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Is the Use of Fishmeal and Fish Oil in Aquaculture Diets Sustainable?

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INTRODUCTION

The conversion of small wild fish into fishmeal and fish oil (F&FO) for use in formulated diets for farmed fish and crustaceans has become a hotly debated topic[1-4]. Some argue that the practice of using wild fish in the form of F&FO to feed farmed fish species potentially competes with their direct use for human consumption and their value in the ecosystem[5]. At the centre of the debate are two questions: (i) How many kilograms of wild fish in the form of F&FO does it take to produce 1 kg of farmed fish? (ii) Is the use of wild fisheries to produce F&FO sustainable [3-7] ?

The issues around the use of F&FO in compound aquaculture diets are wide-ranging and complex[8]. One of the main areas of contention is the presumption that although aquaculture production is expected to continue its rapid rise in the foreseeable future, catches from wild fisheries, which are the source of F&FO, are expected to remain static, or even decrease[2,8-10]. Fears have been raised that this trend may have disastrous consequences for the ecosystem, fuelling concerns that aquaculture is not a net contributor to world fish supplies, but is instead, adding more pressure on wild fisheries[1,3,5,10].

Opponents of F&FO-based diets for aquaculture argue that the practice of feeding ‘fish to fish’ is inefficient and wasteful, that it can take more than 6 kg of wild fish to produce 1 kg of farmed fish[3,5]. This is said to be particularly true for the culture of carnivorous fish species, such as salmon and most marine species. This argument supports the belief that it is better for the aquaculture industry to focus on the production of omnivorous species, such as tilapia, or better still, herbivorous species, such as carp or milkfish, which need less F&FO[3,6,7].

Supporters of the use of F&FO in aquaculture diets believe that focusing only on the conversion rate of wild fish to farmed fish is simplistic and misleading[11]. It is argued that factors such as the sustainability of the F&FO resource, trends in F&FO usage as well as current research to find alternatives to F&FO must all be taken into consideration when assessing the environmental impact of using F&FO from wild fish stocks[1,12-14]. The fact that the production of F&FO results in small, bony, wild fish, which are usually inedible to humans, being ultimately turned into high quality, healthy, fish fillets which are being increasingly demanded by consumers must also be taken into account[1].

This Technote presents current information about the use of F&FO in today’s aquaculture industry, including where F&FO come from, who produces them and why they are used. Information is also provided on the sustainability of the wild fishery and the research that is being conducted to develop alternatives to F&FO.

WHAT IS FISHMEAL AND WHAT IS FISH OIL?

F&FO facts[11]

Fishmeal is the brown flour obtained after cooking, pressing, drying and milling (collectively called 'reducing or reduction') fresh raw fish and fish trimmings.

It is made from almost any type of seafood but is generally manufactured from wild-caught, small, bony/oily marine fish which are usually deemed not suitable for direct human consumption.

The wild fish destined for reduction into F&FO are often referred to in the literature as *industrial fish* or *feed grade fish*[8,13,15] or are sometimes incorrectly referred to as *trash fish* [1,10]. The latter term implies that these fish have little or no value; however, both biologically and economically that implication is incorrect[6,10].

There are four different products sold as fish meal:

1. High quality or super prime meal, which contains over 67% protein, is mainly used for larval rearing and growing of marine species.

2. LT (low temperature) meal, which is highly digestible, is used in salmon and piglet production.

3. Prime meal, which is mainly used in general aquaculture feeds.

4. FAQ (fair average quality) meal, which is lower in protein, is used in pig and poultry feeds.

The fishmeal industry started in the 19th century when surplus catches of herring were processed for their oil for use in tanning, soap production and other industrial purposes[16]. For many years the oil was also often burnt as a waste product[17]. Today fish oil is recognised as a valuable nutrient for both livestock and humans.

World annual production of fishmeal and fish oil is about 6.5 million tonnes and 1.0 million tonnes, respectively from 33 million tonnes of whole fish and trimmings.

Seventeen percent of F&FO are derived from trimmings left over from processing of wild fish.

F&FO are manufactured in purpose-built plants and not in the same factories that produce meat or bone meals.

WHY USE FISHMEAL AND FISH OIL?

Historically, most of the world's fishmeal was used to feed domesticated livestock such as pigs and chickens and, to a limited extent, in the production of chemicals such as pharmaceuticals and fertilisers. With the rapid rise in aquaculture production since the 1970s, an increasing proportion of fishmeal is now diverted away from terrestrial animal feeds to aquatic feeds[18]. The use of fish oil in aquaculture feeds has also increased, becoming a key source of both energy and essential fatty acids[8,19,20].

There are many reasons why F&FO are favoured in the diet of farmed animals, including:

F&FO are natural feed ingredients, which are very high in protein, essential amino acids, minerals and essential marine oils (omega-3 fatty acids). Total protein in fishmeal can be higher than 70%[16].

F&FO have been reported to offer major benefits to animal health, including improved immunity against disease, higher survival and growth, and reduced incidences of deformities[16].

F&FO are highly digestible, which leads to increased growth and less wastage of food.

F&FO are also considered to increase feed appeal. This encourages farmed fish and crustaceans to locate feed and increases consumption, thereby reducing wastage.

An important point in the discussion on F&FO usage is that there are no 'unique' nutrients in them but they are very convenient nutrient 'packagers'. The fact that there are no unique nutrients is important to the process of finding replacements for F&FO in aquaculture feeds.

The reported use of world fishmeal and fish oil supplies by various industry sectors is shown in Figures 1 and 2, respectively. Assuming that supplies continue to be steady, aquaculture has the theoretical potential to utilise the total annual fishmeal supply by 2020 and almost all of the annual fish oil supply by 2010[3,10]. Chinese aquaculture alone has potential requirements of nearly half the global supply of fish oil and 30% of the global supply of fishmeal by 2015[10].

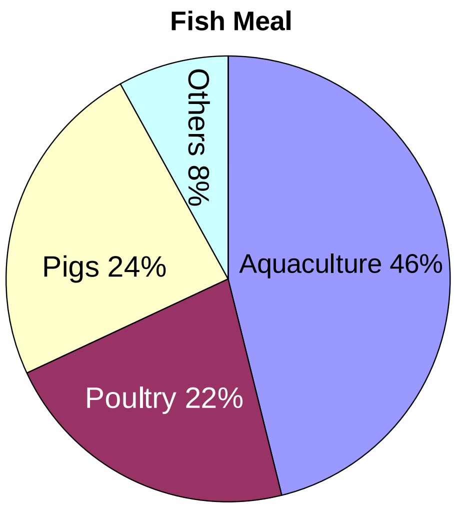

Figure 1. Summary of the global use of fishmeal in 2002[21]

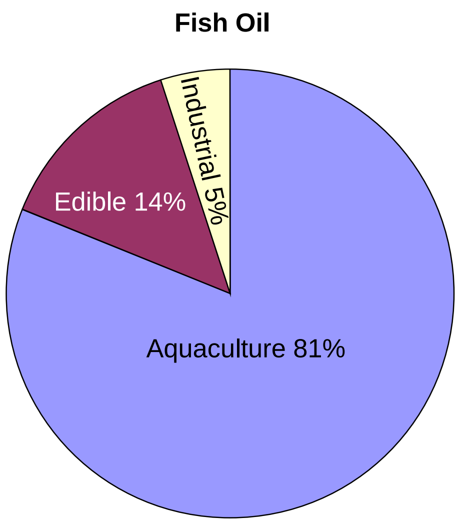

Figure 2. Summary of the global usage of fish oil in 2002[21]

It is considered unlikely that aquaculture will ever consume all of the F&FO resource. If new sources of supply or alternatives are not found, market forces dictate that increasing competition for the available supplies and the resultant increases in cost to feed manufacturers, combined with the need to reduce production costs in fish and shrimp farms, will soon become the determining factors[10]. The implications of this are serious and obviously mean that for aquaculture production to grow either F&FO supplies will have to increase, F&FO consumption by aquaculture species will have to be reduced and /or alternative sources of essential marine oils and proteins will have to be found. Acceptable and economic alternative means of supplying the nutritional requirements of farmed species must be found or further expansion of intensive aquaculture production (particularly of carnivorous species) will be constrained[10]. This will be discussed in more detail in the Section on F&FO replacements.

WHERE DO F&FO COME FROM?

The majority of the world's industrial fisheries are located in the Pacific Ocean off South America, accounting for nearly 40% of world F&FO production. In Scandinavia, Denmark, Iceland and Norway are all significant suppliers, each providing around 5% of global supply[22].

Total world fisheries production for the period of 1970 to 2004 is summarised in Figure 3 and regional production of F&FO is summarised in Table 1. Figure 3 shows that the total world capture fishery production (industrial fisheries plus food fisheries) has flattened out at approximately 90 million tonnes per year, of which around 30 million tonnes are used to produce F&FO[8]. Additionally, another 5 million tonnes of fish by-product (product left over after processing food fish) is estimated to be used for the production of F&FO [13].

The production statistics for world industrial fisheries landings also show that steeply increasing aquaculture production has so far not been correlated with increased production from the industrial fisheries[18]. The reason given for this, as stated in the previous Section, is that while the use of F&FO for aquaculture has increased, their use for other purposes, such as poultry and pig feeds, has decreased. Over the last 20 years, the quantity captured by the industrial fisheries has shown no overall long term trends either up or down. The exception was a major drop in supply during the El Niño event of 1998. The F&FO industry has used the rapid recovery in production, post El Niño, as evidence that the industry is being managed for sustainability[9,10].

The population dynamics of many small fish species are characterised by their short life-cycle and high reproductive rates[1,8,22]. This allows these fish stocks to respond rapidly with increases in stock size in favourable conditions[22]. It has been acknowledged that these fisheries often follow a boom and bust cycle which is dictated more by climate than fishing pressure[23].

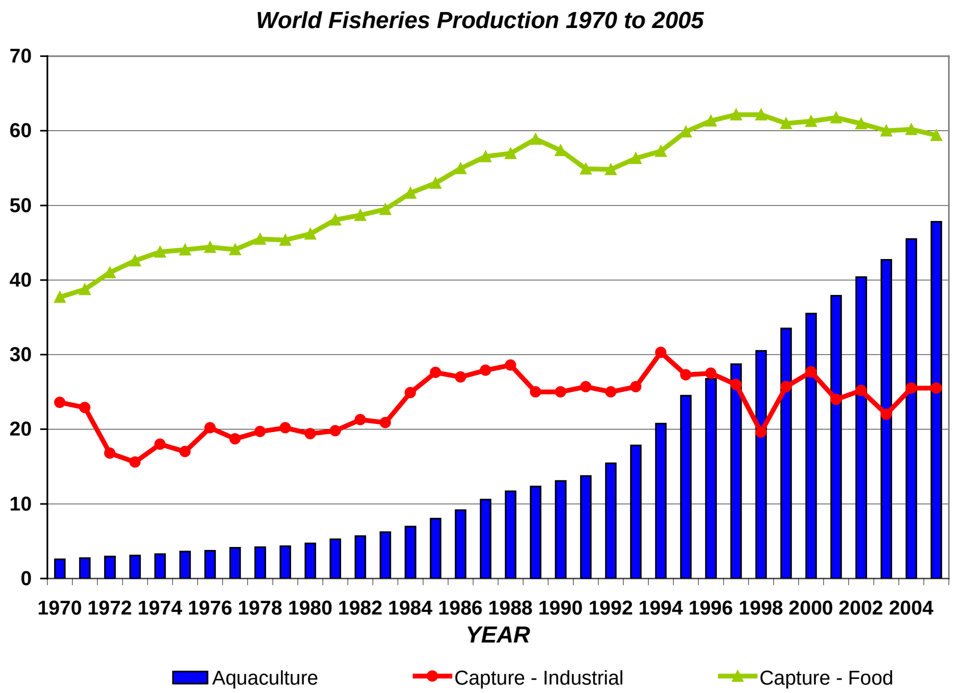

Figure 3. Trends in world fisheries production, 1970 to 2004
Values are expressed in millions of tonnes produced. Source: FAO 2005[13].

Table 1. Regional production of F&FO in 2003
Values are expressed in tonnes produced plus percentage of world production[13].

Region	***Fishmeal***	***%***	***Fish oil***	%
S. America	2,083,560	37.7	351,388	38.0
Asia	1,693,582	30.7	98,308	10.6
Europe	1,054,700	19.1	338,385	36.6
N. America	422,307	7.6	112,211	12.1
Africa	223,884	4.1	21,284	2.3
Oceania	42,237	0.8	2,850	0.3
Total	5,520,270	100	924,426	99.9

The species caught in the industrial fisheries include anchovies, herring, anchovetta, capelin, sand eels and blue whiting[24]. The quantities of the main species caught in 2003 are shown in Table 2.

Table 2. Production of species commonly caught in the world's industrial fisheries in 2003[13].

Species	Reported production in 2003 (tonnes)
Peruvian anchovy	6 202 447
Blue whiting	2 385 007
Japanese anchovy	2 088 744
Atlantic herring	1 958 795
Chub mackerel	1 851 753
Chilean jack mackerel	1 735 625
Capelin	1 148 106
European pilchard	1 049 344
Californian pilchard	691 625
European sprat	631 823
Gulf menhaden	522 195
Sandeels	341 512
Atlantic horse mackerel	214 889
Norway pout	37 833

While humans eat small quantities of some of these species, they are generally small, oily and bony and not considered prime food[11,18]. It is estimated that there is no significant human consumption market for 90% of the fish caught for F&FO production[15,16,24]. Despite this, some argue that a greater proportion of the industrial fisheries could and should go to direct human consumption[3,6,9] although it is counter argued that the cost of getting the fish to market in good condition probably exceeds their value[9]. These fish are generally caught in such large numbers that it is often difficult and expensive to process them so that they remain fit for human consumption[16].

Over the past few years, the prices paid for industrial fishes have continued to rise making it more cost-effective to divert increasing proportions of these fish to human consumption[25]. In Peru, it is government policy to encourage the supply of processed anchovy to low income Peruvians. The fishmeal industry has invested in canning and freezing factories in order to comply[25].

HOW MANY KILOGRAMS OF WILD FISH DOES IT TAKE TO PRODUCE ONE KILOGRAM OF FARMED FISH[§]?

One of the main criticisms levelled at the aquaculture and F&FO industries is that harvesting wild fish to feed to farmed carnivorous fish is wasteful because it can take many kilograms of wild fish, turned into F&FO, to produce one kilogram of farmed fish[4]. While some have claimed conversion rates of wild fish to farmed salmon as high as 10:1[26] others put the figure at somewhere between 2 and 5: 1[9].

Figure 4 is adapted from a Fishmeal Information Network fact sheet[15] which contains a detailed explanation of the conversion of wild fish into F&FO and subsequently into farmed salmon. According to the fact sheet, if the claim that 90% of the wild fish used in fishmeal is unpalatable to humans is accepted[24], then the amount of *edible and palatable* wild caught fish used to produce each kilogram of farmed salmon - actually diverted from human consumption – is a great deal less than 3 kg – perhaps even as little as 0.3kg.

[§] *Definition of food conversion ratio: The term food conversion ratio or FCR is normally used in aquaculture literature to refer to how much of a formulated diet it takes to produce 1.0 kg of farmed fish and is normally expressed as a ratio of the weight of feed converted into wet weight of fish. For the purposes of this Technote the focus on FCR is on the conversion of the whole wet weight of wild fish into the whole wet weight of farmed fish.*

How many kg of wild fish does it take to produce 1kg of farmed salmon?

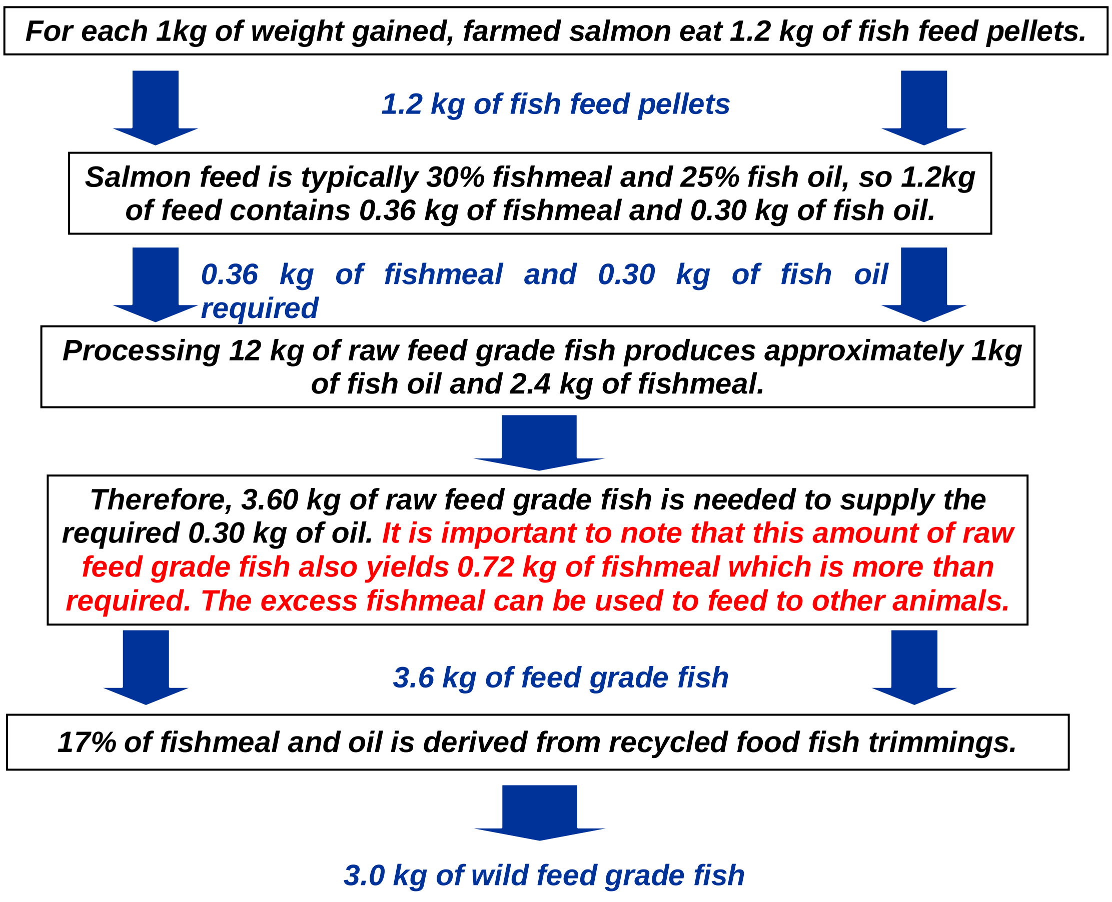

Figure 4. Flow chart explanation of the conversion of wild feed grade fish into farmed salmon[15]

The proportion of dietary F&FO used in salmon feeds has changed dramatically over the past two decades. Inclusion rates of fishmeal have fallen from 60% in 1985 to an average of 30% today. At the same time, the level of oil increased from 10% in 1985 to a high of 35-40% in 2005 and has recently declined again to about 25%[13]. The rationale behind these changes has been to increase dietary energy density (fish oil is high in energy), which results in an increased growth rate and better food conversion by sparing protein for growth rather than using it for energy. Salmon production cycles are now 20-25% shorter than they were 10 years ago. The good news is that conversion ratios have improved over time; fewer kilograms of wild fish were needed to produce 1 kg of farmed fish for all species categories in 2004 relative to 1997[2]. This trend is expected to continue. It has been estimated that the conversion ratio of wild fish into salmon should fall to less than 1.5: 1 by 2010[13]. Other figures quoted in the literature for conversion of wild fish to farmed fish vary from less than 300 g for fish such as tilapia and carp to between 2.5 - 3.7 kg for marine fish[9]. For barramundi fed a standard commercial diet containing 25% fishmeal and 18% fish oil, it can be estimated that the wild fish conversion ratio is around 2.5: 1.

While some argue that even a conversion ratio as low as 1.5: 1 is still ‘wasteful’ because the amount of wild fish used is still greater than the amount of farmed fish produced; it is seen by others to be mitigated by the fact that under culture conditions it involves the much more efficient conversion of lower trophic level species (species lower in the food chain), with low commercial value, into higher trophic, high-value species than occurs in the wild[8]. Aquaculture is claimed to be more efficient because farmed fish are protected from causes of mortality, such as disease and predators, and there is a higher transmission of energy between trophic levels, i.e. farmed fish use less energy on a daily basis and can use the protein in their food for body growth and not for energy (as in the wild) for escaping predators or swimming against strong water currents[2,8]. Food conversion figures for wild carnivorous fish are usually much higher than 6 : 1[27].

In reality the argument about the relative efficiencies of wild fish and farmed fish is somewhat misleading and narrow in its focus as it fails to consider other ecosystem impacts and therefore, whilst perhaps an interesting topic, it is not necessarily helpful to the present discussion.

It is therefore true, that currently more kilograms of wild fish are used in aquaculture feeds to produce fewer kilograms of farmed carnivorous fish. It is this particular fact that opponents of aquaculture use to bolster their argument that rather than increasing seafood production, aquaculture of carnivorous fish increases the pressure on wild fisheries. However, just as focussing on the relative efficiency with which farmed and wild fish can convert their food into body mass may be misleading, so too can just focussing on the wild to farmed conversion ratio. Even the argument made by some that the shift in fishmeal use away from terrestrial animals to aquaculture is environmentally friendly because fish are more efficient feed converters than terrestrial stock[28] only tells part of the story. What is really at issue here is the sustainability of the wild resource and also, what initiatives the aquaculture industry is implementing to improve the sustainability of feed supplies.

ARE INDUSTRIAL FISHERIES MANAGED SUSTAINABLY?

The main species caught in industrial fisheries are subject to management through such mechanisms as total allowable catch (TAC), area catch limits, minimum mesh sizes, fleet capacity controls, satellite tracking, closed seasons and closed areas[8], Table 3.

Table 3. Summary of the capture controls in place for the world's industrial fisheries[11,22]

Species	TACs Note 1	Area catch limit	Clos-ed area	Seas-onal bans	By-catch limits	Type of gear Note 2	Any effe-ct on sea-bed	Min mesh size	Min fish land-ing size	Vess-el reg	Sate-llite track-ing	ITQ syst-em Note 3
North East Atlantic and North Sea												
Capelin	✓	✓	✓	✓		P	No	✓	✓	✓	✓	✓
Blue whiting	✓	✓				MT	No	✓		✓	✓	
Sandeel	✓	✓	✓	✓		T	Negl-igible	✓		✓	✓	
Sprat	✓	✓	✓	✓	✓	P	No	✓		✓	✓	
Herring	✓	✓	✓	✓	✓	P	No	✓	✓	✓	✓	✓
Norway pout	✓	✓	✓			P	No	✓		✓	✓	
South America												
Anchovy	✓	✓	✓	✓		P	No	✓	✓	✓	✓	
J Mackerel	✓	✓	✓	✓		P	No	✓	✓	✓	✓	See pg 19
H' Mack	✓	✓	✓	✓		P	No	✓	✓	✓	✓	
Sardine	✓	✓	✓	✓		P	No	✓	✓	✓	✓	

1.Total catch limits for the North East Atlantic and the North Sea are agreed by the EU Council (with advice from ICES). In South America the Institutes of Fisheries Research in Chile and Peru advise national government's.
2. P is Purse Seiner, T is Trawler and MT is Mid Water Trawler.
3. Individual Transferable Quota.

As an example, the government controls applied to the fishery for Peruvian anchovy include:

- All fishing boats operating outside the 5 n mile limit are fitted with a satellite tracking system which allows the government to monitor the position of all boats at any given time.
- Closed fishing seasons, closed entry of new fishing boats and vessel licences to fish within the 200 nautical mile limit.
- Limits on the minimum size of fish that can be landed with local short term fishing closures if the proportion of small fish exceeds the number allowed.
- An independent surveillance company, SGS of Switzerland, was appointed in 2004 to monitor and record all fishing landings on the coast of Peru for government management purposes. Only authorised vessels with the correct licences are permitted to unload fish at the 115 unloading points. This system is effective 24 hours a day.
- Fishing stops during February and March to protect the growth of anchovy and sardine juveniles. A fishing closure from August to October protects spawning stocks.
- To assess the environmental status of fish stocks (mainly anchovy), the Peruvian Fisheries Research Institute (Instituto del Mar del Perú (IMARPE)) conducts a regular hydro-acoustic evaluation of pelagic resources along the entire Peruvian coastline.
- IMARPE advises on fisheries controls based on ecosystem effects. The approach is a multi-step procedure, which includes identification of ecosystems, relevant ecosystem components and linking human activities to impacts on the ecosystems.

The impact of control measures such as these on the productivity of the anchovy fishery can be clearly seen in Fig. 4. Prior to 1984, when fishery controls were either very poor or non-existent, the fishery went through a boom and bust cycle, such that by 1983 only 22 000 tonnes of fish were caught. Subsequently, industry and the government worked together and the control measures that were implemented resulted in the recovery of the fishery. The rapid recovery of the fishery, after one of the strongest El Niños ever recorded (1998), is seen as evidence the current controls on the fishery are appropriate and, most importantly, working[25].

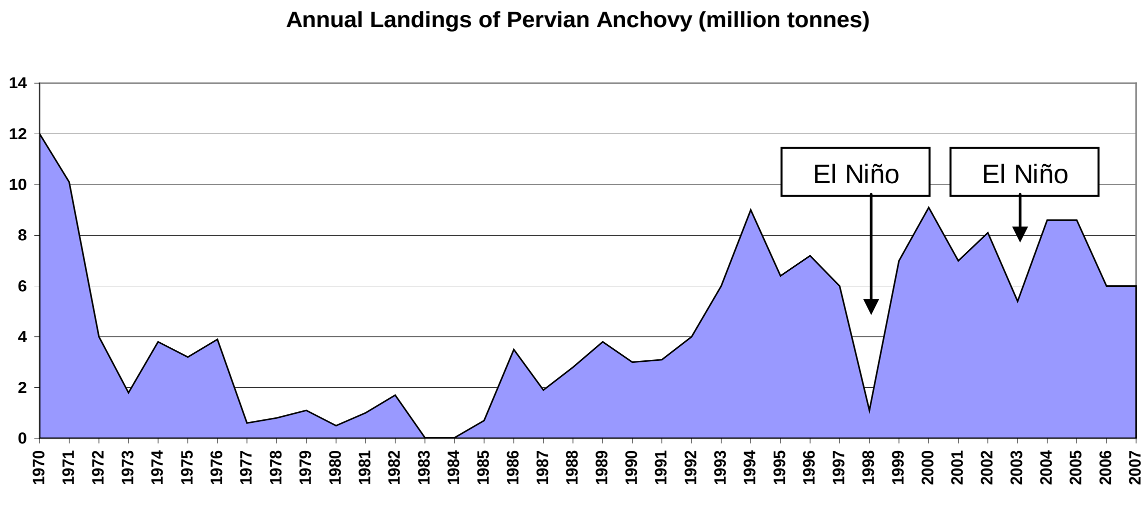

Figure 4. Historical catch data for the Peruvian anchovy fishery. Catch for 2007 is an estimate[25].

Apart from restrictions on catch effort, controls on the F&FO industry also include monitoring programs which link fishing activity to specific indicator or 'trigger' points. One of the trigger points used for the industry in the North Sea is the level of breeding success of sea bird species which are totally dependent on bait fish for survival. As an example, the EU Council has a seasonal closure for fishing for sandeels in a 20 000 km^2 band of the North Sea. The closure covers the period when kittiwake, puffin, gannet and other species use the sandeel to feed their chicks. The thresholds to close and re-open the sandeel fisheries in areas important for foraging by the kittiwake colonies are based on using 0.5 and 0.7 fledged chicks per well-built nest, respectively [18,22].

Controls such as those listed above have led some to conclude that industrial fisheries may have better management than some food fisheries and that with tight quotas on feed grade fish, over-fishing in these fisheries, as a result of pressures from aquaculture, is not likely[18]. The situation is very different for south-east Asian bait fisheries. It is generally acknowledged that over-fishing for bait fish in this region is a likely cause of rapidly declining fish stocks[29]. The over-fishing can be attributed to both increasing carnivorous fish aquaculture and to the unsustainable and inefficient practice of feeding whole bait fish, instead of properly formulated pellet feed diets, to farmed fish stocks[29]. This is further discussed in the Section on improving on-farm feeding practices.

Obviously many of the controls placed on the industrial fisheries are only as good as the accompanying enforcement program and despite the introduction of satellite tracking and remote vessel monitoring systems (VMS), there is still concern over their management [3,6,8]. Industry supporters point to the relative constant level of production since the early 1980s as a strong indicator that the fisheries are being managed for sustainability[11,18]. Others say that whilst there may be some validity in reporting on the repeatability of catch rates as an indicator of sustainability, these figures do not tell the full story [22].

Both the United Nations Food and Agriculture Organisation (FAO) and the International Council for the Exploration of the Seas (ICES) have reported that many of the industrial fisheries may be close to full exploitation and a few may be at the risk of over-exploitation. It is also acknowledged that there is a lack of understanding of broader ecosystem effects [6,9,30] and that there needs to be a move to more holistic sustainability targets[9]. The long term effect of removal of large quantities of feed organisms from some marine ecosystems is an issue that is yet to be properly quantified[3,4,6,8,13,22]. The F&FO industry itself also recognises and endorses the need to move to ecosystem based management[15]. In April 2007 Skretting (one of the World's largest fish feed manufacturing companies) commenced a joint project with the Marine Stewardship Council (MSC) to develop a certification scheme for fish feeds to ensure that all F&FO ingredients are derived from sustainable sources[30]. This is the first attempt at such a certification scheme. MSC uses a product label to reward environmentally responsible fishery management and practices and is seeking to harness consumer purchasing power to generate change and promote environmentally responsible stewardship of the world's most important renewable food source.

WHAT IS THE AQUACULTURE INDUSTRY DOING ABOUT IMPROVING THE SUSTAINABILITY OF FEED SUPPLIES?

In some ways it may be irrelevant who prevails in the argument on the sustainability of the wild industrial fisheries. The irrefutable fact is that the wild feed resource is finite. If aquaculture production is to continue to grow, there are really only two alternatives that must happen: either the industry moves to produce only low F&FO consuming species such as tilapia and carp as recommended by some authors[2,3,6,32] or use sustainable alternatives and supplements to F&FO on a wide scale for the farming of carnivorous species.

It is highly unlikely that world aquaculture production will shift entirely to produce only herbivores and omnivores. Existing consumer preference in some countries, particularly Western Europe, the USA and Australia, is towards 'high end' marine carnivorous fish. There is also an increasing preference for this type of fish in developing countries as they become more affluent. China has experienced an annual growth in carnivorous fish production of nearly 6% over recent years and in 2003 produced over 1 million tonnes or about 30% of total global supply.

Low fishmeal consuming species already dominate world aquaculture production with nearly 24 million tonnes produced in 2004[33]. Since 1974 China has increased its production of freshwater fishes on average by 10.8% per year and now produces nearly 20 million tonnes of freshwater fish[33]. The bulk of this production was carp, but it also includes 1 million tonnes of tilapia[34]. Most of China's freshwater fish production is consumed locally and very little is exported.

World demand for 'high end' carnivorous fish, such as salmon and marine fish, has also been on a steady rise. Apart from an ever increasing world population, one of the reasons for the increase in demand is the often reported health benefits attributed to fish and its omega 3 or essential marine oil content. Carnivorous fish species such as salmon and marine fish can have more than four times the omega 3 content of fish such as carp[35] and are therefore becoming more sought after for their health-giving benefits. Demand for carnivorous fish is predicted to keep increasing, and because there is little scope for increasing production from wild fisheries, the only way that consumer demands can be met is from aquaculture and, as already noted above, the only way that aquaculture can meet the increasing demand for carnivorous fish in the longer term is by improving on-farm feeding practices and by substituting or supplementing F&FO in its diets.

IMPROVED FEEDING PRACTICES

Improving feeding practices has played, and continues to play, an important role in increasing the economic efficiency of operating a fish farm. At the same time, increased feeding efficiencies also help the sustainability of the world's F&FO supplies, while supporting the continued growth of farmed fish production. Improvements, such as species-specific feed formulations, better pelleting technology, better feed distribution systems and better on-farm feed management, have all contributed to reducing feed wastage and improving the food conversion efficiency of farmed fish. For example, the FCR of farmed salmon is reported to have reduced from more than 5.0: 1 in the early 1980s to its present level of less than 1.3:1 and, in some cases, to even less than 1.0:1 (weight of formulated pellets converted into wet weight of fish)[13].

There is no room for complacency, however, and further improvements can and must be made to feeding practices. In particular, there is an urgent need to convince/encourage traditional farmers in the Asian-Pacific region to use formulated diets rather than whole fish and to use better feed management[27,29]. In 2002, it was estimated that 3-4 million tonnes of bait fish was used for marine aquaculture in China alone. Traditional FCRs using whole fish are always much higher than 6.0:1[27] and also carry an increased risk of disease transfer from the wild caught fish to the farmed fish[36]. This practice certainly causes environmental problems and is considered to be totally unsustainable[10]. The preferred, and most environmentally responsible, course of action would be to ban the use of potentially high-risk feed items such as whole bait fish and invertebrates in farmed fish diets[14].

F&FO REPLACEMENTS AND SUPPLEMENTS

The major challenge for the aqua-feed industry is to find alternative feed resources that are sustainable and have all the necessary nutrients and qualities of F&FO while minimising undesirable side effects such as slower growth, decreased animal health and changes to the nutritional content of the end product [10,37-39]. Industry research must not only measure the effect of replacement feed ingredients on standard farming parameters like growth, survival rates and FCR, but also their impact on other factors such as immune function and disease resistance [11]. It is imperative that the impact of potential F&FO replacements on the nutritional, sensory, processing, and safety characteristics of aquaculture products is also carefully considered[11,39-40].

Since the early 1980s, the amount of research conducted to find suitable supplements and alternatives to F&FO has grown exponentially. The European Union in particular has funded a range of programs targeted to find alternatives, including researching alternatives to fish oil in aquaculture (RAFOA), fish oil substitution in salmonids (FOSIS) and PUFAFEED and investigating the use of cultivated marine micro-organisms as an alternative to fish oil[8].

The scientific literature now contains many studies demonstrating that F&FO in feeds for carnivorous species, including European sea bass, salmon, cod and barramundi, can be totally, or substantially, replaced by alternative protein and oil sources[41--43].

RAFOA established that, with judicious care, much if not all of the fish oil currently used in feed to produce salmon, rainbow trout, sea bream and sea bass can be replaced with a blend of vegetable oils, without comprising growth performance of any of the species. The substantial changes in the fatty acid composition of fillets resulting from the vegetable oil blend were readily and largely reversed in all species with a "finishing diet" of fish oil[44,45].

Fishmeal can now be replaced with protein derived from a range of non-fish sources such as by-products from land animal processing, micro-algae, plants, zooplankton or even insects and bacteria[4,46-49]. Micro-algae in particular, are seen as a very promising alternative for F&FO because they are easy to grow in large quantities, some have a very high protein content and may also be rich in omega 3 fatty acids [50,51].

Most studies show that the partial replacement of fishmeal or oil by vegetable or plant based raw materials does not affect the health or the growth of fish and even though feeds may be based on ingredients which contain lower levels of omega 3 fatty acids. Careful application of the replacements can ensure that the end product remains as a good source of omega 3[44,52]. Test panels have even indicated that consumers might prefer the taste of salmon fed mixtures of plant and fish oil to those fed only fish oil [53].

According to the leading fish feed producers in Norway, vegetable-based alternatives are now widely in use, and will be increasingly used in the near future. Fish farmers have welcomed the use of plant ingredients in fish feed hoping it can help stabilise feed costs [4].

CONCLUDING COMMENTS AND THE FUTURE

The available evidence suggests that the production of F&FO for use in feeding edible marine fish utilises a sustainable resource that may otherwise be lost to the human food chain. Widespread government controls and fishing limits help to ensure that feed grade (generally inedible) fish can be caught sustainably without serious detrimental effects on the environment. There appears to be little evidence that the growth of the aquaculture industry has had much impact on the capture of fisheries dedicated for F&FO production. The industry is just using a greater proportion of static supplies with less going to feeds for other livestock. In the unlikely event that the aquaculture industry stopped using all F&FO in aqua-feeds tomorrow, the available supply would be taken up immediately by the feedstuff industry for use in poultry, pig and (to a lesser extent) ruminant nutrition[10].

The current practice of feeding fish-based aquaculture diets is acceptable if the primary resource is sustainable[9]. The general effect of increasing prices of raw materials is not increasing fishing pressure, but it is increasing pressure to find cost-effective alternatives[10,13]. The alternatives are being developed at a rapid rate and are increasingly being used to replace and supplement F&FO in aqua-feeds. The overall picture is therefore one of gradual substitution of F&FO and an increasing eco-efficiency of aquaculture which is unlikely to result in undue pressure on industrial fish stocks[28].

All this has led FAO, in its *2006 Report on the State of World Fisheries and Aquaculture* [33], to conclude:

"…. as the production of fishmeal and fish oil is expected to remain stable over the next decade, the proportion of fishmeal use by the animal production sector is expected to fall and the use of vegetable-based protein and oil to increase.

In addition, with technological advances, greater efficiencies in feeding are expected. It is therefore unlikely that the supply of fishmeal and fish oil will be a limiting factor in aquaculture feeding. However, this optimism should be considered with certain caution; the demand for fishmeal and fish oil from developing economies such as China may have a profound impact on overall supply and demand".

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