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Fish as feed: Using economic allocation to quantify the Fish in - Fish-out ratio of major fed aquaculture species

Björn Kok[a,b,*], Wesley Malcorps[c], Michael F. Tlusty[d], Mahmoud M. Eltholth[c,e,f], Neil A. Auchterlonie[g], David C. Little[c], Robert Harmsen[b], Richard W. Newton[c], Simon J. Davies[h]

[a] *Independent researcher, Utrecht, 3561 JN, the Netherlands*
[b] *Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, 3508 TC, the Netherlands*
[c] *Institute of Aquaculture, University of Stirling, Stirling FK9 4LA City, United Kingdom*
[d] *School for the Environment, University of Massachusetts Boston, Boston, MA 02125, USA*
[e] *Department of Hygiene and Preventive Medicine, Faculty of Veterinary Medicine, Kafrelsheikh University, Kafrelsheikh, Egypt*
[f] *Global Academy of Agriculture and Food Security, The Royal (Dick) School of Veterinary Studies and The Roslin Institute, The University of Edinburgh, Edinburgh, United Kingdom*
[g] *IFFO, The Marine Ingredients Organisation, London SE17 3BZ, United Kingdom*
[h] *Fish Nutrition and Aquaculture Group, Department of Animal Production, Welfare and Veterinary Sciences, Harper Adams University, Newport TF10 8NB, United Kingdom*

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ABSTRACT

Efficiency assessments of marine ingredient use in aquaculture are required to fully understand their contribution to global seafood supply and their impacts on all UN Sustainable Development Goals. Fish In: Fish Out (FIFO) ratios have become the principal metric used to ensure aquaculture does not negatively impact wild fish stocks. However, several approaches have been advocated to calculate the FIFO ratio and there have been criticisms that the different approaches employed lead to over- or under- estimates of the dependence of aquaculture on marine ingredients. Critically, FIFO does not align with Life Cycle Assessment as a measure of other environmental impacts. In this paper we present an alternative method to calculate the FIFO ratio based on the principle of economic allocation (economic Fish In: Fish Out – eFIFO) as commonly used in Life Cycle Assessments. Economic allocation acts as a proxy for the nutritional value of ingredients and places higher importance on the more limiting co-products generated and their relative demand. Substitution of marine ingredients by alternate feed ingredients has significantly reduced the amount of fishmeal and fish oil in aquafeed formulations for most farmed fish species, resulting in a continually decreasing FIFO ratio. Results show that most aquaculture species groups assessed in this study are net producers of fish, while salmon and trout aquaculture are net neutral, producing as much fish biomass as is consumed. Overall, global fed-aquaculture currently produces three to four times as much fish as it consumes. Tracking historical prices of fish oil against fishmeal, the relative higher price of fish oil leads to relatively higher allocation of fish to fish oil compared to fishmeal. This leads to relatively higher eFIFO for species with high fish oil requirements.

1. Introduction

Fish and shellfish, (seafood), fulfil a crucial role in global food and nutritional security being valuable sources of essential nutrients (FAO, 2018; Hicks et al., 2019). Seafood is considered to be the only readily available source of long-chain omega-3 highly unsaturated fatty acids (HUFAs) such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), the consumption of which are associated with various health benefits (Calder, 2018; Spiller et al., 2019; Tacon and Metian, 2017). Among animal derived foods, seafood is a particularly rich, and highly bioavailable, source of key micronutrients, such as iron, zinc and selenium (Hicks et al., 2019). Over the past decades, the contribution of aquaculture to aquatic, and particularly seafood production, has steadily increased while capture fisheries production has stagnated (FAO, 2018; Pauly and Zeller, 2016; Tacon and Metian, 2018). Considering animal food source equivalents of edible product (fish head on gutted;

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* Corresponding author at: Independent researcher, Utrecht, 3561 JN the Netherlands. E-mail address research@bjornkok.nl
E-mail addresses: research@bjornkok.nl (B. Kok), wesley.malcorps@stir.ac.uk (W. Malcorps), Michael.Tlusty@umb.edu (M.F. Tlusty), neilauchterlonie@btinternet.com (N.A. Auchterlonie), d.c.little@stir.ac.uk (D.C. Little), r.harmsen@uu.nl (R. Harmsen), richard.newton@stir.ac.uk (R.W. Newton), sdavies@harper-adams.ac.uk (S.J. Davies).

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crustacean tail meat, peeled, deveined tail on; and mollusc meat without shells) total seafood production was 104 million metric tonnes (mmt), of which 54 mmt (52%) came from capture fisheries, and 50 mmt (48%) originated from aquaculture (Edwards et al., 2019).

Traditional extensive aquaculture in Asia did not rely on feed, instead was dependent on primary productivity encouraged by fertilisation but currently, approximately 70% of farmed fish is produced as fed-aquaculture with the remaining, mostly carp, still being produced in traditional unfed systems that rely on fertilisation only (supplementary information Table 1) (FAO, 2018; Tacon and Metian, 2015). Intensification of aquaculture with improved strains and feeding increased global production from approximately 12 to 51 mmt between 1995 and 2015 (FAO, 2018). Omnivorous freshwater species; carp, tilapia and catfish now represent over half the fed aquaculture production sector and a substantial amount of global aquafeed production (Tacon, 2019). Most Life Cycle Assessments (LCAs) show that feed use probably accounts for more than 90% of the cumulative environmental impact of aquaculture supply chains (Little et al., 2018)

Significant levels of marine ingredients are derived from wild fish and fish processing by-products (secondary or lower value products) (Tacon et al., 2011). Marine ingredients continue to be critically important feed ingredients, vital to the aquaculture industry (Konar et al., 2019). Fishmeal supplies mainly protein for fish and livestock growth, but is also a valuable source of micronutrients such as vitamins, minerals, and lipids. Moreover it contributes to enhanced digestibility and palatability of any feed, which is particularly important in early-stage diets for many species (Jannathulla et al., 2019; Shepherd and Jackson, 2013). The primary role of using fish oil in feeds for carnivorous fish species is to satisfy stringent requirements for essential long chain HUFAs of the omega-3 series fundamental to their metabolism and physiology (Rosenlund et al., 2016). In addition they are vital to maintain essential fatty acids such as DHA and EPA in the flesh of fish like farmed salmon for the benefit of the consumer to safeguard human health and well-being. Although fish oil for human consumption can be provided in the form of fish oil capsules (Pike and Jackson, 2010) assimilation from whole fish is seen to be more beneficial as reported by Zibaeenezhad et al. (2017). However, during the last 25 years, fish oil has been significantly replaced by a blend of vegetable oils including rapeseed oil in diets for salmon leading to a drop in omega-3 content to half between 2006 and 2015 (Sprague et al., 2016). It should be noted that vegetable oils can meet the energy requirements of fish via non-essential fatty acid catabolism allowing fish oil inclusion to be minimised. This delicate balance between meeting omega-3 fatty acids from marine fish oil for both fish and human needs is a challenging area. Recent developments in microalgae and other technologies to produce omega-3 (EPA and DHA) could mitigate the use of fish oil to some extent (Sprague et al., 2017).

Fishmeal and fish oil are considered highly digestible ingredients for farmed fish feed supplying bioavailable nutrients (proteins and essential amino acids) essential lipids and energy (FAO, 2018). The inclusion of marine ingredients is generally higher for high-value species, such as shrimp and salmon (FAO, 2018), which require elevated levels to meet their stringent nutritional needs (Froehlich et al., 2018; Naylor et al., 2009; Tacon and Metian, 2015). Shrimp and salmon aquaculture are the largest consumers of fishmeal and fish oil respectively (Shepherd et al., 2017; IFFO estimates). Omnivorous species, in general, have lower fishmeal inclusion rates in their feed, but their production volumes make them a significant users of global fishmeal supplies (Tacon and Metian, 2008). However, market forces have been driving the substitution of marine ingredients by a variety of plant-based ingredients, animal-by-products and novel feed ingredients (Davies et al., 2019; Froehlich et al., 2018; Pelletier et al., 2018; J. Shepherd and Bachis, 2014) driven by prices, availability and legislation (Gatlin et al., 2007). This transition towards plant ingredients in combination with the increase in aquaculture production could potentially lead to additional pressure on essential agricultural resources with associated socio-economic and environmental impacts (Blanchard et al., 2017; Froehlich et al., 2018; Malcorps et al., 2019; Roberts et al., 2015). Even though the fraction of land use destined for aquaculture is relatively small with approximately 4% of the total global animal feed supply (Troell et al., 2014).

The use of marine ingredients has long raised concerns about the effect of aquaculture on marine fish stocks, and the continued supply of marine ingredients, largely in the form of fishmeal and fish oil (Blanchard et al., 2017; Troell et al., 2014; Stead, 2019; Naylor et al., 2000). Some stakeholders argue that aquaculture is a solution to meet the global demand for fish and seafood (Tidwell and Allan, 2001), while others continue to argue it leads to the deterioration of marine fish stocks (Golden et al., 2016; Kristofersson and Anderson, 2006; Naylor et al., 2000). Increasing demand for aquafeed, it is claimed, would put increasing pressure on capture fisheries and could diminish their valuable ecosystem services (Konar et al., 2019). This view is undermined by the peak in fishmeal production, in 1994–1995, occurring well before the major expansion in aquaculture (Shepherd and Jackson, 2013). The concerns of increased fishing pressure due to demand for marine ingredients seem to assume a lack of fishery management. In fact, various governance practices such as fish stock management and certification schemes as well as long-term business decisions, ethical principles, and market forces have sustained these fisheries (Byelashov and Griffin, 2014; FAO, 2018). The volumes of catches for reduction to fishmeal and fish oil have decreased over the past decades despite the continuous increase of aquaculture production (FAO, 2018).

The majority of the pelagic fish used for reduction to fishmeal and fish oil is suitable for direct human consumption (Cashion et al., 2017a; Olsen and Hasan, 2012; Shepherd and Jackson, 2013). Some authors emphasize that the use of these species for feed limits their use for meeting local nutritional needs (Hicks et al., 2019; Kent, 1997). However, in the majority of cases, there may be little to no potential to expand the market for such species for direct human consumption, due to consumer preference for larger and more expensive species, as well as practical and logistical barriers (Wijkström, 2012). Export of these low pelagic fisheries may also allow for the imports of other food types and thus economically allowing for contributions to local nutrition (Asche et al., 2015). However, there are concerns, for example in West Africa, where harvest by foreign vessels for marine ingredients appears to be limiting access and affordability for direct consumption locally by poor and vulnerable communities. (Hicks et al., 2019; Pauly, 2019).

In 2016, 15 mmt of fish were destined for reduction to fishmeal and fish oil (FAO, 2018). The main fisheries destined for reduction originates from Peru, Chile, Scandinavia and Thailand (Shepherd, 2013; Soliman et al., 2017). Additionally, an increasing share of up to 33% of fishmeal and fish oil production is produced from by-products originating from fish processing (Jackson and Newton, 2016; Shepherd, 2013). This share continues to rise as there is remaining potential for increased by-product utilisation (FAO, 2018; Jackson and Newton, 2016; Newton et al., 2014; Stevens et al., 2018). Both fishmeal and fish oil originate from the same production process and are co-products (primary or high value products) from fish rendering (Shepherd and Jackson, 2013). On average the processing of one metric tonne of pelagic fish yields 225 kg fishmeal and 50 kg fish oil (Hamilton et al., 2020; Tacon and Metian, 2008). However, there is significant variation between species and within species with size and season (supplementary information table 2) (Cashion et al., 2017b; Ytrestøyl et al., 2015).

It should be noted that the proportion of fishmeal and fish oils included within aquafeeds rarely match the relative yields from whole fish or by-products. Therefore, a calculation incongruity arises within the Fish In: Fish Out (FIFO) ratio methods on how to match the different proportions, leading to several approaches to this assessment. Two main concepts for FIFO have since emerged and been adopted by various assessment organisations. The approach taken by Tacon and Metian (2008) and Naylor et al. (2009), adopted by the Aquaculture Stewardship Council (ASC), calculates the whole fish demand for fishmeal and additional fish oil production separately. However, the fishmeal that is produced in parallel to the additional fish oil and the fish oil left over for species that require little or no fish oil are not accounted for in these methods and is wasted (Byelashov and Griffin, 2014). This leads to double counting of whole fish use when multiple uses of fishmeal are considered (Byelashov and Griffin, 2014; Jackson, 2009). Jackson (2009), adds the fishmeal and fish oil inclusion and yields together, equally distributing the whole fish used depending on the mass yield of fishmeal and fish oil. However, according to Naylor et al. (2009) this approach obscures the effect of growing demand for fish oil as a limiting ingredient, potentially increasing the use of forage fish and misrepresenting the pressure on fisheries. The various FIFO methods also differ in the way they treat fish by-product inclusions within their calculation, but broadly they are not considered or discounted from the FIFO score.

The allocation of resources and environmental impact between co-products is also an important methodological issue in LCAs for which various alternative methods have been described (Ardente and Cellura, 2012). The main alternatives are the use of physical relationships, such as mass or non-physical relationships, such as economic value of the products (Ardente and Cellura, 2012; Henriksson et al., 2012).

In the case of fishmeal and fish oil production, the interconnectivity of the products cannot be ignored, as fishmeal cannot be produced without producing fish oil and vice versa. Ayer et al. (2007) argued that the aim of food production is to supply dietary energy and therefore gross chemical energy should be used as basis for allocation. However, Mackenzie et al. (2017) argues that this kind of biophysical approach does not necessarily reflect the behaviour of the system, because it does not reflect causal relationships within the system. Additionally, energy allocation does not consider the various other functions provided by fishmeal and fish oil in aquaculture feed. In economic allocation, the fish is allocated based on the economic value of the co-products. Huppes argues that "In a social sense, the value created causes the process" (Huppes, 1993, p. 203). Feed formulations are based on the least-cost basis to provide the required nutritional specifications for each species at optimum ingredient inclusion and value. The different nutritional functions of fishmeal and fish oil have different values and this represents the fundamental reason for the reduction of fish and the utilisation of fish by-products to support the production of fishmeal and fish oil. Therefore, the fraction of the total resource used, in this case whole fish, is calculated as the share of proceeds of the product from the total (Ardente and Cellura, 2012). As prices fluctuate significantly in the commodity market this may influence the allocation of whole fish to fish oil and fishmeal. Since the investment in reduction facilities are significant, and thus tend to be long-term investments, short term price fluctuations are not of interest to determine the driving forces behind fish reduction. Therefore, a long term average is more appropriate (Guinée et al., 2004). Economic allocation has been frequently used in aquaculture and fisheries LCAs studies (Henriksson et al., 2012). For example, Ziegler and Valentinsson (2008) argue that the high price of the targeted species generally drives fishing activity, rather than the lower price of by-catch that is also landed. It is also applied to other cases, e.g. processing soy to soybean meal and soybean oil (Dalgaard et al., 2008), as well as for main products and by-products from fish processing (Ziegler et al., 2003). Although it is not used in the calculation of the FIFO ratio, according to Guinée et al. (2004), economic allocation is the most generally applicable and consistent allocation approach. This is also the allocation method preferred in the Product Environmental Footprint Footprint Category Rules (PEFCR) feed for food-producing animals guidelines of the European Commission (PEFCR Feed for food producing animals, 2018).

An in-depth understanding of the use and availability of marine ingredients in aquafeeds, and the raw materials from which they are derived, is crucial to support the sustainable growth of the industry. Therefore there is a need to harmonise the FIFO ratio with LCA methodology to facilitate a broader assessment of the environmental effects of aquaculture. Therefore, we present a novel approach to calculate the Fish in - Fish-out ratio based on the principle of economic allocation, as commonly used in LCAs.

2. A novel approach to calculate the fish demand for aquaculture: The economic Fish in: Fish out (eFIFO) ratio

2.1. eFIFO ratio

The FIFO ratio represents the amount of fish used to produce 1 kg of farmed fish. The amount of fish required is dependent on the amount of feed necessary to support 1 kg of growth, which is also known as the (economic) Feed Conversion Ratio (eFCR), and the fraction of feed that is fishmeal and fish oil multiplied by the embodied fish per kg of fishmeal and fish oil. This gives the following formula (Eq. (1)):

$$eFIFO = Fish\ in = EFCR * \Sigma(F_{i,j} * EF_{i,j}) \tag{1}$$

where:

eFCR = Economic Feed Conversion Ratio
F_i = Fractions of ingredient i in the feed (%)
EF_i = Embodied Fish in ingredient i
i = FM or FO
j = Source of ingredient

2.2. Embodied fish in fishmeal and fish oil

The embodied fish in fishmeal and fish oil is dependent on the raw material (species, size, season etc.). The availability, quality and demand result in a fluctuation of fishmeal and fish oil prices, but using a long term average, can smooth out variations (Guinée et al., 2004). Depending on the price difference of both commodities the relative economic allocation (P_{FM} & P_{FO}) is calculated using the Eq. (2) (Ardente and Cellura, 2012).

$$P_i = \frac{n_i * x_i}{\Sigma(n_i * x_i)} \tag{2}$$

where:

P_i = Partitioning factor of co-product i
n_i = Quantity of the ith product
x_i = Price of the ith product
i = Fishmeal (FM) or Fish oil (FO).

When the partitioning factor is divided by the co-product yield it gives the embodied pelagic fish per kg FM and FO. This gives Eq. (3) for the embodied fish (EF) per unit volume of the co-products.

$$EF_{i,j} = \frac{\frac{Y_{i,j} * V_{i,j}}{\Sigma\ Y_{i,j} * V_{i,j}}}{Y_{i,j}} = \frac{V_{i,j}}{\sum_{i,j} Y_{i,j} * V_{i,j}} \tag{3}$$

$V_{i,j}$ = Price of ingredient i from source j$Y_{i,j}$ = Yield of ingredient i from source ji = FM or FOj = Source of ingredient

2.2.1. By-product utilisation

For the calculation of the global average eFIFO and whole fish demand, fish by-products from processing are considered to have negligible value for the producer, so the embodied whole fish in the by-products and resulting marine ingredients is zero. However, with rising prices for fishmeal and fish oil and the increasing utilisation of fish by-products, the value of by-products for processors is not always negligible, and likely to rise (Stevens et al., 2018). The embodied fish in by-products (EF_{bp}) is calculated using the same formula as for reduction fisheries as shown below (Eq. (4)).

$$EF_{i,j} = \frac{\frac{Y_{i,j} * V_{i,j}}{\Sigma\ Y_{i,j} * V_{i,j}}}{Y_{i,j}} = \frac{V_{i,j}}{\sum_{i,j} Y_{i,j} * V_{i,j}} \tag{4}$$

V_k = Price of co and by-products (k) from fish processingY_k = Yield of co and by-products (k) from fish processing

In order to calculate the embodied fish in the feed ingredients originating from by-products, the embodied fish in by-products is then multiplied with the embodied by-product in each ingredient.

$$EF_{i,bp} = EF_{bp} * \frac{V_{i,bp}}{\sum_i (Y_{i,bp} * V_{i,bp})} = \frac{V_k}{\sum_k (Y_k * V_k)} * \frac{V_{i,bp}}{\sum_i (Y_{i,bp} * V_{i,bp})} \tag{5}$$

2.3. Comparison

For this study price data from the OECD-FAO agricultural outlook (2018) was employed in calculations. Fishmeal and fish oil yields for the main species reduced to fishmeal and fish oil was obtained from Cashion et al. (2016). For the comparison of the eFIFO method with the existing methods, the global average yield of 22.5% and 5%, respectively, was used (Hamilton et al., 2020; Shepherd and Jackson, 2013; Tacon and Metian, 2008). The embodied fish for the most important sources of fishmeal and fish oil and global average from 1997 till 2027 are given in supplementary table 2.

To compare the eFIFO method with the existing methods, the eFIFO has been calculated for both fed production as well as total production per species group (fed and non-fed). The eFIFO ratio including non-fed production was calculated by multiplying the fed only eFIFO and multiplying it with the share of fed production from Tacon et al. (2011).

The fish demand of aquaculture was calculated by multiplying the eFIFO values for the fed production with the fed production share from Tacon et al. (2011). The eFIFO values and total fish demand including by-product utilisation were calculated by subtracting the share of by-products from the total fish demand assuming the by-products have no value, thereby giving a lower bound to the effect of by-product utilisation. The share of by-products was calculated using a linear trend based on the by-product shares from 1997 (5%) (Naylor et al., 2009) and 2015 (33%) (Jackson and Newton, 2016). This gave a yearly increase of 1.26% per year which is comparable with the 1 to 2% increase of by-product utilisation, as reported by Shepherd and Jackson (2013).

3. eFIFO results and validation

3.1. Recalculation of FIFO ratio for main aquaculture species groups

Our calculated eFIFO results for the main aquaculture species groups compared with results from literature are presented in Figs. 1-4. Fig. 1 presents the species groups with a low inclusion of marine ingredients, Figs. 2 and 3 show the species groups with low inclusion of fish oil, but higher inclusions of fishmeal, while the species groups in Fig. 4 require higher levels of fish oil, and relatively lower levels of fishmeal. The results from Tacon and Metian (2008) are averages of total production including non-fed production, while the results of Naylor et al., 2000 and Jackson (2009) only include fed-production, the eFIFO values are shown for both. The results overall indicate a large variation of the FIFO ratio between the different types of fish produced in aquaculture. The freshwater species (catfish, tilapia and carp) and milkfish, historically have a low FIFO ratio that has further declined to between 0.06 and 0.15 in 2020.

Comparing our eFIFO results with the FIFO ratios given in literature for species groups with relatively low inclusions of marine ingredients showing that results for tilapia (Fig. 1a) and catfish (Fig. 1b) are comparable to Tacon and Metian (2008) and lower than reported by Naylor et al. (2000). Contrarily, our results for non-filter feeding carp (Fig. 1c) are similar to Naylor et al. (2000) but somewhat lower than those presented by Tacon and Metian (2008). The findings for tilapia, catfish and non-filter feeding carp, are very comparable to the results presented by Jackson (2009), while the calculations for milkfish (Fig. 1d) compare well with the results from Tacon and Metian (2008), but higher than results presented by Jackson (2009).

The species groups' marine fishes, eels, miscellaneous carnivorous freshwater species (Fig. 2) show a calculated eFIFO ratio from 4.6–5.3 in 1995, which declined to between 0.9 and 2.2 in 2015. The calculated eFIFO for marine fish (Fig. 2a), compared to Naylor et al. (2000), shows higher values in 1995, while the values of Jackson (2009) in 2010 show similar values compared to our eFIFO calculations. On the other hand, for eel (Fig. 2b), our eFIFO results show similar values over time compared with Naylor et al. (2000), Tacon and Metian (2008) and Jackson (2009). The available literature for freshwater carnivorous fish (Fig. 2c) is currently limited, but the results of Jackson (2009) show much lower results in 2009 compared to our eFIFO ratio.

The results for crustaceans (shrimp and freshwater crustaceans) show eFIFO values have decreased from 2.6 in 1995 to 0.5 in 2020. The eFIFO results for shrimp (Fig. 3a) are similar with the results from Tacon and Metian (2008) and Jackson (2009), while Naylor et al. (2000) shows a much higher value with 2.8 in 2000. Conversely, our eFIFO values compare well with Tacon and Metian (2008) while differing strongly with Jackson (2009).

Salmonid (mainly salmon and trout) production is all based on fed production, therefore there is no difference in scope between the different results that include fed only or total aquaculture production. The eFIFO results for salmonids show medium FIFO ratios decreasing from 3.8 in 1995 to 1 in 2020. The comparison between the eFIFO results and previously published FIFO ratios for salmonids (Fig. 4) show that the eFIFO values are much lower than assessed by Tacon and Metian (2008) and Naylor et al. (2009) (FIFO of 5 for salmon in 2007), while being more comparable with the results presented by Jackson (2009) and Naylor et al. (2000). The relatively high fish oil requirement of salmonids leads to the whole fish demand for fish oil being higher than the whole fish demand for fish oil.

3.2. Recalculation of the aquaculture industry FIFO & whole fish demand

Comparing the results of our eFIFO calculations with the results provided in literature for global average FIFO (Fig. 5a.) and whole fish demand (Fig. 5b.) shows that the eFIFO method yields comparable results with those of Tacon and Metian (2008), Naylor et al. (2000) and Jackson (2009). However, the global FIFO reported by Tacon and Metian (2008) is not the same as the weighted average of the FIFO ratio of the species groups (Jackson, 2009). Fig. 5 also demonstrates the effect of continually intensifying aquaculture where the difference between the FIFO ratio of fed aquaculture compared to total aquaculture (i.e. including unfed) diminishes as the share of fed production increases.

The total whole fish demand of aquaculture is displayed in Fig. 5b. Our eFIFO calculation results indicate how the total impact of aquaculture on the world's pelagic fisheries has grown strongly from 9 mmt in 1995 to a maximum of 17 mmt in 2005, reflecting a larger proportion of global supplies directed to aquaculture. However, since then, whole fish demand of aquaculture has slightly declined to 15 mmt in 2015. In the same period fed aquaculture production increased from 11 mmt in 2005 to 32 mmt in 2015. The decline in fishery dependence, coupled with aquaculture growth reflect a reduced diet dependency on marine ingredients shown in the eFIFO ratio for fed aquaculture, (excluding by-products, Fig. 5a), dropping from 1.4 in 2005 to 0.4 in 2015, indicating no additional demand for marine capture fisheries. When including the share of marine ingredients from by-products, the eFIFO ratio declined from approximately 0.36 to 0.27 for 2020, this shows that the increased utilisation of by-products is a key factor to reduce the pressure on the marine environment.

The whole fish demand of aquaculture calculated in this study is very comparable to the whole fish destined for fishmeal and fish oil production. According to the FAO approximately 16 mmt in 2014 (FAO, 2016) and 15 mmt in 2015 (FAO, 2018) of fish was rendered into fishmeal and fish oil. This compares well with the 11.8 mmt whole fish

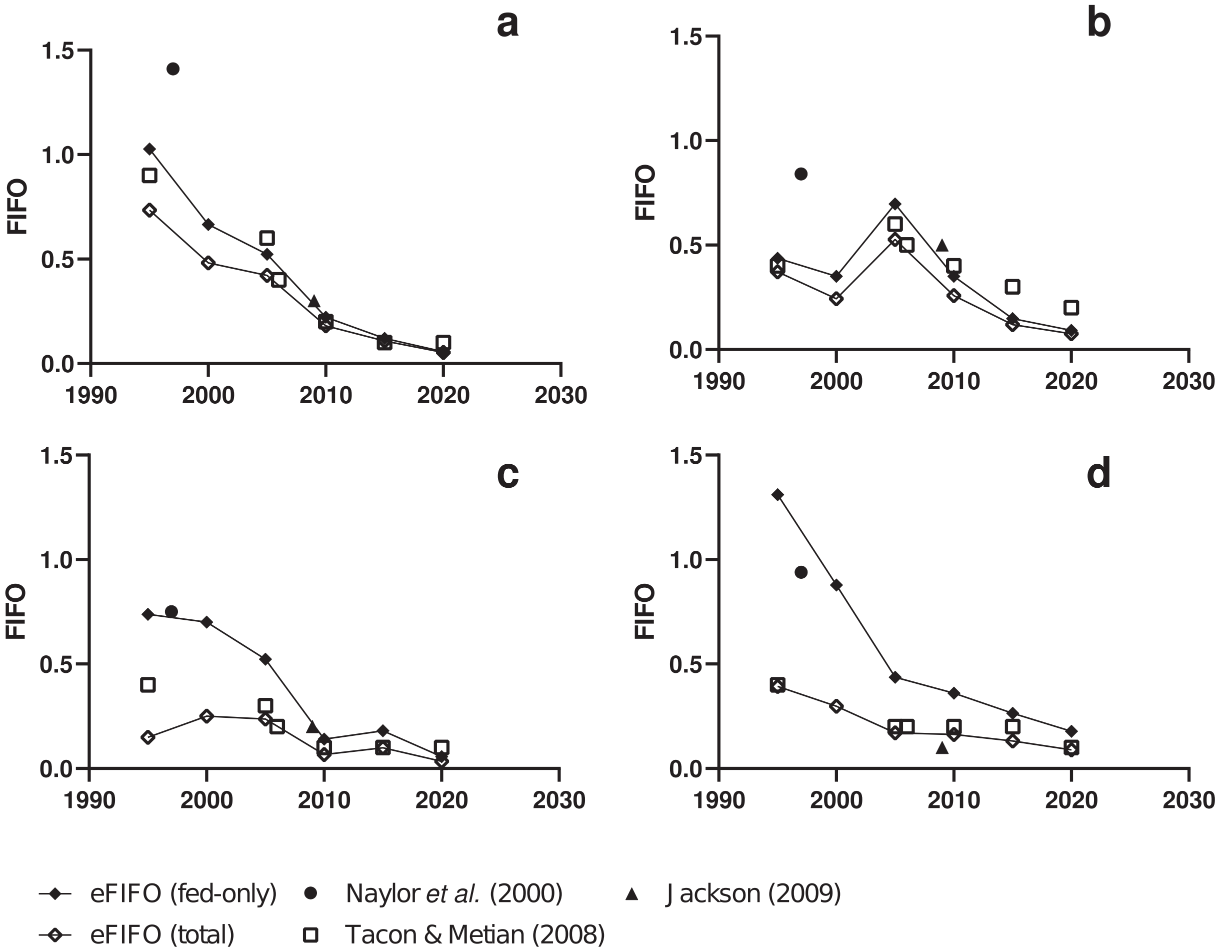

Fig. 1. Comparison of FIFO ratio between our method (eFIFO) and results presented in literature (Naylor et al. (2000), and Jackson (2009) fed only and Tacon and Metian (2008) total aquaculture) for species groups with low inclusion levels of marine ingredients: tilapia (a), catfish (b), non-filter feeding carp (c), and milkfish (d). (Table of eFIFO results is available in supplementary table 3).

demand calculated in this study, while considering the use of fishmeal and fish oil used in livestock and direct human consumption, which represent 25% of the fishmeal and fish oil consumption outside of aquaculture.

3.3. Effect of price trends of marine ingredients on embodied fish

The use of economic allocation adjusts the embodied fish in marine ingredients according to their relative value. Fig. 6a delineates the three-year rolling average price trend, indicating the strong increase of marine ingredient prices resulting in lower levels of marine ingredients in most aquafeeds. Fig. 6b demonstrates how the global average embodied fish in fishmeal and fish oil changed due to shifting economic allocation. This demonstrates that there is a clear shift in allocation from fishmeal to fish oil as fish oil becomes relatively more limiting. The increase of the embodied fish in fish oil is stronger than the decrease in embodied fish for fishmeal, as the yield of fish oil is lower than fishmeal. The increased allocation to fish oil considers the effect of growing demand from species (or other applications) that require high levels of fish oil, which could lead to increased pressures on forage fish.

4. Discussion

We conclude that certain methodologies for the calculation of the fish demand for aquaculture production do not always reflect the requirements for whole fish in a complex market with multiple applications of fishmeal and fish oil within and beyond the aquaculture industry. The approach used by Tacon and Metian (2008) and Naylor et al. (2009) do not consider that surplus fishmeal is produced parallel to the required fish oil for some species, which is utilised for other purposes. This generally overestimates the FIFO, especially of species with elevated fish oil demands, such as salmon, from a global supply perspective. In contrast, the method used by Jackson (2009) does not consider the limiting nature of the oil compared to the meal, meaning increasing demand for species with high fish oil requirements have raised concerns over unsustainable pressures on wild fisheries (Naylor et al., 2009). Additionally, the growing importance of fish by-products is not fully integrated into most FIFO calculation methods.

In contrast, our proposed approach ‘eFIFO’ utilises the principle of economic allocation to avoid double accounting of whole fish demand, whilst placing importance on the limiting nature of wild fisheries to support marine ingredient supply. The use of economic allocation considers the different functions of fishmeal and fish oil within and beyond the aquaculture industry. Our method is consistent in aggregation from the ingredient level up to global aquaculture, while taking into consideration the increasing importance of fish by-product utilisation. This is essential, as fish oil supply becomes more limited, the price rises, and the allocation of the whole fish used to produce fishmeal and fish oil is adjusted accordingly to reflect this limiting factor. Although a consequence could be a continued or increased reliance on forage fish, another likely outcome, especially given current trends, is an acceleration in the use of alternatives, such as micro-algal derived oils.

An increased utilisation of fish by-products in fishmeal and fish oil

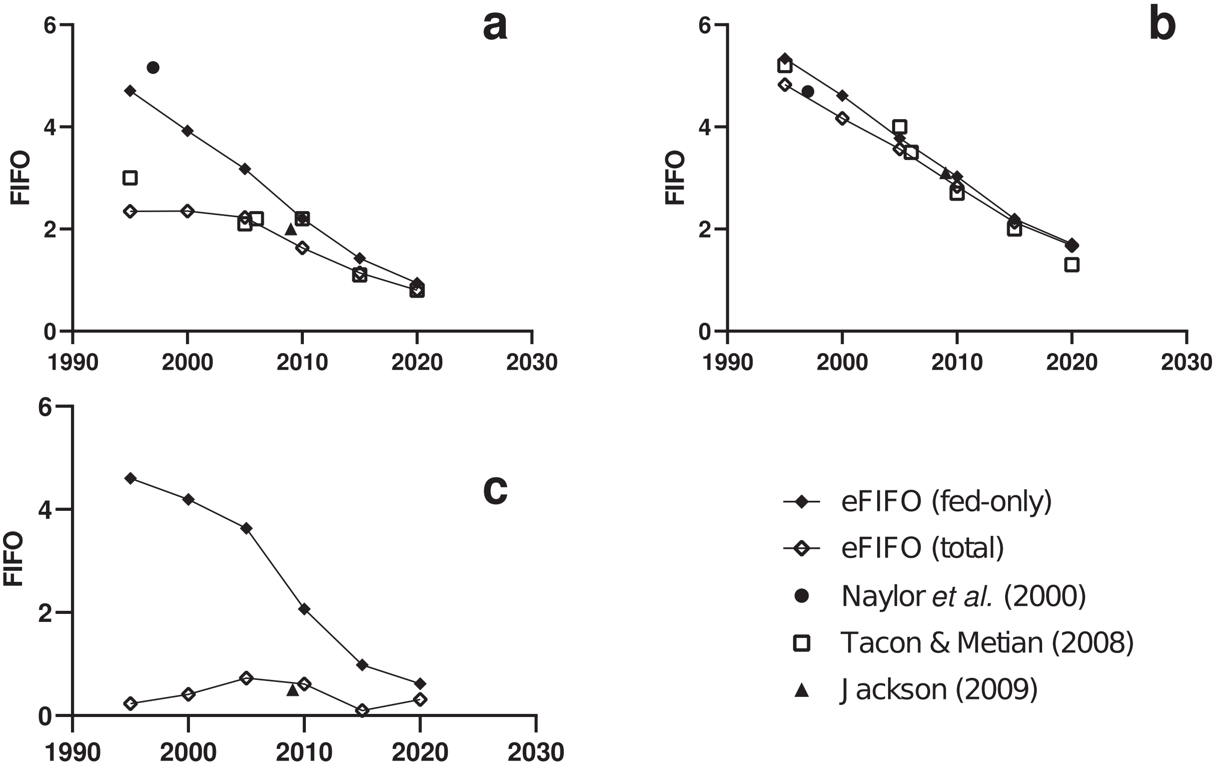

Fig. 2. Comparison of FIFO ratio between our method (eFIFO) and results presented in literature (Naylor et al. (2000), and Jackson (2009) fed only and Tacon and Metian (2008) total aquaculture) for species groups with high inclusion levels of fishmeal: marine fish (a), eel (b), and other freshwater carnivorous fish (c). (Table of eFIFO results is available in supplementary table 3).

production is also both predictable and desirable. Where an increased valorisation of fish by-products results in an allocation shift, the eFIFO ratio is adjusted accordingly. According to LCA methodology (ISO, 2006) waste has no value or embodied impact until it is utilised. The environmental impact of by-products is non-existent when it is not utilised, but as soon as by-products become a functional stream, the by-product represents the environmental burden according to its allocation. In the case of mass or energy allocation this represents an unrealistically absolute shift in the embodied burden at the point of utilisation, which does not drive waste reduction, as large impacts are attributed to the user of the waste rather than the creator. Effective implementation of waste in the circular economy, requires industry "pull" as well as "push", where the pull is the stronger driver in most cases (Arnison and Carrick, 2015). Using economic allocation gives a gradual transition as economic value is created by utilising the resulting by-products in valuable industries, thus providing both push and pull (Arnison and Carrick, 2015).

The range of FIFO values from the different methods indicates uncertainty as a result of the different approaches used by various workers in the field. The eFIFO gives in general lower Fish In: Fish Out values in

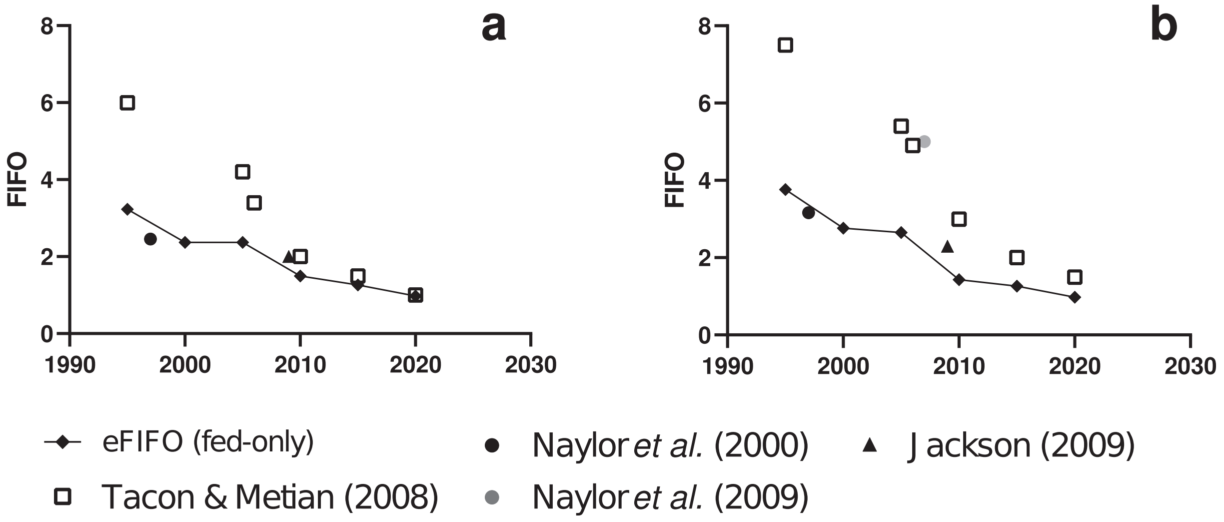

Fig. 3. Comparison of FIFO ratio between our method (eFIFO) and results presented in literature (Naylor et al. (2000), and Jackson (2009) fed only and Tacon and Metian (2008) total aquaculture) for the main crustacean species groups: shrimps (a), and freshwater crustaceans (b). (Table of results is available in supplementary table 3).

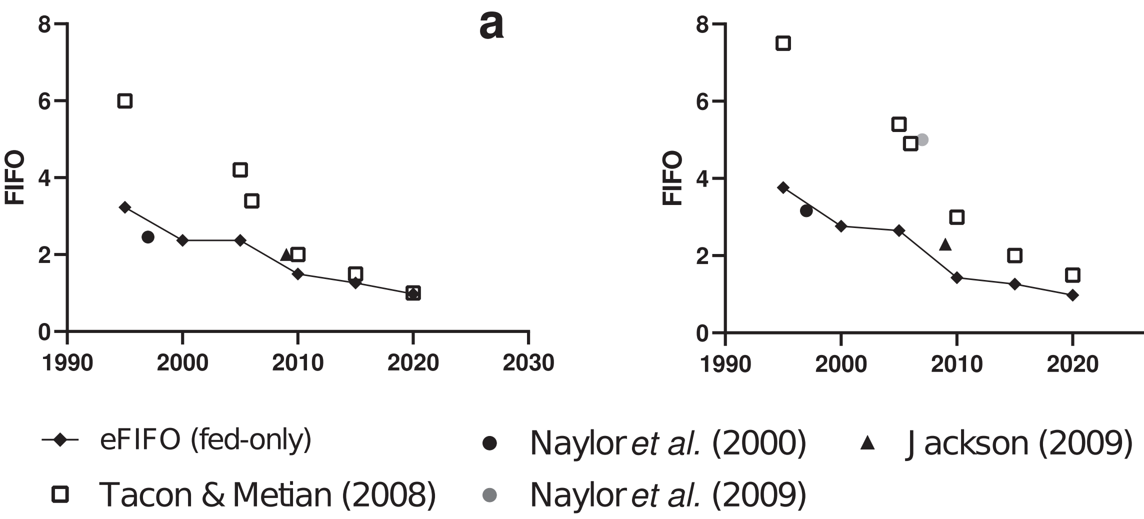

Fig. 4. Comparison of FIFO ratio between our method (eFIFO) and results presented in literature for the main salmonid species groups trout (a), and salmon (b). Both trout and salmon are species that are only produced in fed aquaculture systems.(Table of results is available in supplementary table 3).

the same situation as the methods used by Tacon and Metian (2008) and Naylor et al. (2009) due to the consideration of multiple uses of fishmeal and fish oil. This is especially the case for high fish oil demanding species, as the lower yield of fish oil gives high whole fish requirements for additional fish oil. Economic allocation reflects the socio-economic incentive to harvest fish.

There are other limitations in the use of FIFO ratio. Although it is an important tool to measure the efficient use of marine ingredients, it does little to improve understanding of the effect of aquaculture on the marine environment, as it does not incorporate any measure of the status of fish stocks and their place in complex marine ecosystems (e.g. see Konar et al., 2019). Other constraint is that FIFO only addresses live weight fish in and live weight fish out without any quality metrics, including fundamental aspects, such as edible yields. The FIFO ratio should therefore be considered in context of a broader view on sustainability including environmental and social dimensions. However, especially because of limited scope, it is essential that the FIFO ratio is calculated accurately and captures the nuances of marine ingredient use. The eFIFO method takes these nuances into consideration and gives a consistent result from the ingredient level to the global aquaculture industry.

Results of our study supports various previous investigations that have shown that as a result of lower inclusion levels of fishmeal and fish oil in the past few decades, and the use of by-products, the dependency of aquaculture on global fisheries has steadily declined (Jackson, 2009; Tacon and Metian, 2008; Ytrestøyl et al., 2015). As a result of this declining dependency, increased aquaculture production has not required more marine ingredients. Furthermore, increased utilisation of fish by-products has helped to reduce the overall dependency on whole fish utilisation. The estimated total whole fish demand of aquaculture since 2000, excluding the utilisation of fish by-products of 12 to 18 mmt, is comparable with the approximately 75% of 20 mmt total raw material used for reduction to fishmeal and fish oil. However in this study fishmeal and fish oil inclusion from Tacon et al. (2011) were used. These estimates show some differences with the latest estimates from the IFFO. The IFFO data for total fishmeal and total fish oil demand is considerably lower than Tacon et al. (2011). Additionally, the eFCR estimates from Tacon et al. (2011), is considerably lower than the

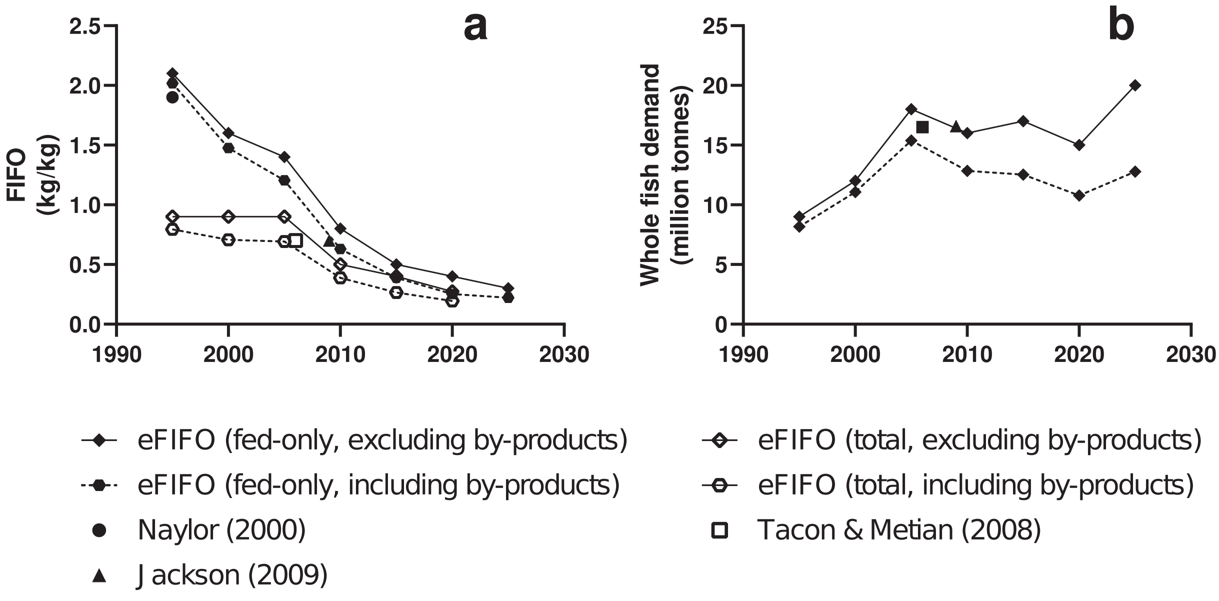

Fig. 5. Comparison of FIFO and total whole fish demand of aquaculture. (Tables of results are available in supplementary table 4).

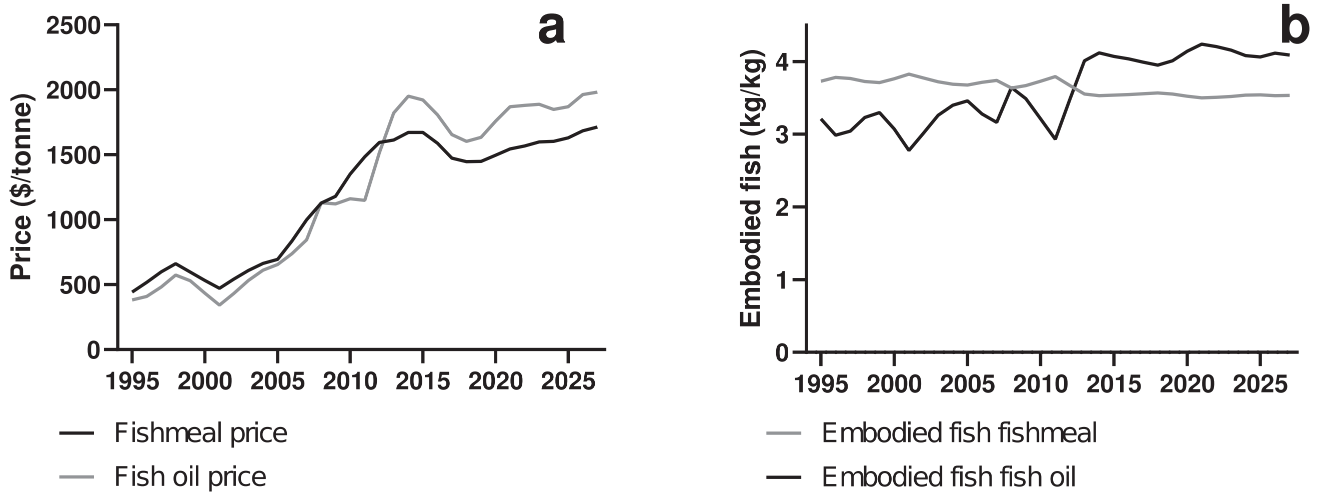

Fig. 6. Three year rolling average (based on the approach of Guinée et al. (2004)) of marine ingredient price(a) and embodied fish in fishmeal and fish oil (b). (Tables of results are available in supplementary table 5) (price data from OECD-FAO (2018)).

IFFO estimates.

However, driven by economic and sustainability incentives, over the past decades marine ingredients have been substituted mainly by terrestrial crop ingredients and animal by-products. High quality novel feed ingredients such as single cell proteins (e.g. algae, yeasts, bacteria) (Glencross et al., 2014; Naylor et al., 2009; Stamer, 2015), algal and GM oils (Sprague et al., 2017) and more recently insect meals (Froehlich et al., 2018; Pelletier et al., 2018; Shepherd et al., 2017; Belghit et al., 2018) are beginning to enter the market but the widespread use of plant based ingredients have, in the meantime, affected the nutritional composition and value of the final aquaculture product (FAO, 2018). Various studies have reported that higher inclusion of vegetable oils in aquafeed reduces the omega-3 fatty acid and increases monounsaturated fatty acid (MUFA) content in aquaculture products (Fry et al., 2016; Turchini et al., 2009). Consequently, the nutritional value of the farmed salmon is compromised, requiring larger portion sizes to satisfy recommended EPA + DHA intake (Sprague et al., 2016). Additionally, a shift from the ocean onto the land puts additional pressure on valuable agriculture resources, such as water, land and phosphorus, which have socio-economic and environmental implications (Blanchard et al., 2017; Boissy et al., 2011; Fry et al., 2016; Malcorps et al., 2019; Pahlow et al., 2015; Roberts et al., 2015) as well as unknown trade-offs between terrestrial and aquatic ecosystem impacts (Newton and Little, 2018).

5. Conclusion

Efforts to reduce the dependency of aquaculture on marine resources by alternate feed ingredients have significantly reduced the amount of fishmeal and fish oil in aquafeed formulations for most farmed fish species. Results show that most aquaculture species groups assessed in this study are net producers of fish, while farm raised salmon and trout are net neutral, producing as much fish biomass as is consumed. Of the species groups analysed in this research, only the production of eel is a net consumer of fish. However, it is important to note that FIFO could vary within species and between production systems. Overall, global fed-aquaculture as a whole, currently produces three to four times as much fish as it consumes.

Our study highlights that previous assessments of FIFO ratios can be misleading and resulting in adverse opinions in the scientific community, as well as on a retailer and consumer level. These can then in turn lead to several socio-economic and environmental implications, including failure to provide authentic information for marine resource planning, a lack of comprehension of realist goals and attainment of viable management pathways for use of commodities like fishmeal and fish oil for sustainable aquaculture practices. Marine ingredients continue to be essential in the diets of most aquaculture species, but research has been continuing on ways to use them more strategically in commercial diet formulations to optimize their value. Additionally, the strategic utilisation of fish by-products in feed results in a more efficient use of valuable marine resources.

Therefore, it is imperative that models are based on a sound data platform and reflect accurately demand and supply to form a more robust and objective scenario for marine ingredient utilisation in aquaculture. This tool would enable policy makers and people in the industry to make well informed choices. Such a strategy contributes to the sustainable growth of the aquaculture industry and its crucial role in the global food system and nutritional security, being a valuable source of essential nutrients in the human diet.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2020.735474.

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