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Omega-3 long-chain polyunsaturated fatty acids and aquaculture in perspective

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ABSTRACT

In the 40 years since the essentiality of polyunsaturated fatty acids (PUFA) in fish was first established by determining quantitative requirements for 18:3n−3 and 18:2n−6 in rainbow trout, essential fatty acid (EFA) research has gone through distinct phases. For 20 years the focus was primarily on determining qualitative and quantitative EFA requirements of fish species. Nutritional and biochemical studies showed major differences between fish species based on whether C_{18} PUFA or long-chain (LC)-PUFA were required to satisfy requirements. In contrast, in the last 20 years, research emphasis shifted to determining "optimal" levels of EFA to support growth of fish fed diets with increased lipid content and where growth expectations were much higher. This required greater knowledge of the roles and functions of EFA in metabolism and physiology, and how these impacted on fish health and disease. Requirement studies were more focused on early life stages, in particular larval marine fish, defining not only levels, but also balances between different EFAs. Finally, a major driver in the last 10–15 years has been the unavoidable replacement of fish oil and fishmeal in feeds and the impacts that this can have on n−3 LC-PUFA contents of diets and farmed fish, and the human consumer. Thus, dietary n−3 in fish feeds can be defined by three levels. Firstly, the minimum level required to satisfy EFA requirements and thus prevent nutritional pathologies. This level is relatively small and easy to supply even with today's current high demand for fish oil. The second level is that required to sustain maximum growth and optimum health in fish being fed modern high-energy diets. The balance between different PUFA and LC-PUFA is important and defining them is more challenging, and so ideal levels and balances are still not well understood, particularly in relation to fish health. The third level is currently driving much research; how can we supply sufficient n−3 LC-PUFA to maintain these nutrients in farmed fish at similar or higher levels than in wild fish? This level far exceeds the biological requirements of the fish itself and to satisfy it we require entirely new sources of n−3 LC-PUFA. We cannot rely on the finite and limited marine resources that we can sustainably harvest or efficiently recycle. We need to produce n−3 LC-PUFA *de novo* and all possible options should be considered.

1. Introduction

Fish accounted for 16.7% of the global population's intake of animal protein and 6.5% of all protein consumed in 2010 (FAO, 2014). However, in addition to protein, fish are also important dietary sources of minerals including iodine and selenium, and vitamins such as A, D and E (Tacon and Metian, 2013). Arguably, of greatest importance for consumers in the developed world, fish and seafood are unique and rich sources of omega-3 (n−3) long-chain polyunsaturated fatty acids (LC-PUFA), particularly eicosapentaenoic (EPA; 20:5n−3) and docosahexaenoic (DHA; 22:6n−3) acids (Tur et al., 2012), that have well-known and generally accepted beneficial effects in a range of human pathologies including cardiovascular and inflammatory diseases, and an important role in neural development (Calder, 2013; Campoy et al., 2012; Delgado-Lista et al., 2012; Gil et al., 2012). However, marine fisheries worldwide are stagnating with 63% of assessed fish stocks requiring rebuilding (Worm et al., 2009) and so, consequently, an increasing proportion of fish are farmed, accounting for almost half of all fish for human food in 2012 (FAO, 2014). Feeds for farmed carnivorous species were traditionally based on fishmeal (FM) and fish oil (FO) and, while this practice was good for the supply of n−3 LC-PUFA (Sargent et al., 2002), the reliance on finite marine resources derived from capture fisheries was an unsustainable practice (Naylor et al., 2000; Tacon and Metian, 2009). Therefore, the continued growth of aquaculture was dependent upon the development of more sustainable feeds with alternative ingredients, generally derived from terrestrial agriculture, with important consequences for the supply of n−3 LC-PUFA (Gatlin et al., 2007; Tocher, 2009; Turchini et al., 2011a). This short review

Abbreviations: ARA, arachidonic acid (20:4n−6); CVD, cardiovascular disease; DHA, docosahexaenoic acid (22:6n−3); DPA, docosapentaenoic acid (22:5n−3); EFA, essential fatty acid; Elovl, fatty acid elongase; EPA, eicosapentaenoic acid (20:5n−3); Fads, fatty acyl desaturase; FM, fishmeal; FO, fish oil; LC-PUFA, long-chain polyunsaturated fatty acids (≥C20 ≥ 3 double bonds); LOA, linoleic acid (18:2n−6); LNA, linolenic acid (18:3n−3); PUFA, polyunsaturated fatty acid; TAG, triacylglycerol; VO, vegetable oil.

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summarises the important issues surrounding omega-3 LC-PUFA as key nutrients, particular in the context of aquaculture and its role in the provision of dietary n − 3 LC-PUFA for the human consumer. In doing so, it aims to clarify the issues underpinning the use of marine ingredients and their replacement, highlighting the influence and limitations of fish metabolism, and critically assessing options for the future, sustainable supply of n − 3 LC-PUFA.

2. Fish oil — historical perspective, recent trends and current status

The production and use of FO goes back to antiquity when it was the original liquid fuel and burnt in lamps for light, a process that converted n − 3 LC-PUFA to CO_2, or "greenhouse" gas. In the 20th century FO, including whale oil, was used extensively in margarine production that required hydrogenation and conversion of n − 3 LC-PUFA to saturated and, even worse, trans-fatty acids. Now, in the 21st century the main use of FO is in feeds for aquaculture, primarily as a source of n − 3 LC-PUFA that are now prized for their health benefits, not only to the farmed fish itself, but also to the human consumers through the production of high-quality food. Although, FO has also been used in terrestrial animal feeds (pigs and poultry) and small amounts were always used for direct human consumption (particularly cod liver oil), history demonstrates that, in terms of n − 3 LC-PUFA, aquaculture represents arguably the best use of bulk FO to date.

However, there are constraints on the use of FO (and FM) in aquaculture. The primary constraint is that these are essentially finite marine resources with production necessarily limited through strict regulation of fishing and catch quotas (Jackson and Shepherd, 2012; Shepherd and Jackson, 2013). Production of FM and FO had been slightly declining in recent years, largely due to increased regulation and reduced quotas in South America, but this situation is appearing more stable (FAO, 2012). The status of FO use in 2012, showed that around 75% of total global supply was used in aquaculture, with 22% going for direct human consumption (IFFO, 2013) (Fig. 1A). Over 80% of FO used in aquaculture feeds was consumed by salmonids (62%) and marine fish (19%) (Fig. 1B). Despite the continued growth of aquaculture (FAO, 2014), the use of FO in aquaculture was relatively stable over the last decade with, on average, around 0.8 million mt being used (IFFO, 2013) (Fig. 1C). Increased use of seafood and aquaculture by-products (including by-catch and trimmings etc.) to produce FM and, to a lesser extent, FO, has partially offset some of the reductions in production from whole fish as a result of increased restrictions on the reduction fisheries (Jackson and Shepherd, 2012; OECD-FAO, 2013). Production is also subject to environmental influences and, whereas the potential impact of climate change is not well understood (Callaway et al., 2012), acute phenomena such as El Niño have well-known consequences and the next significant event will have major effect on FM and FO supply (FAO/GIEWS, 1997).

Although, the finite and limited nature of FO production and supply is the main constraint to its use in aquaculture, there are other major factors (Bell and Waagbø, 2008). Sustainability issues are, of course, key drivers limiting overall supply, and these will have an increasing impact with the many initiatives currently being developed with respect to both national and international standards and certification of marine ingredients, particularly FM and FO products. In fisheries, international standards are being set by the Marine Stewardship Council (MSC; http://www.msc.org) that operates a certification programme promoting sustainable fishing practices, and similar national schemes also exist such as the UK's Responsible Fishing Scheme (RFS; http://rfs.seafish.org). The Marine Ingredients Organisation (IFFO) also operates

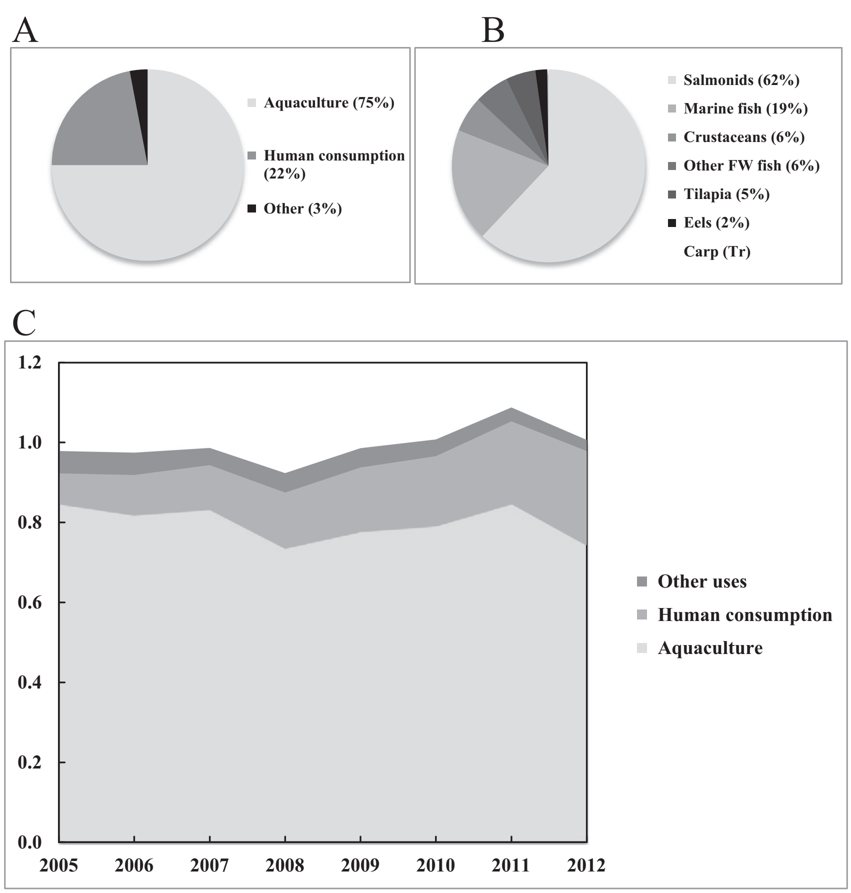

Fig. 1. Current global use of fish oil. A. Major fates of fish oil in 2012; B. Consumption of fish oil by the various aquaculture sectors in 2012; C. Trend in volumes (million tonnes) of fish oil used by aquaculture and other sectors from 2005 to 2012.