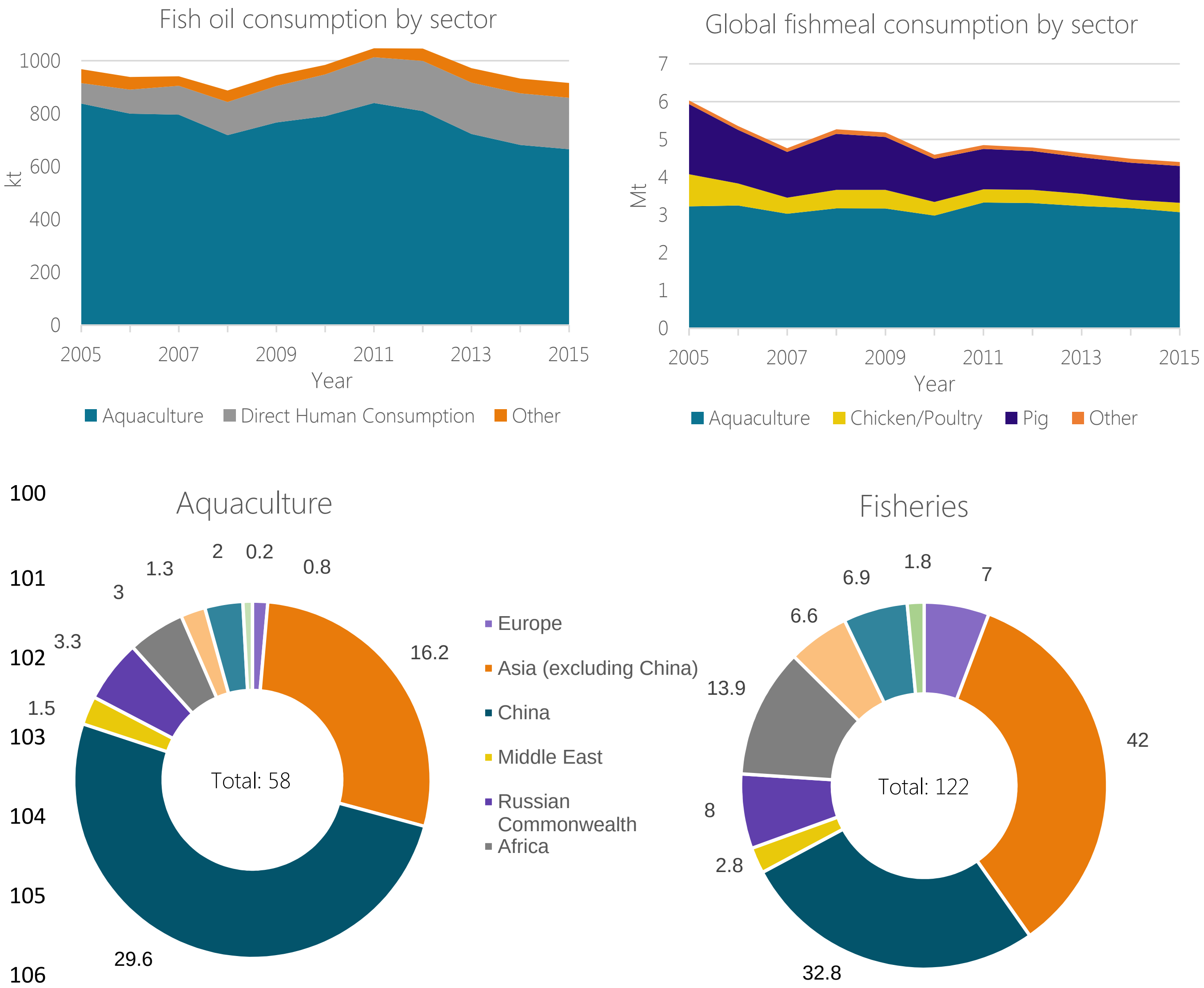

Figure 2. Top: Global FM and FO consumption by sector (kt FO or FM/yr) Bottom: EPA/DHA potential from unutilized by-products from aquaculture and fisheries processing by region in 2017 (kt EPA/DHA/yr) Data source: FAO

While many options exist to fill the EPA/DHA gap, each has challenges. Aquaculture's strategic FM and FO in feed use at key life-stages can i) influence the EPA/DHA utilization efficiency by farmed fish and ii) optimize the benefits of marine ingredients from a fish and human health perspective, e.g. finishing diets to increase EPA/DHA towards harvest time.[10] Fish stock recovery could increase long-term fish yields and the EPA/DHA supply (albeit with likely short-term decreases).[4] However, forage fish harvesting may have a lowered effect on stock size as compared to environmental factors that affect reproductive success.[11] With the krill harvesting rate (~300,000 tonnes biomass in 2018) being below the catch limit of 5.6 million tonnes annually as defined by Commission for the Conservation of Antarctic Marine Living Resources, increasing krill catch for use as feed could substantially increase the EPA/DHA supply.[12] However, Antarctic krill harvesting operations face challenges related to geography and costs, and effective stock management is imperative to ensure sustainable harvesting levels.

Avoiding trophic losses could increase supply by i) consuming EPA/DHA from a lower trophic level (e.g. seaweeds, krill and bivalve mollusks), ii) increasing non-fed fish farming and/or iii) diverting more wild catch to human consumption through direct consumption or oil supplementation produced from these species. However, for this to prove effective, the digestibility, bioavailability and efficacy of EPA/DHA in these products need to be understood (e.g. the bioavailability of FA in fish oil is lower than fish[13]) and although the nutraceutical market is strong, the wild fish market depends on factors including, amongst others, the catch quality, acceptance and temporal challenges, i.e. seasonal surplus of fish catch that cannot be absorbed by the market.[14] In addition, logistical challenges exist for the distribution to populations that are EPA/DHA deficient. [15]

Improved by-product utilization and food waste avoidance can substantially increase the supply of EPA/DHA while reducing waste. Processing by-products can be used for FM and FO production for aquafeed and/or human consumption provided the regulatory frameworks are followed.[16] However, a major challenge is collection and processing, as by-products are often geographically dispersed. For example, Asia, where most of the by-product potential is concentrated (figure 2 bottom), has the culture of buying fish whole and disposing of by-products at the household level.[17] Centralized fish processing is needed to recover byproducts in this region but would require a substantial cultural shift in the way fish is consumed. Food waste prevention is also an effective means for increasing supply, as it avoids the unnecessary use of EPA/DHA to produce food that is wasted.

Future options to produce EPA/DHA include large-scale production of natural and genetically modified (GM) microalgae, microbacteria and higher plants. However, current technologies and concerns about GM material limit volume of supply, their cost-effectiveness and widespread penetration into the market,[19] although regulatory challenges related to GM feed use are primarily constrained to Europe.[20]

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Author contributions

H.H. and D.M. designed the study. H.H., R.N. and N.A. quantified the system and conducted the analysis. H.H. made the figures. H.H., R.N., N.A. and D.M. contributed to the data interpretation. H.H. wrote the paper. H.H., R.N., N.A. and D.M. contributed to manuscript editing.

Competing financial interests

The authors declare no competing interests.

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Methods

We used a multi-layer material flow analysis framework (ML-MFA) to quantify the stocks and flows of EPA/DHA throughout our defined system. The ‘mother’ layer contains the biomass system (tonnes wet weight/yr) and the ‘child’ layer includes the sum of EPA and DHA balance (tonnes EPA+DHA/yr). From a mass balance standpoint, quantifying the EPA/DHA content of biological organisms is a methodological challenge due to i) marine and freshwater species storing EPA/DHA within their lipids and, thus, metabolizing them as an energy source and ii) organisms endogenously producing EPA/DHA through the elongation of alpha-linolenic acid (ALA, 18:3n-3) at various rates depending on, amongst others, the species, time of the year and habitat.[21] Therefore, unlike substances (i.e. chemical elements), EPA/DHA can be created or destroyed, which limits mass balance conservation when modeling and makes it necessary to consider production and destruction. Preliminary estimates have shown endogenous EPA/DHA production to contribute little to the EPA/DHA supply from farmed fish (i.e. EPA/DHA consumed by aquaculture equals the EPA/DHA contents of the produced fish).[22] However, for certain species, endogenous EPA/DHA production can be potentially significant, especially for bivalve mollusks and carp.[23] Therefore, we accounted for this by calculating the net EPA/DHA production of each biological process for which EPA/DHA can be created/destroyed. We assumed processes that mechanically transform the flows (i.e. fish processing) do not affect the EPA/DHA content of the biomass.

We defined the system to include the natural and anthropogenic stocks and flows of EPA/DHA. Freshwater ecosystem food chains were not considered due to their minor role relative to the marine ecosystem and limited data availability; however, we included the EPA/DHA contained in freshwater fish capture and freshwater aquaculture. In addition, we did not consider natural export from marine to terrestrial ecosystems, e.g. due to the consumption of drifted algae by lizards, birds and other terrestrial animals, as preliminary estimates (24 kt EPA+DHA/yr) have shown this to be insignificant relative to the overall marine food web.[24]

Primary data are sourced from scientific publications, reports, statistics and industry data from the International Marine Ingredients Organization (IFFO). Ocean carbon flows are based on Stock et al.[25] and represent a 20 year average (1994-2014). The long time frame minimizes the uncertainty related to yearly variations in primary production due to, e.g., El

Nino events[26]. Capture data is based primarily on the FAO dataset FishStat and includes an average between 2009 and 2013 to normalize yearly variations. Due to the large number of species, we only accounted for the top 20 fish, cephalopod and crustacean species caught and farmed in each geographical region. EPA/DHA calculations are performed at a species level. However, we accounted for all wild and farmed bivalve mollusks and plants. Overall, we accounted for over 90% of fishery and aquaculture production. Avoidable food waste is defined to include all edible food that was wasted at the household level. Unavoidable food waste includes the remaining inedible fraction, such as peels, shells and bones. Further information regarding the methods can be found in the supplementary information.

Data Availability

This work uses data collected from a variety of sources, both proprietary and freely available. See references in the supplementary information for data specification. All figures are based on this collected dataset and geographically aggregated data will be made available upon request from the corresponding author.

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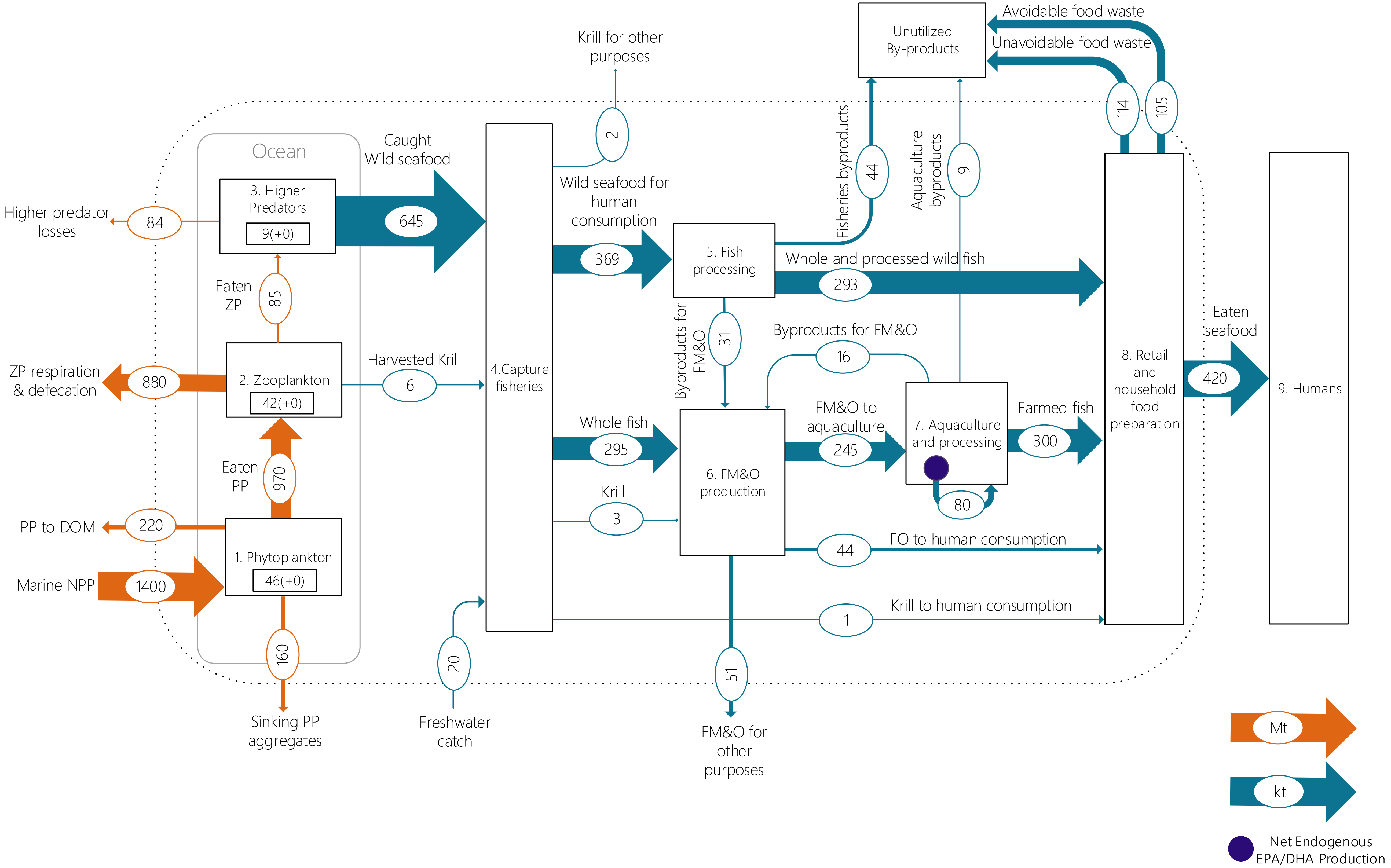
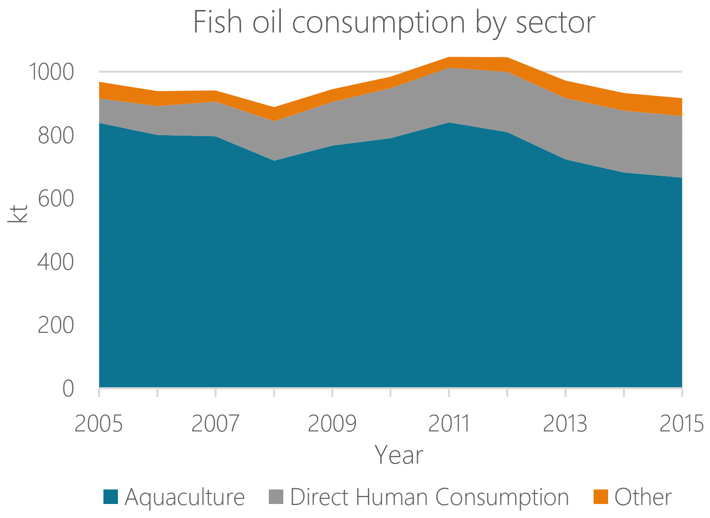
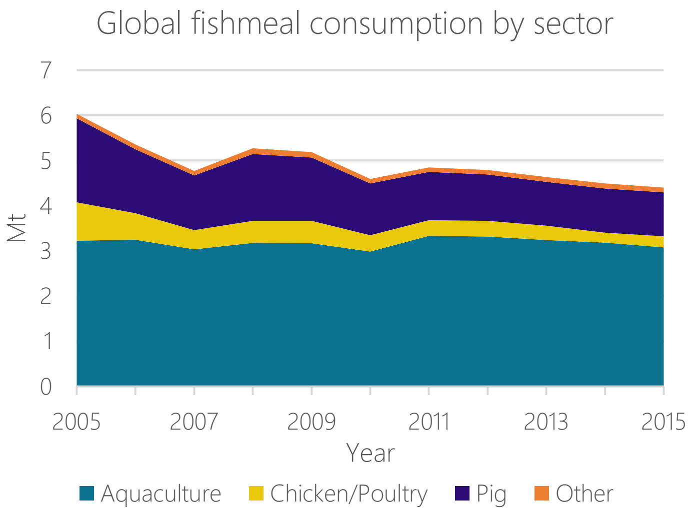
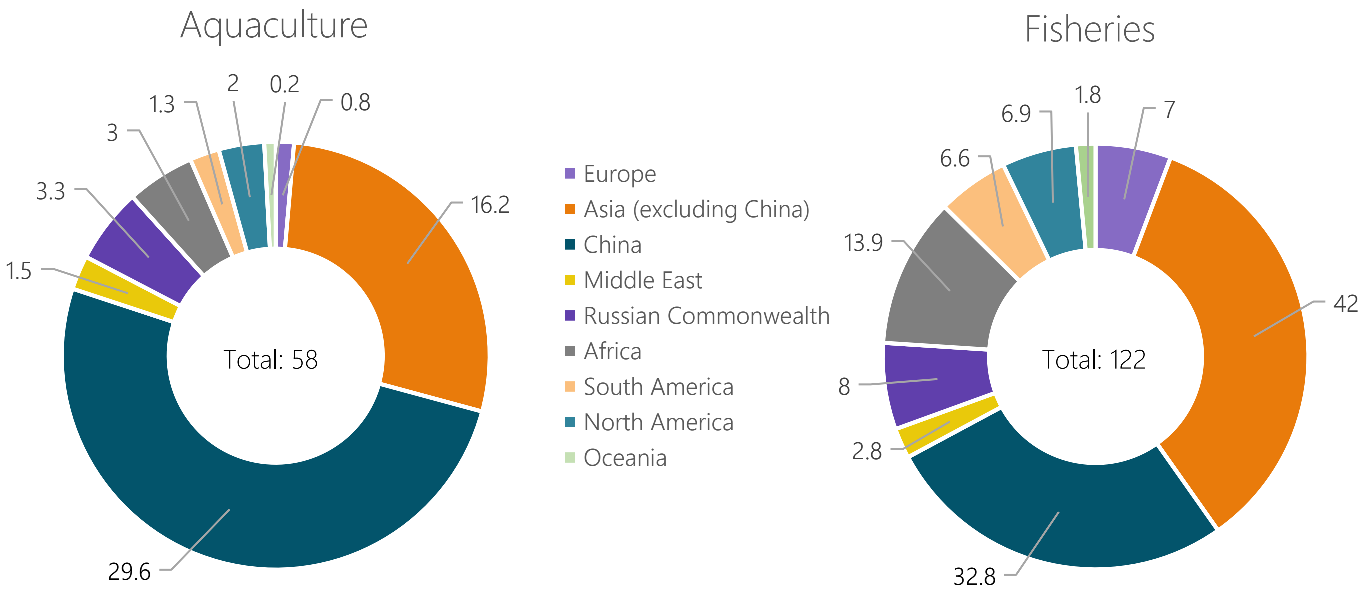

Ocean
Caught Wild seafood
645
Higher predator losses
84
3. Higher Predators
9(+0)
Eaten ZP
85
ZP respiration & defecation
880
2. Zooplankton
42(+0)
Harvested Krill
6
Eaten PP
970
PP to DOM
220
Marine NPP
1400
1. Phytoplankton
46(+0)
160
Sinking PP aggregates
20
Freshwater catch
4.Capture fisheries
Krill for other purposes
2
Wild seafood for human consumption
369
5. Fish processing
Whole fish
295
Krill
3
6. FM&O production
51
FM&O for other purposes
Krill to human consumption
1
Byproducts for FM&O
31
Byproducts for FM&O
16
FM&O to aquaculture
245
7. Aquaculture and processing
80
FO to human consumption
44
Fisheries byproducts
44
Aquaculture byproducts
9
Unutilized By-products
Avoidable food waste
Unavoidable food waste
114
105
Whole and processed wild fish
293
Farmed fish
300
8. Retail and household food preparation
Eaten seafood
420
9. Humans
Mt
kt
● Net Endogenous EPA/DHA Production


Fish oil consumption by sector
kt
1000
800
600
400
200
0
2005
2007
2009
2011
2013
2015
Year
Aquaculture
Direct Human Consumption
Other


Global fishmeal consumption by sector
Mt
7
6
5
4
3
2
1
0
2005
2007
2009
2011
2013
2015
Year
Aquaculture
Chicken/Poultry
Pig
Other


Aquaculture
Total: 58
2
0.2
1.3
0.8
3
3.3
16.2
1.5
29.6
Europe
Asia (excluding China)
China
Middle East
Russian Commonwealth
Africa
South America
North America
Oceania
Fisheries
Total: 122
1.8
6.9
7
6.6
13.9
42
8
2.8
32.8

1. Supplementary Information:

A. Flat Files

Item	**Present?**	**Filename** This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. The extension must be .pdf	**A brief, numerical description of file contents.** i.e.: *Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.*
Supplementary Information	Yes	Hamilton_Supplements.pdf	Supplementary Figure 1, Supplementary Methods, Supplementary Discussion, and Supplementary Tables 1-3.
Reporting Summary	Yes	Reporting_summary.pdf	

2. Source Data

Complete the Inventory below for all Source Data files.

Parent Figure or Table	**Filename** This should be the name the file is saved as when it is uploaded to our system, and should include the file extension. i.e.: *Smith_SourceData_Fig1.xls*, or *Smith_Unmodified_Gels_Fig1.pdf*	**Data description** e.g.: Unprocessed Western Blots and/or gels, Statistical Source Data, etc.
Source Data Fig. 1	Hamilton_SourceData_Fig1.xlsx	Numerical data used to generate figure 1
Source Data Fig. 2	Hamilton_SourceData_Fig2.xlsx	Numerical data used to generate figure 2, top and bottom