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

Helen A. Hamilton[*,1], Richard Newton[2], Neil A. Auchterlonie[3], Daniel B. Müller[1]

[1]Norwegian University of Science and Technology (NTNU), Industrial Ecology Programme, Sem Sælands Vei 7, Trondheim, Norway

[2]Institute of Aquaculture, University of Stirling, Stirling, FK9 4LA, UK.

[3]IFFO, Marine Ingredients Organisation, Printworks, Unit C, 22 Amelia Street, London, SE17 3BZ

Key words: Aquaculture, Fisheries, EPA, DHA, Material flow analysis

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]

36   First estimates show that aquaculture, fisheries and other marine sources supply 0.8 million

37   tonnes of EPA/DHA per year for human consumption.[2] This is below the human nutritional

38   demand of 1.4 million tonnes required to supply the global population with 500 mg

39   EPA+DHA daily and will be further exacerbated by population growth. EPA/DHA

40   deficiencies have been observed worldwide and particularly affect populations located in

41   North America, central Europe, the Middle East, India, Brazil and the U.K., with regional and

42   socio-economic differences seen within the countries.[3] Filling the EPA/DHA supply gap is

43   unlikely to occur through capture fisheries, due to 63% of fish stocks being considered

44   exploited and in need of rebuilding.[4] Aquaculture can increase the supply of EPA/DHA,

45   however, many farmed species require the input of fish meal (FM) and fish oil (FO) sourced

46   from capture fisheries and seafood byproducts to meet their nutritional needs and maintain

47   the FA profile of the fish.[5] Due to the scarcity and increasing price of marine oils, the

48   aquafeed industry has reduced FM and FO inclusion by partial substitution with plant

49   ingredients.[6] Thus, aquaculture production has grown at 5.8% per annum, without

50   considerably increasing FM and FO consumption.[7] However, reduced FM and FO inclusion

51   has affected the FA profile of certain fed species (e.g. salmonids), with lowered EPA/DHA

52   contents.[6]

53   The growing EPA/DHA supply gap, related potential human health consequences and the

54   need to protect marine ecosystems makes it essential to optimize the management of long-

55   chain omega-3 FA, considering all relevant intervention options and evaluating their

56   combined effects. Here, we use a systems approach and quantify the global EPA and DHA

57   cycle to i) provide a comprehensive problem description to improve overall resource

58   efficiency and ii) identify system-wide opportunities and challenges for meeting the human

59   EPA/DHA demand. We, thereafter, aim to inform decision makers on the current EPA/DHA

60   status, its drivers and the most effective intervention options at a global level.
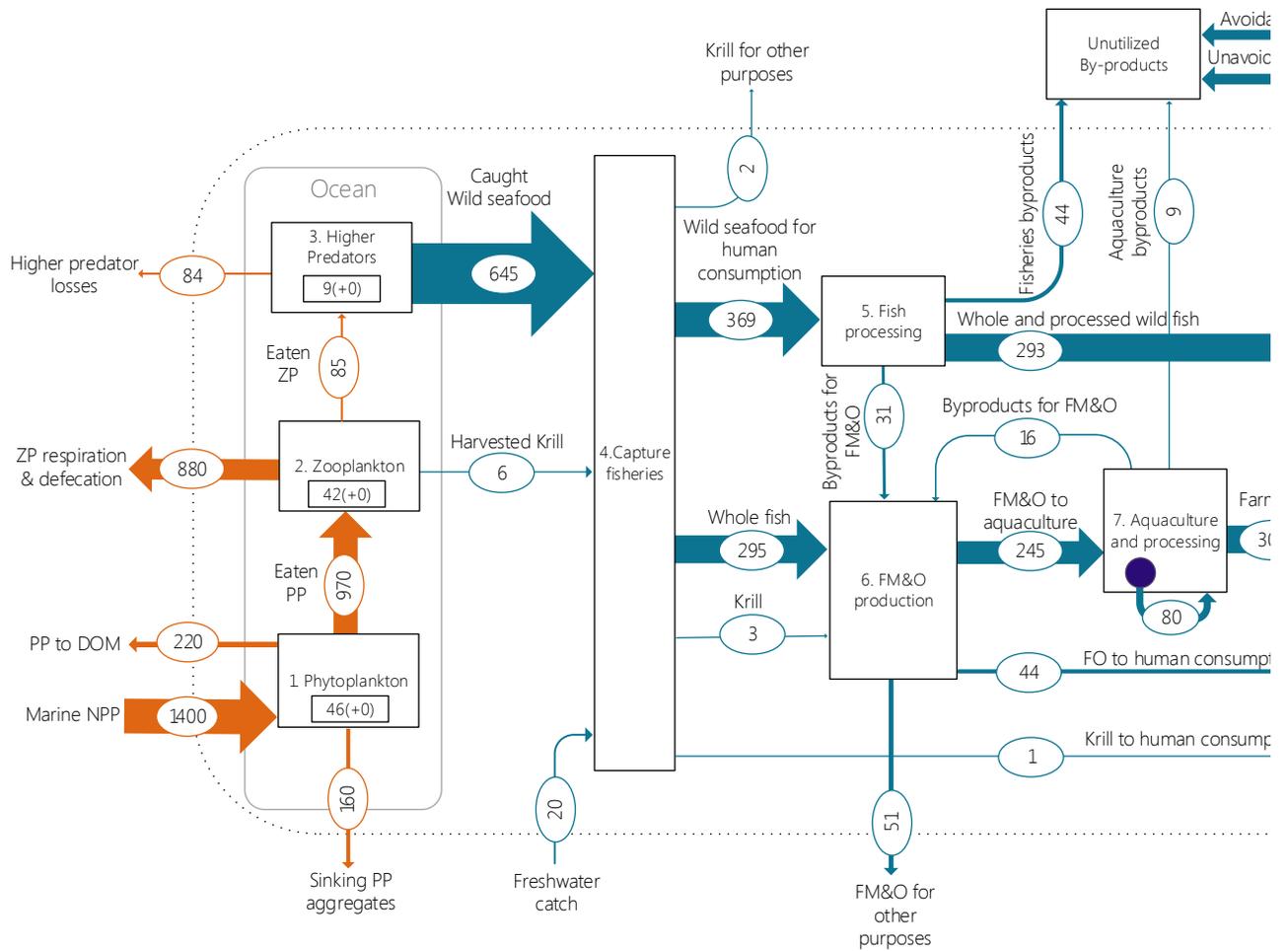
Figure 1. Global EPA and DHA balance; Orange arrows in Mt, Blue arrows in kt EPA+DHA/yr;
Purple dot denotes net endogenous EPA/DHA production by fish; NPP = Net primary production; PP
= Phytoplankton; DOM = Dissolved organic matter; ZP = zooplankton; FM&O = fish meal and oil.
Mass balance inconsistencies 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.
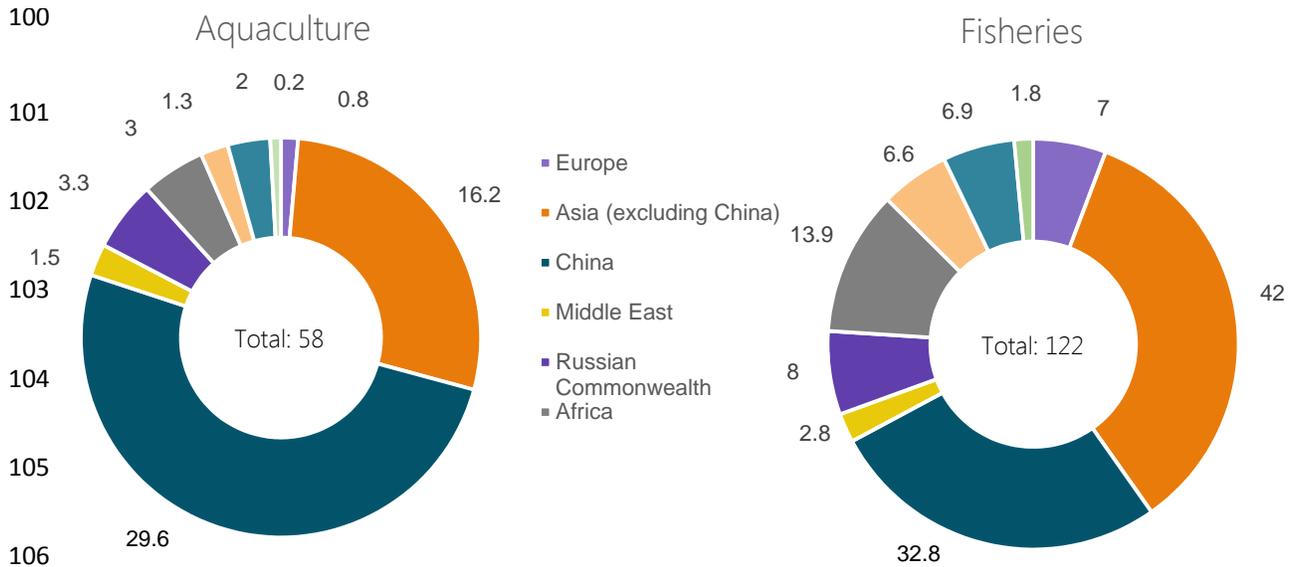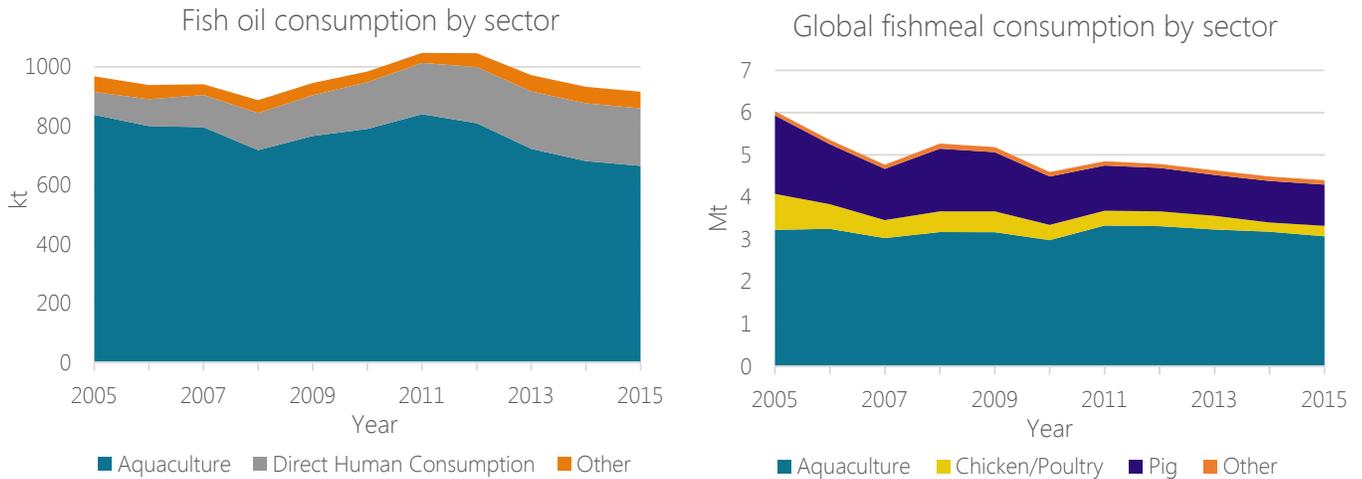
69 We find that between net primary production (NPP) and higher predators, approximately

70 90% of EPA/DHA is lost via respiration, defecation and deaths, indicating large trophic

71 losses up the food chain (figure 1). The zooplankton and phytoplankton stocks are of

72 comparable sizes (approximately 40 Mt EPA+DHA), with no net yearly addition to stock.

73 Caught wild seafood accounts for 0.04% of the EPA/DHA produced via NPP. Approximately

74 half of harvested marine EPA/DHA is managed through FM and FO production (primarily

75 for aquaculture consumption, figure 2 top) and half for direct human consumption.

76 Despite aquaculture being a major consumer of EPA/DHA, it is also a major producer via

77 non-fed species, such as molluscs and carp, accumulating EPA/DHA from their environment

78 and/or endogenous production through the elongation of shorter-chained FA. Freshwater fish

79 are better at elongation compared to marine fish due to unique enzymes and desaturase genes

80 that allow for EPA/DHA synthesis.[8] In contrast, fed high-trophic salmonid species i)

81 consume a high proportion of aquaculture's use of FM and FO (58% and 22%, respectively,

82 in 2015), ii) have EPA/DHA retention rates varying from 30 to 75% and iii) are inefficient at

83 FA elongation[9], but also supply EPA/DHA through a farmed product based on an otherwise

84 under-utilized wild fish resource.

85 We find the supply of EPA/DHA for human consumption is 420 kt/year or 149 mg

86 EPA+DHA/capita daily, representing 30% of global demand. We, therefore, confirm the

87 supply gap identified by Tocher et al.[2] but find it to be twice as large as previous estimates.

88 Significant losses occur due to unavoidable and avoidable food waste (114 and 105 kt

89 EPA+DHA/yr, respectively) and unutilized fish processing byproducts (53 kt EPA+DHA/yr),

90 with the largest losses in Asia (figure 2, bottom).

91

92

Fish oil consumption by sector

Global fishmeal consumption by sector

100
101
102
103
104
105
106

Aquaculture

Fisheries

Total: 58

Total: 122

Europe
Asia (excluding China)
China
Middle East
Russian Commonwealth
Africa

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

116 with likely short-term decreases).[4] However, forage fish harvesting may have a lowered

117 effect on stock size as compared to environmental factors that affect reproductive success.[11]

118 With the krill harvesting rate (~300,000 tonnes biomass in 2018) being below the catch limit

119 of 5.6 million tonnes annually as defined by Commission for the Conservation of Antarctic

120 Marine Living Resources, increasing krill catch for use as feed could substantially increase

121 the EPA/DHA supply.[12] However, Antarctic krill harvesting operations face challenges

122 related to geography and costs, and effective stock management is imperative to ensure

123 sustainable harvesting levels.

124 Avoiding trophic losses could increase supply by i) consuming EPA/DHA from a lower

125 trophic level (e.g. seaweeds, krill and bivalve mollusks), ii) increasing non-fed fish farming

126 and/or iii) diverting more wild catch to human consumption through direct consumption or

127 oil supplementation produced from these species. However, for this to prove effective, the

128 digestibility, bioavailability and efficacy of EPA/DHA in these products need to be

129 understood (e.g. the bioavailability of FA in fish oil is lower than fish[13]) and although the

130 nutraceutical market is strong, the wild fish market depends on factors including, amongst

131 others, the catch quality, acceptance and temporal challenges, i.e. seasonal surplus of fish

132 catch that cannot be absorbed by the market.[14] In addition, logistical challenges exist for the

133 distribution to populations that are EPA/DHA deficient. [15]

134 Improved by-product utilization and food waste avoidance can substantially increase the

135 supply of EPA/DHA while reducing waste. Processing by-products can be used for FM and

136 FO production for aquafeed and/or human consumption provided the regulatory frameworks

137 are followed.[16] However, a major challenge is collection and processing, as by-products are

138 often geographically dispersed. For example, Asia, where most of the by-product potential is

139 concentrated (figure 2 bottom), has the culture of buying fish whole and disposing of by-

140 products at the household level.[17] Centralized fish processing is needed to recover by-

7

141 products in this region but would require a substantial cultural shift in the way fish is

142 consumed. Food waste prevention is also an effective means for increasing supply, as it

143 avoids the unnecessary use of EPA/DHA to produce food that is wasted.

144 Future options to produce EPA/DHA include large-scale production of natural and

145 genetically modified (GM) microalgae, microbacteria and higher plants. However, current

146 technologies and concerns about GM material limit volume of supply, their cost-effectiveness

147 and widespread penetration into the market,[19] although regulatory challenges related to GM

148 feed use are primarily constrained to Europe.[20]

Sources

150 1.   Kris-Etherton, P.M., Grieger, J.A. & Etherton, T.D. *Prostaglandins Leukot. Essent.*
151   *Fat. Acids* **81**, 99–104 (2009).

152 2.   Tocher, D.R. *Aquaculture* **449**, 94–107 (2015).

153 3.   Stark, K.D., Van Elswyk, M.E., Higgins, M.R., Weatherford, C.A. & Salem, N. *Prog.*
154   *Lipid Res.* **63**, 132–152 (2016).

155 4.   Worm, B. et al. *Science (80-.).* **325**, 578–585 (2009).

156 5.   Tocher, D.R. *Aquac. Res.* **41**, 717–732 (2010).

157 6.   Sprague, M., Dick, J.R. & Tocher, D.R. *Sci. Rep.* **6**, 1–9 (2016).

158 7.   FAO (Rome, Italy, 2016).at <http://www.fao.org/fishery/sofia/en>

159 8.   Rodrigues, B.L. et al. *PLoS One* **12**, 1–15 (2017).

160 9.   Tocher, D.R. *Rev. Fish. Sci.* **11**, 107–184 (2003).

161 10.   Codabaccus, M.B., Ng, W.K., Nichols, P.D. & Carter, C.G. *Food Chem.* **141**, 236–244
162   (2013).

163 11.   Hilborn, R. et al. *Fish. Res.* **191**, 211–221 (2017).

164 12.   CCAMLR *Comm. Conserv. Antarct. Mar. Living Resour.* 29 (2018).

165 13.   Schram, L.B. et al. *Food Res. Int.* **40**, 1062–1068 (2007).

166 14.   Alder, J. & Pauly, D. (Vancouver, Canada, 2006).at
167   <https://open.library.ubc.ca/cIRcle/collections/facultyresearchandpublications/52383/it
168   ems/1.0074759>

169 15.   Stark, K.D., Van Elswyk, M.E., Higgins, M.R., Weatherford, C.A. & Salem, N. *Prog.*
170   *Lipid Res.* **63**, 132–152 (2016).

171 16.   EC Council *Off. J. EU* **147**, 1–40 (2001).

172   17.   Wang, F., Zhang, J., Mu, W., Fu, Z. & Zhang, X. *Food Control* **20**, 918–922 (2009).

173   18.   Hamilton, H.A., Peverill, M.S., Müller, D.B. & Brattebø, H. *Environ. Sci. Technol.* **49**,
174   (2015).

175   19.   Qi, B.X. et al. *Nat. Biotechnol.* **22**, 739–745 (2004).

176   20.   Spicer, A. & Molnar, A. *Biology (Basel).* **7**, 21 (2018).

Acknowledgements

Author contributions

184   H.H. and D.M. designed the study. H.H., R.N. and N.A. quantified the system and conducted

185   the analysis. H.H. made the figures. H.H., R.N., N.A. and D.M. contributed to the data

186   interpretation. H.H. wrote the paper. H.H., R.N., N.A. and D.M. contributed to manuscript

187   editing.

Competing financial interests

189   The authors declare no competing interests.

Correspondence

191   Correspondence should be addressed to Helen Hamilton; helen.a.hamilton@ntnu.no

Methods

193   We used a multi-layer material flow analysis framework (ML-MFA) to quantify the stocks

194   and flows of EPA/DHA throughout our defined system. The 'mother' layer contains the

195   biomass system (tonnes wet weight/yr) and the 'child' layer includes the sum of EPA and

196   DHA balance (tonnes EPA+DHA/yr). From a mass balance standpoint, quantifying the

197   EPA/DHA content of biological organisms is a methodological challenge due to i) marine

198   and freshwater species storing EPA/DHA within their lipids and, thus, metabolizing them as

9

199   an energy source and ii) organisms endogenously producing EPA/DHA through the

200   elongation of alpha-linolenic acid (ALA, 18:3n-3) at various rates depending on, amongst

201   others, the species, time of the year and habitat.[21] Therefore, unlike substances (i.e. chemical

202   elements), EPA/DHA can be created or destroyed, which limits mass balance conservation

203   when modeling and makes it necessary to consider production and destruction. Preliminary

204   estimates have shown endogenous EPA/DHA production to contribute little to the EPA/DHA

205   supply from farmed fish (i.e. EPA/DHA consumed by aquaculture equals the EPA/DHA

206   contents of the produced fish).[22] However, for certain species, endogenous EPA/DHA

207   production can be potentially significant, especially for bivalve mollusks and carp.[23]

208   Therefore, we accounted for this by calculating the net EPA/DHA production of each

209   biological process for which EPA/DHA can be created/destroyed. We assumed processes that

210   mechanically transform the flows (i.e. fish processing) do not affect the EPA/DHA content of

211   the biomass.

212   We defined the system to include the natural and anthropogenic stocks and flows of

213   EPA/DHA. Freshwater ecosystem food chains were not considered due to their minor role

214   relative to the marine ecosystem and limited data availability; however, we included the

215   EPA/DHA contained in freshwater fish capture and freshwater aquaculture. In addition, we

216   did not consider natural export from marine to terrestrial ecosystems, e.g. due to the

217   consumption of drifted algae by lizards, birds and other terrestrial animals, as preliminary

218   estimates (24 kt EPA+DHA/yr) have shown this to be insignificant relative to the overall

219   marine food web.[24]

220   Primary data are sourced from scientific publications, reports, statistics and industry data

221   from the International Marine Ingredients Organization (IFFO). Ocean carbon flows are

222   based on Stock et al.[25] and represent a 20 year average (1994-2014). The long time frame

223   minimizes the uncertainty related to yearly variations in primary production due to, e.g., El

224 Nino events[26]. Capture data is based primarily on the FAO dataset FishStat and includes an

225 average between 2009 and 2013 to normalize yearly variations. Due to the large number of

226 species, we only accounted for the top 20 fish, cephalopod and crustacean species caught and

227 farmed in each geographical region. EPA/DHA calculations are performed at a species level.

228 However, we accounted for all wild and farmed bivalve mollusks and plants. Overall, we

229 accounted for over 90% of fishery and aquaculture production. Avoidable food waste is

230 defined to include all edible food that was wasted at the household level. Unavoidable food

231 waste includes the remaining inedible fraction, such as peels, shells and bones. Further

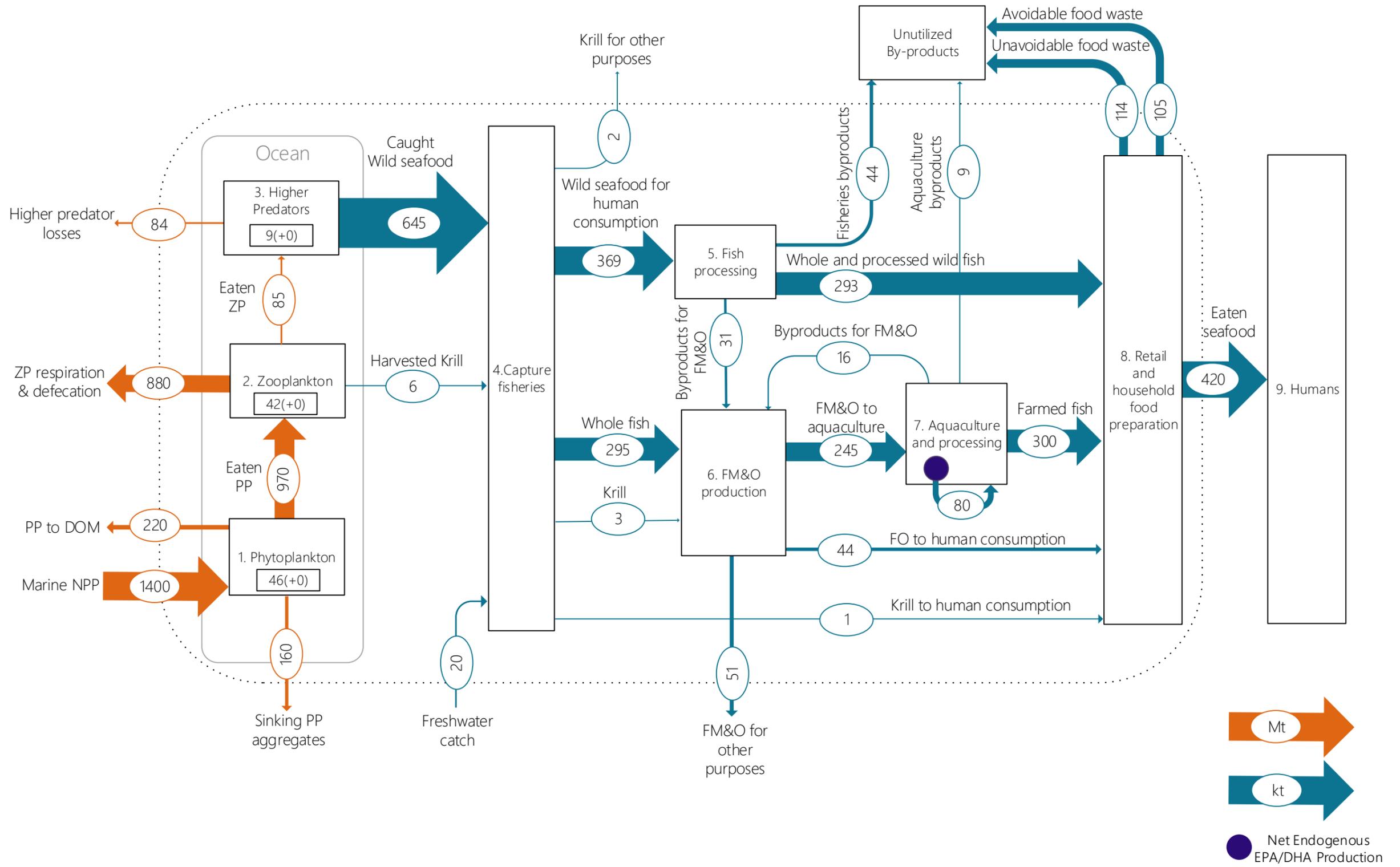232 information regarding the methods can be found in the supplementary information.

Data Availability

234 This work uses data collected from a variety of sources, both proprietary and freely available.

235 See references in the supplementary information for data specification. All figures are based

236 on this collected dataset and geographically aggregated data will be made available upon
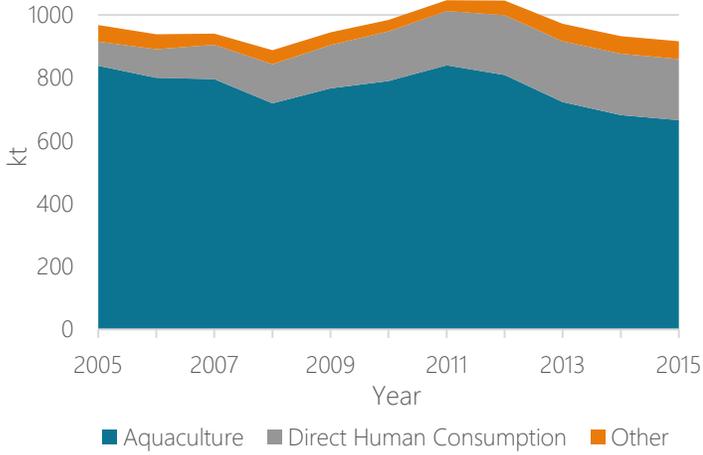
237 request from the corresponding author.

238

239 1.   Veloza, A.J., Chu, F.L.E. & Tang, K.W. *Mar. Biol.* **148**, 779–788 (2006).

240 2.   FAO *GLOBEFISH - Anal. Inf. world fish trade* (2017).at <http://www.fao.org/in-

241   action/globefish/fishery-information/resource-detail/en/c/338773/>

242 3.   FAO *GLOBEFISH - Anal. Inf. world fish trade* (2017).

243 4.   Gladyshev, M.I., Arts, M.T. & Sushchik, N.N. *Lipids Aquat. Ecosyst.* 179–210 (2009).

244 5.   Stock, C.A., Dunne, J.P. & John, J.G. *Prog. Oceanogr.* **120**, 1–28 (2014).

245 6.   Strutton, P.G. & Chavez, F.P. *J. Geophys. Res.* **105**, 260987–26101 (2000).
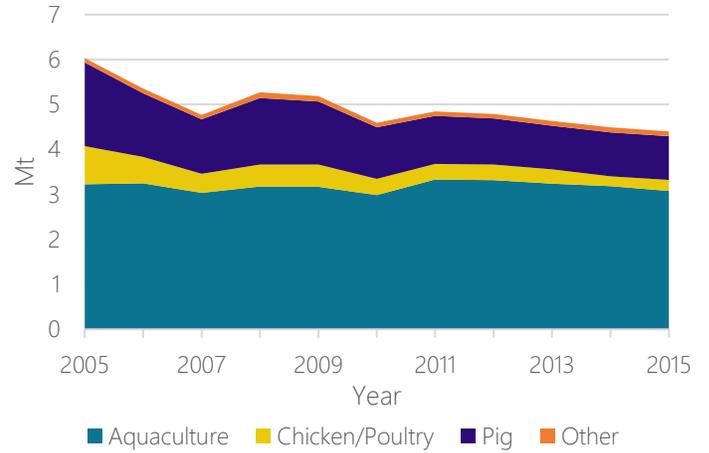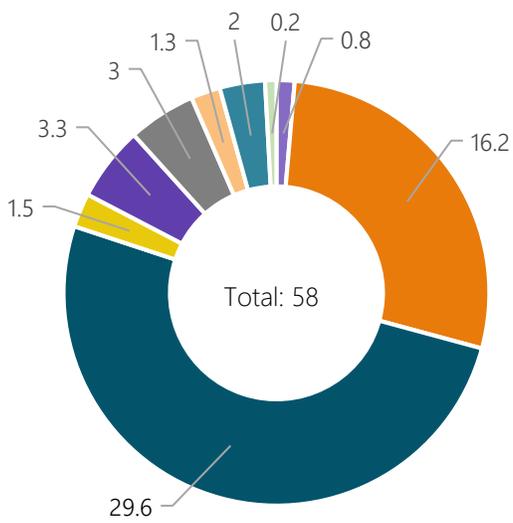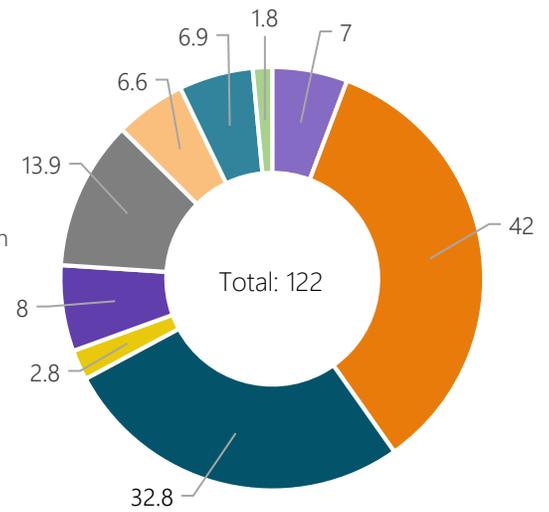
246

Fish oil consumption by sector

kt / Year

- ■ Aquaculture
- ■ Direct Human Consumption
- ■ Other

Global fishmeal consumption by sector

Mt / Year

- ■ Aquaculture
- ■ Chicken/Poultry
- ■ Pig
- ■ Other

Aquaculture

Total: 58

16.2
29.6
1.5
3.3
3
1.3
2
0.2
0.8

- ■ Europe
- ■ Asia (excluding China)
- ■ China
- ■ Middle East
- ■ Russian Commonwealth
- ■ Africa
- ■ South America
- ■ North America
- ■ Oceania

Fisheries

Total: 122

42
32.8
2.8
8
13.9
6.6
6.9
1.8
7

1

1. Supplementary Information:

A. Flat Files

4

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	

5

6

2. Source Data

Complete the Inventory below for all Source Data files.

9

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