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BRIEF COMMUNICATION

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

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

Long-chain omega-3 fatty acids—in particular, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)—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 1,000 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 these acids 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 United Kingdom, with regional and socioeconomic differences seen within the countries[3]. The EPA/DHA supply gap is unlikely to be filled 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 and fish oil sourced from capture fisheries and seafood by-products to meet their nutritional needs and maintain their fatty acid profile[5]. Due to the scarcity and increasing price of marine oils, the aquafeed industry has reduced fish meal and fish oil inclusion by partial substitution with plant ingredients[6]. Thus, aquaculture production has grown at 5.8% per annum without considerably increasing fish meal and fish oil consumption[7]. However, reduced fish meal and fish oil inclusion has affected the fatty acid profile of certain fed species (for example, 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 make it essential to optimize the management of long-chain omega-3 fatty acids, 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: (1) provide a comprehensive problem description to improve overall resource efficiency; and (2) identify system-wide opportunities and challenges for meeting the human EPA/DHA demand. Thereafter, we aim to inform decision-makers on the current EPA/DHA status, its drivers and the most effective intervention options at a global level.

We find that between net primary production and higher predators, approximately 90% of EPA/DHA is lost via respiration, defecation and deaths, indicating that large trophic losses occur up the food chain (Fig. 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 net primary production. Approximately half of harvested marine EPA/DHA is managed through fish meal and fish oil production (primarily for aquaculture consumption; Fig. 2a) and half is reserved 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, which accumulate EPA/DHA from the environment and/or endogenous production through the elongation of shorter-chained fatty acids. Freshwater fish are better at elongation compared with marine fish due to unique enzymes and desaturase genes that allow for EPA/DHA synthesis[8]. In contrast, fed high-trophic salmonid species: (1) consume a high proportion of aquaculture's use of fish meal and fish oil (58 and 22%, respectively, in 2015); (2) have EPA/DHA retention rates varying from 30 to 75%; and (3) are inefficient at fatty acid elongation[9], but also supply EPA/DHA through a farmed product based on an otherwise under-utilized wild fish resource.

We find that the supply of EPA/DHA for human consumption is 420 kt yr^{-1}, or 149 mg EPA + DHA per capita daily, representing 30% of global demand. Therefore, we confirm the supply gap identified by Tocher[2] but find it to be over 50% larger than previous estimates suggest. Significant losses occur due to unavoidable and avoidable food waste (114 and 105 kt yr^{-1} of EPA + DHA, respectively) and unutilized fish-processing by-products (53 kt yr^{-1} of EPA + DHA), with the largest losses in Asia (Fig. 2b).

While many options exist to fill the EPA/DHA gap, each has associated challenges. Aquaculture's strategic use of fish meal and fish oil in feed at key life stages can: (1) influence the EPA/DHA utilization efficiency by farmed fish; and (2) optimize the benefits of marine ingredients from a fish and human health perspective (for example, 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 probable short-term decreases)[4]. However, forage fish harvesting may have a decreased effect on stock size compared with environmental factors that affect

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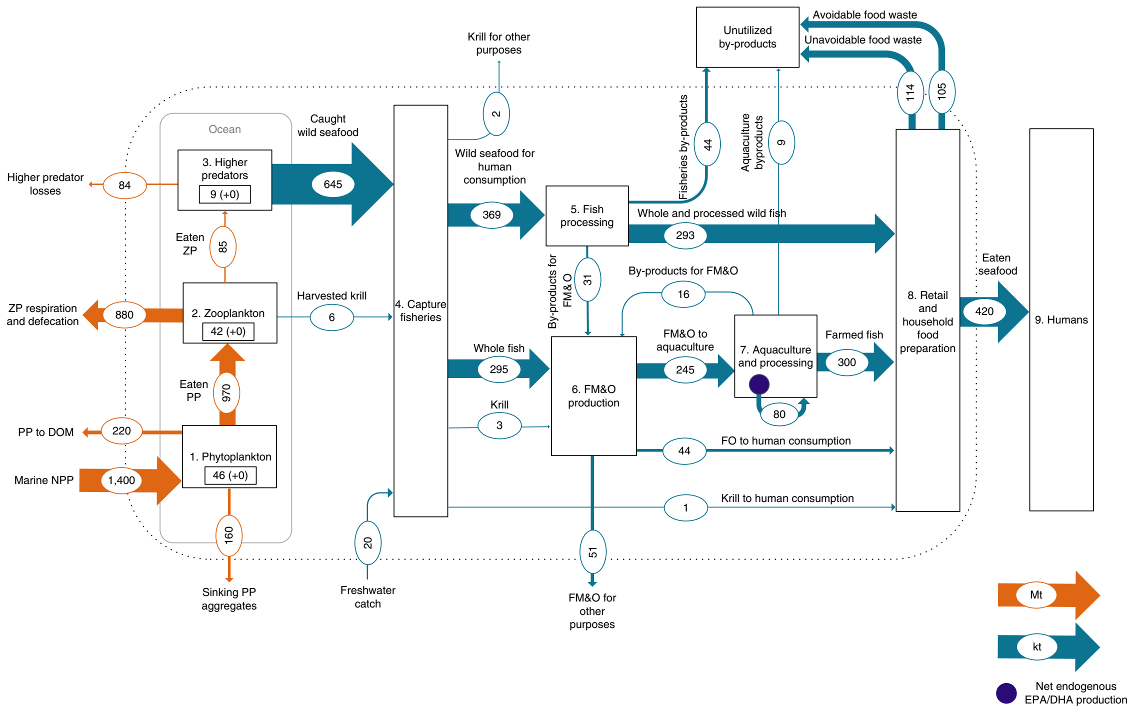

Fig. 1 | Global EPA and DHA balance. Orange and blue arrows show values of EPA + DHA per year in Mt and kt, respectively. The purple dot denotes net endogenous EPA/DHA production by fish. Mass balance inconsistencies are due to rounding errors and uncertainty. All flows in process 6 were calculated independently, and the remaining mass balance inconsistency is <1% of total flows in this process. Net endogenous production in the ocean system is not visualized. DOM, dissolved organic matter; FM&O, fish meal and oil; FO, fish oil; NPP, net primary production; PP, phytoplankton; ZP, zooplankton.

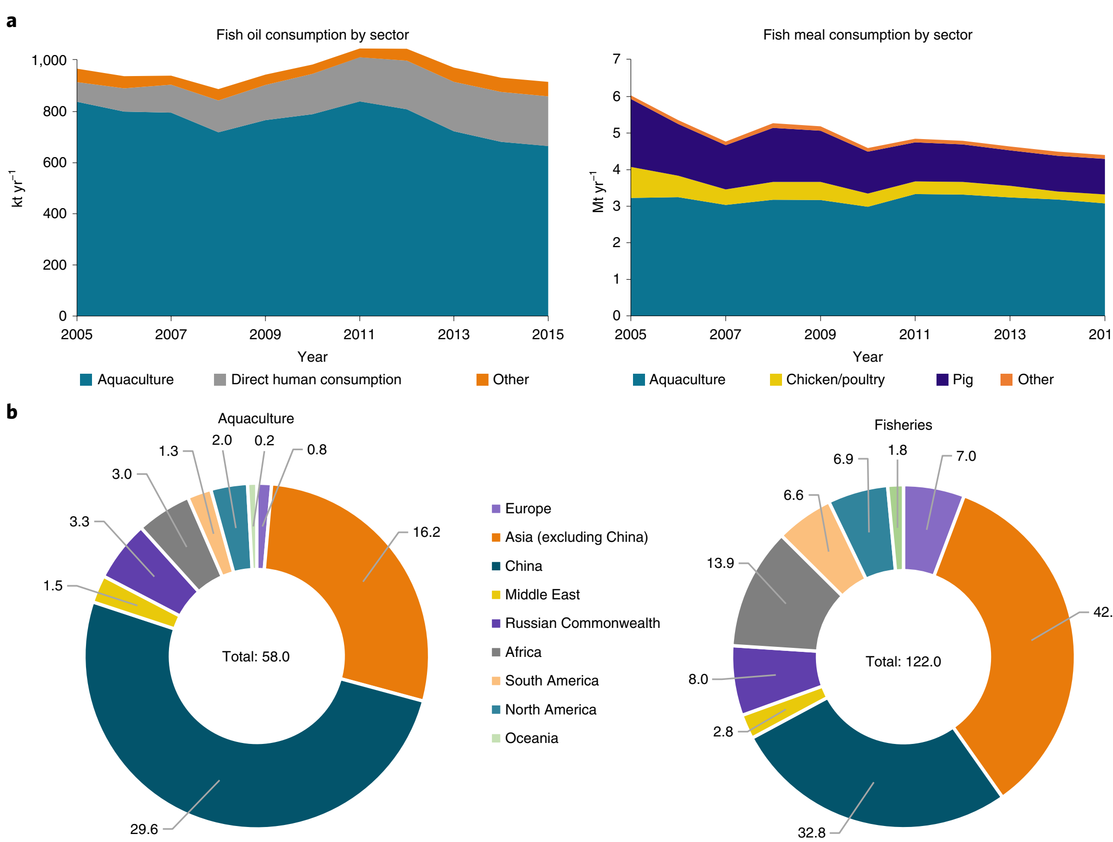

Fig. 2 | Global fish oil and fish meal consumption, and EPA/DHA potential from by-products. a, Global fish oil (left) and fish meal consumption (right) by sector. **b**, EPA/DHA potential from unutilized by-products from aquaculture (left) and fisheries processing (right) by region in 2017 (in $kt\,yr^{-1}$). Data source: Food and Agriculture Organization.

reproductive success[11]. With the krill harvesting rate (~300,000 tonnes of biomass in 2018) being below the catch limit of 5.6 million tonnes annually, as defined by the 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.

Trophic losses could be avoided (and supply increased) by: (1) consuming EPA/DHA from a lower trophic level (for example, seaweeds, krill and bivalve molluscs); (2) increasing non-fed fish farming; and/or (3) 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 (for example, the bioavailability of fatty acids in fish oil is lower than in fish[13]), and although the nutraceutical market is strong, the wild fish market depends on factors including, among others, catch quality, acceptance and temporal challenges (that is, the 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[3].

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 fish meal and fish oil production for aquafeed and/or human consumption, provided the regulatory frameworks are followed[15]. 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 (Fig. 2b)—has a culture of buying fish whole and disposing of by-products at the household level[16]. Centralized fish processing is needed to recover by-products 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[17].

Future options to produce EPA/DHA include large-scale production of natural and genetically modified microalgae, microbacteria and higher plants. However, current technologies and concerns about genetically modified material limit the volume of supply, their cost-effectiveness and widespread penetration into the market[18], although regulatory challenges related to genetically modified feed use are primarily constrained to Europe[19].

Methods

We used a multi-layer material flow analysis framework to quantify the stocks and flows of EPA/DHA throughout our defined system. The 'mother' layer contains the biomass system (tonnes of wet weight per year) and the 'child' layer includes the sum of EPA and DHA balance (tonnes of EPA + DHA per year). From a mass balance standpoint, quantifying the EPA/DHA content of biological organisms is a methodological challenge due to: (1) marine and freshwater species storing EPA/DHA within their lipids and, thus, metabolizing them as an energy source; and (2) organisms endogenously producing EPA/DHA through the elongation of α-linolenic acid (18:3$n-3$) at various rates depending on, among others, the species, time of the year and habitat[20]. Therefore, unlike substances (that is, chemical elements), EPA/DHA can be created or destroyed, which limits mass balance conservation when modelling 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 (that is, EPA/DHA consumed by aquaculture equals the EPA/DHA contents of the produced fish)[21]. However, for certain species, endogenous EPA/DHA production can be potentially significant, especially for bivalve molluscs and carp[21]. 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 that processes that mechanically transform the flows (that is, 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 (for example, due to the consumption of drifted algae by lizards, birds and other terrestrial animals), as preliminary estimates (24 kt yr^{-1} of EPA + DHA) have shown this to be insignificant relative to the overall marine food web[22].

Primary data were sourced from scientific publications, reports, statistics and industry data from the International Marine Ingredients Organization (IFFO). Ocean carbon flows were based on Stock et al.[23] and represent a 20-year average (1994–2014). The long time frame minimized the uncertainty related to yearly variations in primary production due to, for example, El Nino events[24]. Capture data were based primarily on the Food and Agriculture Organization dataset FishStat, and include 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 were performed at the species level. However, we accounted for all wild and farmed bivalve molluscs and plants. Overall, we accounted for over 90% of fishery and aquaculture production. Avoidable food waste was defined to include all edible food that was wasted at the household level. Unavoidable food waste included the remaining inedible fraction, such as peels, shells and bones. Further information regarding the methods can be found in the Supplementary Information.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

This work used data collected from a variety of sources—both proprietary and freely available. See the references in the Supplementary Information for data specification. All figures are based on this collected dataset, and geographically aggregated data (in more refined detail than the source data) will be made available on request from the corresponding author. Source data for Figs. 1 and 2 are provided with the paper.

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Author contributions

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

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s43016-019-0006-0.

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Software and code

Policy information about availability of computer code

Data collection	Primary data are sourced from scientific publications, reports, statistics and industry data from the International Marine Ingredients Organization (IFFO). Data and their associated sources are detailed in the supplementary information and will be made available upon request.
Data analysis	The data was analysed using a MatLab script. This script performs mass balance calculations and are detailed extensively in the supplementary information. The script can be made available upon request.

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Study description	The study is quantitative, using the method 'material flow analysis'. This method is based on conservation of mass principles and relies on statistics to quantify mass balances.
Research sample	Primary data are sourced from scientific publications, reports, statistics and industry data from the International Marine Ingredients Organization (IFFO).
Sampling strategy	No sampling was performed in this analysis.
Data collection	The data was collected via online platforms.
Timing	Data was collected from statistics to represent a 20 year average for oceanic flows and a 5 year average for anthropogenic flows. The long time frame was used to minimize the uncertainty related to yearly variations in primary production due to, e.g., El Nino events.
Data exclusions	No data was excluded
Non-participation	Not applicable
Randomization	Not applicable

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