
Aquaculture feeds: addressing the long-term sustainability of the sector

Expert Panel Review 1.3

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Abstract

It is estimated that about 29 million tonnes of farmed fish and crustaceans (44.5 percent of the total global aquaculture production in 2007) is dependent upon the supply of external nutrient inputs provided in the form of fresh feed items, farm-made feeds or commercially manufactured feeds. Total industrial compound aquafeed production has increased over three-fold from 7.6 million tonnes in 1995 to 27.1 million tonnes in 2007, with production growing at an average annual rate of 11.1 percent. Aquafeed production is expected to

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continue growing at a similar rate to 70.9 million tonnes by 2020. Although current estimates for industrially produced aquafeed for the period 2007–2010 vary between 24.4 and 28.9 million tonnes, aquafeed volume represents only 4 percent of total global animal feed production of over 708 million tonnes in 2009. In contrast to compound aquaculture feeds, there is no comprehensive information on the global production of farm-made aquafeeds (estimated at between 18.7 and 30.7 million tonnes in 2006) and/or on the use of low-value trash fish or forage fish species as feed, with current estimates for China in 2008 ranging between 6 and 8 million tonnes.

Feed-fed aquaculture production, and in particular the production of higher-trophic-level finfish and crustaceans (e.g. shrimp, salmonids, marine finfish, eels) is largely dependent upon capture fisheries for major dietary sources of protein and lipid. For example, in 2007 the aquaculture sector is estimated to have consumed 3.84 million tonnes of fishmeal (or 68.4 percent of global production) and 0.82 million tonnes of fish oil (or 81.3 percent of global production for that year). However, despite the continued dependence of aquaculture production upon the use of fishmeal and fish oil, there is wide variation in fishmeal and fish oil usage between major producing countries for individual farmed species.

It is estimated that the total usage of terrestrial animal by-product meals and oils within compound aquafeeds ranges between 0.15 and 0.30 million tonnes, or less than 1 percent of total global compound aquafeed production – clearly there is considerable room for increased usage. Among plant feed ingredients, soybean meal is currently the commonest protein source used in compound aquafeeds. Based on total compound aquafeed production of 27.1 million tonnes, it is estimated that the aquaculture feed sector consumed about 6.8 million tonnes of soybean meal (25.1 percent of total compound aquafeeds by weight) in 2007. Other plant proteins that are being increasingly used include corn products, pulses, oilseed meals and protein from other cereal products.

Alternative lipid sources to fish oil are being used in greater amounts. Key alternatives include vegetable oils (preferably those with high omega-3 content) and poultry oil. The use of oil from farmed fish offal is also a potential omega-3 source for other farmed fish. The production of marine microalgae or bacteria with very high content of highly unsaturated fatty acids (HUFA) is currently expensive for use in most aquaculture feeds but as production methods become more cost-efficient, the situation is likely to change.

Prices for food and feed ingredients are likely to continue to increase due to increasing demands from the increasing population, diversion of some grains for use in biofuels, increasing costs of production and transport, and changes in global trade. The focus on carbohydrate-rich fractions for production of biofuels may provide an opportunity to use protein fractions for feed ingredients.

Although the current discussion about the use of marine products as aquafeed ingredients focuses on fishmeal and fish oil resources, the sustainability of the aquaculture sector is more likely to be linked with the sustained supply of terrestrial animal and plant proteins, oils and carbohydrate sources for aquafeeds, particularly so because a significant proportion of aquaculture production is of non-carnivorous species. Therefore, aquaculture-producing countries should place more emphasis on maximizing the use of locally available feed-grade ingredient sources and move away from the use of potential food-grade feed resources.

KEY WORDS: *Aquaculture, Feeds, Development, Global trends, Sustainable aquaculture.*

Introduction

Aquaculture's dramatic rise and emergence as a major provider of much needed aquatic food for the global market has been possible because of a combination of factors that include:

- the recognition of aquaculture as a viable economic activity and source of livelihood;
- the provision of an enabling legislative framework for conducting the activity;
- the availability of suitable land and water resources and technical know-how for conducting farming operations; and
- in the case of most fish and crustacean farming operations, the availability of nutrient inputs in the form of fertilizers and/or feed.

If finfish and crustacean aquaculture is to maintain its current average growth rate of 8 to 10 percent per year to 2025, the availability of nutrient and feed inputs will have to grow at a similar rate. However, while this may have been easily attainable in the past when most aquaculture industries relying on external nutrient inputs were still in their infancy, it will present a much greater challenge as the sector matures and grows into a major consumer and competitor for feed resources. This paper will consider dietary feeds and feeding regimes based on the external provision of fresh feeds (usually fed singly) and farm-made feeds and commercial feeds composed of mixtures of different feed ingredients.

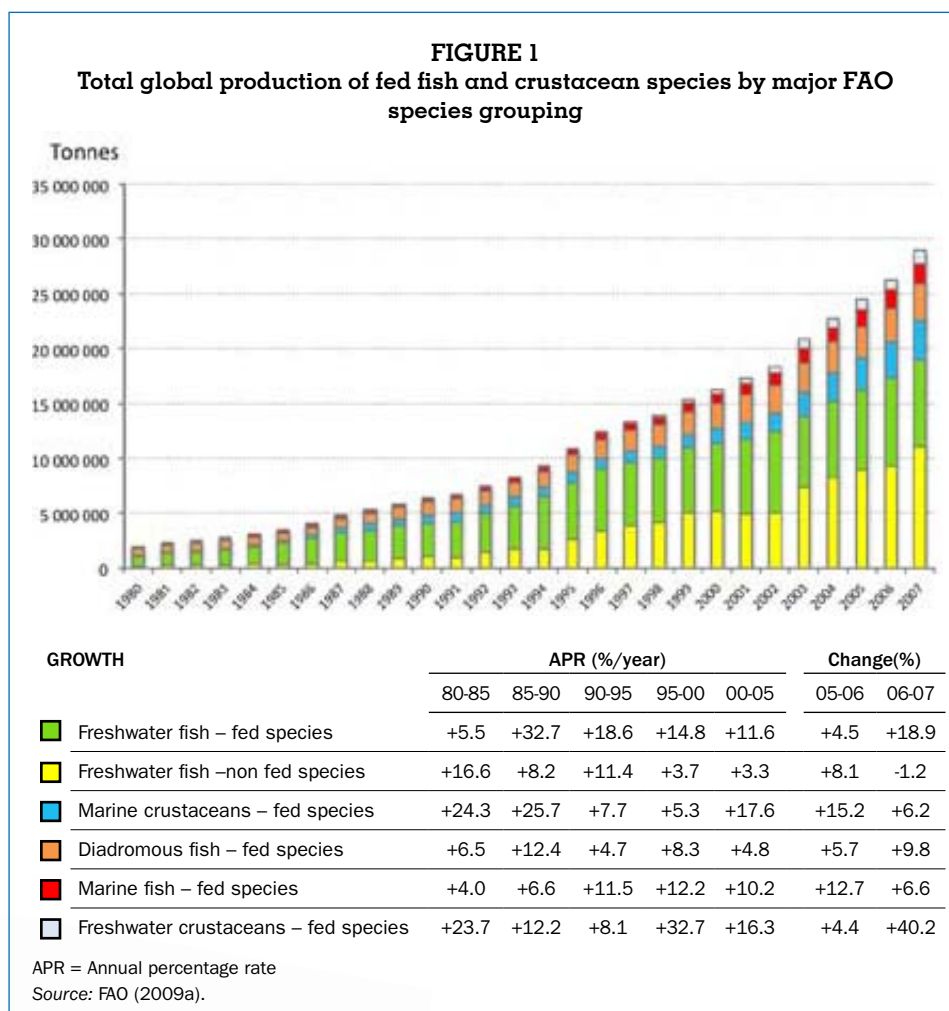
Current feeds and feeding practices

Major fed fish and crustacean species

About 29 million tonnes of farmed fish and crustaceans, or 44.5 percent of the total global production of farmed aquatic animals and plants, is currently dependent upon the supply of nutrient inputs in the form of externally provided fresh feed items, farm-made feeds or commercial pelleted feeds. The above estimate excludes filter-feeding fish species (e.g. silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*): total production 5.8 million tonnes in

2007) and freshwater fish production not reported down to the species level (2.0 million tonnes in 2007; FAO, 2009a). Moreover, of the more than 200 species of fish and crustaceans currently believed to be fed on externally supplied feeds, eight species account for 60 percent of total global fed species production: grass carp (*Ctenopharyngodon idellus*), common carp (*Cyprinus carpio*), whiteleg shrimp (*Litopenaeus vannamei*), catla (*Catla catla*), Nile tilapia (*Oreochromis niloticus*), Crucian carp (*Carassius carassius*), Atlantic salmon (*Salmo salar*), and pangassid catfishes (striped/tra catfish [*Pangasianodon hypophthalmus*] and basa catfish [*Pangasius bocourti*]), (FAO, 2009a). In this respect aquaculture is similar to agriculture; global livestock production is concentrated in a handful of major species like pig, chicken, cattle, sheep, turkey, goat, duck and buffalo (FAO, 2009b).

Figure 1 shows the total global production of fed fish and crustaceans by major species grouping, together with their respective growth at five-year intervals from



1990 to 2007. In marked contrast to capture fisheries, freshwater fish species dominate finfish aquaculture production (Tacon *et al.*, 2010), with over 78.6 percent of fed finfish production being freshwater species in 2007 (FAO, 2009a).

Of particular note are the high double-digit growth rates of all major groupings during the 1980s and 1990s, with the overall growth of fed fish and crustacean aquaculture production stabilizing to an average of 10.5 percent per year by 2007. In contrast, livestock meat production and capture fisheries production have grown at an average percent rate of 2.5 percent and 1 percent per year since 1980, respectively (FAO, 2009b).

The major fed fish and crustacean species groups can be ranked in order of total global production by weight in 2007 as follows:

Freshwater fed fish (18.82 million tonnes, valued at USD23.4 billion)

- Carps – 12.98 million tonnes, 9 major species
- Tilapias – 2.50 million tonnes, 2 major species
- Catfishes – 2.27 million tonnes, 5 major species
- Miscellaneous freshwater fish species – 1.06 million tonnes, 6 major species

Marine fed crustaceans (3.51 million tonnes, valued at USD14.0 billion)

- Shrimp – 3.27 million tonnes, 6 major species
- Crabs – 231 000 tonnes, 1 major species

Diadromous fed fish (3.26 million tonnes, valued at \$ 13.3 billion)

- Salmon – 1.56 million tonnes, 2 major species
- Trout – 694 000 tonnes, 1 major species
- Milkfish – 667 000 tonnes, 1 major species
- Eels – 274 000 tonnes, 1 major species
- Miscellaneous diadromous fish species – 63 000 tonnes, 1 major species

Marine fed fish (1.85 million tonnes, valued at USD6.4 billion)

- Seabass – 365 000 tonnes, 2 major species
- Mulletts – 272 000 tonnes, 1 major species
- Porgies, seabreams – 263 000 tonnes, 2 major species
- Jacks, trevalles – 176 000 tonnes, 1 major species
- Flounders, halibuts, soles – 126 000 tonnes, 1 major species
- Croakers, drums – 115 000 tonnes, 2 major species
- Groupers – 75 000 tonnes
- Miscellaneous marine fish species – 436 000 tonnes, 2 major species

Freshwater crustaceans (1.34 million tonnes, valued at USD6.0 billion)

- Crabs – 489 000 tonnes, 1 major species
- Crawfish, crayfish – 318 000 tonnes, 1 major species
- River prawns – 451 000 tonnes, 2 major species

The fastest-growing major fed species groups over the last decade (2000 to 2007) have been catfish (average rate of 23.1 percent), freshwater crustaceans (17.6 percent), shrimp (16.4 percent), tilapia (11.2 percent) and marine fish (10.0 percent). This contrasts with the reduced growth of salmon (6.2 percent), milkfish (5.2 percent), trout (4.4 percent), fed carps (3.8 percent) and eels (3.7 percent) over the same period (FAO, 2009a).

In-country fed species production and feeding practices

On a global basis, over 84.6 percent of fed fish and crustacean aquaculture production was produced on the Asian continent in 2007 (24.5 million tonnes), followed by the Americas (2.0 million tonnes or 6.8 percent), Europe (1.6 million tonnes or 5.5 percent), Africa (0.82 million tonnes or 2.8 percent) and Oceania (45 418 tonnes or 0.15 percent) (FAO, 2009a). Twenty countries accounted for 94 percent of total global fed fish and crustacean production in 2007, with China alone accounting for over half the global total (Table 1).

It follows therefore from the above that these countries will also be the large producers and consumers of feed, either in the form of commercial feeds, farm-made feeds or fresh feeds.

TABLE 1

The top 20 country producers of fed fish and crustaceans in 2007

Country	Production (million tonnes) (% total)
China	15.10 (52.1)
India	2.89 (10.0)
Indonesia	1.36 (4.7)
Viet Nam	1.30 (4.5)
Thailand	1.02 (3.5)
Norway	0.83 (2.8)
Philippines	0.67 (2.3)
Chile	0.66 (2.3)
Egypt	0.64 (2.2)
Bangladesh	0.60 (2.1)
United States of America	0.37 (1.3)
Japan	0.30 (1.0)
Brazil	0.27 (0.9)
Myanmar	0.26
Taiwan Province of China	0.23
Ecuador	0.17
Mexico	0.15
United Kingdom	0.15
Turkey	0.14
Pakistan	0.13

Source: FISHSTAT (FAO, 2009a).

Fed carps

Fed carps (Chinese carps, Indian major carps, other cyprinids) represent the largest fed species group, with the sector growing at an average rate of 3.8 percent per year over the last decade (FAO, 2009a). It is estimated that the amount of carp that is fed, as a percentage of total carp production (excluding Indian major carps), has increased from 20 percent in 1995 to 48 percent in 2007 (Tacon and Metian, 2008a). Total global commercial carp feed production has increased from 2.1 to 8.2 million tonnes from 1995 to 2007 and is projected to reach 14.8 million tonnes by 2020. In contrast, almost all Indian major carp production is still based on the use of low-cost locally produced farm-made feeds (Ayyappan and Ahamad Ali, 2007), with fresh feed items still only being fed to Chinese carps (primarily grass carp), depending upon the financial resources of the farmer (Barman and Karim, 2007; Weimin and Mengqing, 2007).

Of particular note is the difference in the estimated farm gate unit value of the same species between producing countries, depending upon individual market preferences. For example, grass carp has a minimum reported unit value of USD0.96/kg in China and a maximum reported unit value of USD3.0/kg in Iran (FAO, 2009a), the latter higher market values presumably also allowing the use of more costly farm production methods and feeding methods, if so required.

Tilapias

Tilapias represent the second largest freshwater fish fed species group, with the sector growing at an average rate of 11.2 percent per year over the last decade (FAO, 2009a). It is estimated that the percent of total tilapia production fed on commercial feeds has increased from 70 percent in 1995 to 82 percent in 2007 (Tacon and Metian, 2008a). Total global commercial tilapia feed production increased from 1.0 to 3.5 million tonnes from 1995 to 2007 and is expected to reach 12.0 million tonnes by 2020.

Catfishes

Catfishes represent the third largest freshwater fish fed species group, with the sector growing at a very high rate of 23.1 percent per year over the last decade (FAO, 2009a). It is estimated that about 72 percent of the global catfish were fed commercial feeds in 2007 (Tacon and Metian, 2008a). Commercial catfish feed production increased from 587 000 tonnes in 1995 to 2.4 million tonnes in 2007 and is projected to reach 11.7 million tonnes by 2020.

Miscellaneous freshwater fishes

These represent the fourth largest freshwater fish fed species group, with the sector growing at a high rate of 21.1 percent per year over the last decade (FAO, 2009a). It is estimated that about 17 percent of miscellaneous freshwater fish that are fed received commercial feeds in 2007 (Tacon and Metian, 2008a). Commercial feed production increased from 15 000 tonnes in 1995 to 359 000

tonnes in 2007 and is expected to reach 2.8 million tonnes by 2020. With the exception of omnivorous/herbivorous species (e.g. pirapatinga (*Piaractus brachypomus*), cachama (*Colossoma macropomum*)), most of the fishes within this species group are highly piscivorous and are still usually fed on live/trash fish feed items (Chen *et al.*, 2007; De Silva and Phillips, 2007; Weimin and Mengqing, 2007).

Salmon

Salmon represent the largest diadromous fish species group, with the sector growing at an average rate of 6.2 percent per year over the last decade (FAO, 2009a). It is estimated that 100 percent of total salmon aquaculture production is fed on commercial feeds. Total global commercial salmon feed production increased from 806 000 tonnes in 1995 to 2.0 million tonnes in 2007 and is projected to reach 3.8 million tonnes by 2020.

Trout

Trout represent the second largest diadromous fish species group, with the sector growing at an average rate of 4.4 percent per year over the last decade (FAO, 2009a). It is estimated that 100 percent of total trout aquaculture production is fed on commercial feeds. Total global commercial trout feed production increased from 588 000 tonnes in 1995 to 902 000 tonnes in 2007 and is expected to reach 1.7 million tonnes by 2020.

Milkfish

Milkfish represent the third largest diadromous aquaculture species, with production growing at an average rate of 5.2 percent per year over the last decade (FAO, 2009a). It is estimated that the amount of milkfish fed on commercial feeds, as a percentage of total production, increased from 30 percent in 1995 to 41 percent in 2007 (Tacon and Metian, 2008a). Total global commercial milkfish feed production increased from 220 000 tonnes in 1995 to 547 000 tonnes in 2007 and is expected to reach 1.1 million tonnes by 2020.

Eels

Eels represent the fourth largest diadromous aquaculture species group, with production growing at an average rate of 3.7 percent per year over the last decade (FAO, 2009a). It is estimated that the amount of eels fed on commercial feeds, as a percentage of total production, increased from 90 percent in 1995 to 95 percent in 2007 (Tacon and Metian, 2008a). Total global commercial eel feed production increased from 338 000 tonnes in 1995 to 416 000 tonnes in 2007 and is projected to reach 595 000 tonnes by 2020.

Marine fish

Marine fish represent the last major fish species group, with production growing at an average rate of 10.0 percent per year over the last decade (FAO, 2009a). It is estimated that total marine fish production fed on commercial feeds, as a

percentage of total production, increased from 50 percent in 1995 to 72 percent in 2007 (Tacon and Metian, 2008a). Total global commercial marine fish feed production increased from 533 000 tonnes in 1995 to 2.5 million tonnes in 2007 and is expected to reach 7.6 million tonnes by 2020.

At present, the bulk of marine finfish cage aquaculture production in China is still using lower-cost fresh feeds based on small-sized pelagic fish species in the form of fresh/frozen fish (Chen *et al.*, 2007; Weimin and Mengqing, 2007). China alone reportedly consumed between 4 and 5 million tonnes of lower-value pelagic fish as aquaculture feed in 2005.¹

Shrimp

Shrimp represent the largest crustacean species group, with species group production growing at an average rate of 16.4 percent per year over the last decade (FAO, 2009a). It is estimated that the amount of shrimp fed on commercial feeds, as a percentage of total production, increased from 75 percent in 1995 to 93 percent in 2007 (Tacon and Metian, 2008a). Total global commercial shrimp feed production increased from 1.4 million tonnes in 1995 to 4.8 million tonnes in 2007 and is projected to reach 12.0 million tonnes by 2020.

Freshwater crustaceans

Freshwater crustaceans represent the second largest crustacean species group, with group production growing at an average rate of 17.6 percent per year over the last decade (FAO, 2009a). It is estimated that the amount of freshwater crustaceans fed on commercial feeds, as a percentage of total production, increased from 35 percent in 1995 to 47 percent in 2007 (Tacon and Metian, 2008a). Total global commercial freshwater crustacean feed production increased from 91 000 tonnes in 1995 to 1.3 million tonnes in 2007 and is expected to reach 2.7 million tonnes by 2020.

Global aquaculture feed production by major species group and country

On the basis of the above information, it is estimated that the total global production of commercial aquaculture feeds was 27.1 million tonnes in 2007, including:

- Carp feeds (8.2 million tonnes or 30.4 percent)
- Shrimp feeds (4.8 million tonnes or 17.8 percent)
- Tilapia feeds (3.5 million tonnes or 12.9 percent)
- Marine fish feeds (2.5 million tonnes or 9.3 percent)
- Catfish feeds (2.4 million tonnes or 9.0 percent)
- Salmon feeds (2.0 million tonnes or 7.5 percent)
- Freshwater crustacean feeds (1.3 million tonnes or 4.9 percent)

¹ Source: Paper presented by W. Jin on *Fishmeal as a dietary ingredient in China – first impressions*. International Fishmeal and Fish Oil Organization 2006 Annual Conference, October 23–26, 2006, Barcelona, Spain.

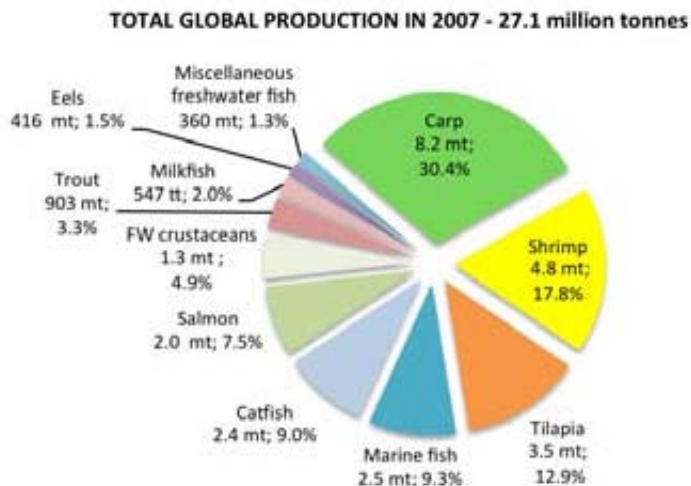
- Trout feeds (902 000 tonnes or 3.3 percent)
- Milkfish feeds (547 000 tonnes or 2.0 percent)
- Eel feeds (416 1000 tonnes or 1.5 percent)
- Miscellaneous freshwater fishes (359 000 tonnes or 1.3 percent)

The above estimate represents a 6.8 percent increase in production from the total estimated commercial aquaculture feed production of 23.4 million tonnes in 2006 (Gill, 2007; Tacon and Metian, 2008a). The commercial aquaculture feed sector has grown over three-fold from 7.6 to 27.1 million tonnes from 1995 to 2007 (average annual rate of 11.1 percent since 1995; Figure 2), and is expected to continue growing at a similar rate over the next decade to 70.9 million tonnes by 2020.

In some countries where the aquaculture sector has been growing very rapidly, there has been a similar rapid production of commercial aquafeeds (e.g. in Viet Nam, official figures show that aquafeed production increased from 336 000 tonnes in 1999 to 762 000 tonnes in 2004, with production more than doubling again to 1 863 000 tonnes in 2008, and estimated at 2.4 million tonnes in 2009, an increase in production of over 700 percent in a decade (Best, 2010a).

Table 2 shows the major country producers of commercial aquafeeds. The results are based on the individual country responses received to an electronic survey conducted for this review. The results show an estimated total

FIGURE 2
Estimated global production of commercial aquaculture feeds by major species grouping in 2007 (values in thousand (tt) or million (mt) tonnes and as percent of total)



Source: Data taken from table above.

production of between 24.7 and 29.1 million tonnes of commercial aquafeeds in the period 2007–2010, in line with the estimates given above for major aquaculture species.

TABLE 2
Major country producers of commercial aquaculture feeds, 2007–2010

Country	Commercial aquaculture feed production estimate (tonnes)
China (2008)	13 000 000 – 15 000 000
Viet Nam (2008/2009)	1 625 000 – 2 800 000
Thailand (2008/2009)	1 210 327 – 1 445 829
Norway (2008/2010)	1 136 800 – 1 382 000
Indonesia (2008/2009)	1 030 000 – 1 184 500
Chile (2008)	883 305 – 1 050 000
United States of America (2008)	700 000 – 750 000
Japan (2008)	500 000
India (2008/2009)	500 000
Philippines (2007)	400 000 – 450 000
Taiwan Province of China (2007)	345 054
Brazil (2008)	324 000
Egypt (2008)	310 000
Mexico (2008/2009)	222 800 – 282 500
Greece (2009)	262 000
Ecuador (2009)	235 000
Malaysia (2009)	226,000
United Kingdom (2008)	212 900
Turkey (2009)	170 000
Canada (2008)	161 600
Peru (2008)	145 000
Korea Rep. (2008)	126 898
Bangladesh (2007)	100 000 – 150 000
Myanmar (2007)	100 000 – 150 000
Russian Federation (2007)	100 000 – 150 000
Colombia (2009)	100 000 – 120 000
Honduras (2007)	75 000 – 100 000
Spain (2007)	75 000 – 100 000
Italy (2007)	68 750
Australia (2008/2009)	58 125
Iran (2007)	50 000 – 100 000
France (2009)	44 400
Denmark (2008)	43 500
Venezuela (2008)	37 580
Germany (2007)	32 000
Nicaragua (2009)	25 508
Costa Rica (2007)	25 000 – 35 000
Nigeria (2007)	20 000 – 30 000
Ireland (2009)	20 000
Argentina (2008)	3 901
Total	24 700 000 – 29 100 000

Source: Tacon, Hasan and Metian (2011).

At present, no precise statistical information exists concerning the total global production of farm-made aquafeeds (Tacon and Hasan, 2007), although production in 2006 has been tentatively estimated to be between 18.7 and 30.7 million tonnes (Tacon, 2008). This figure is in general agreement with total farm-made aquafeed production in Asia, which was reported at 19.3 million tonnes in 2004 (De Silva and Hasan, 2007). As expected, the largest farm-made aquafeed producers in 2006 were all countries from the Asian region and included China (10 to 20 million tonnes), India (6.5 to 7.5 million tonnes), Viet Nam (1 to 1.5 million tonnes), Japan (650 000 to 800 000 tonnes), and Thailand (700 000 to 750 000 tonnes) (Tacon and Metian, 2008a). According to Chinese researchers, farm-made feed production data are not available (Weimin and Mengqing, 2007), although they estimated that farm-made feeds account for about 40 percent of the country's aquaculture production, natural feeds for about 50 percent and commercial feeds for only 10 percent. The same authors stated that 40 to 55 percent of farmed fish production in China is probably fed industrially compounded aquafeeds during the on-growing part of their rearing cycle. These assumptions are similar to that of W. Jin, who estimated that only 20 percent of the aquatic animals that need to be fed on feed in China are fed formulated feeds.² Clearly, more detailed studies and information are required concerning the use of feedfish in China and the extent and status of the on-farm and commercial aquafeed manufacturing sector.

The current widespread use of low-value fish (previously called trash fish) as wet or moist feeds in the Asian region, particularly for the higher-value carnivorous marine fish and crustacean species, is very similar to the situation in the salmon farming industry when it started in Norway in the early 1970s (Talbot and Rosenlund, 2002). The first farmed Atlantic salmon were fed raw fish in the 1970s. The industry progressed to the development of semi-moist and dry pelleted feeds in the 1980s, and to the use of high-energy extruded pelleted feeds in the 1990s and 2000s. Of particular importance is the fact that as a result of these feed technology advancements (see Kearns, 2005; Larraín, Leyton and Almendras, 2005) fish growth and productivity have increased and fish production costs and feed conversion ratios (FCRs) have decreased.

Notwithstanding the above, it is important to highlight the important role played by farm-made aquafeeds, particularly in the production of lower-value (in marketing terms) freshwater fish species for small-scale farmers in countries of South and Southeast Asia and sub-Saharan Africa (Tacon and Hasan, 2007). Farm-made aquafeeds represented over 97 percent of the total carp feeds used by farmers in India (7.5 million tonnes in 2006/2007; Syed Ahamad Ali, Central Institute of Brackishwater Aquaculture, Chennai, India, personal communication, 2009) and still provide the mainstay of feed inputs within many Asian (De Silva

² Source: Paper presented by W. Jin on *Fishmeal as a dietary ingredient in China – first impressions*. International Fishmeal and Fish Oil Organization 2006 Annual Conference, October 23–26, 2006, Barcelona, Spain.

and Hasan, 2007; Ng, Soe and Phone, 2007) and sub-Saharan countries (Hecht, 2007).

Moreover, despite the lack of official published information concerning the direct use of low-value fish and other small pelagic fish species as aquaculture feed, it is estimated that the total use in aquaculture was between 5.6 and 8.8 million tonnes in 2006 (mean of 7.2 million tonnes; Tacon and Metian, 2009a); China alone reportedly consumed 4 to 5 million tonnes in 2005 (see footnote 2). However, estimates for 2008 concerning the direct use of low-value fish as feed in China are currently between 6 to 8 million tonnes; 4–5 million tonnes of marine trash fish and 2–3 tonnes of freshwater fish, including live food fish (approximately 70 percent of this being used for feeding inland carnivorous aquaculture species, and the remainder for marine finfish; Miao Weimin, personal communication, FAO, Bangkok, 2009).

Feed ingredient production and availability

The global production and market availability of feed ingredient sources commonly used in aquaculture feeds has been reviewed by Hasan *et al.* (2007). The review focuses on developing countries; these countries accounted for over 91.5 percent of total fed fish and crustacean production in 2007 (FAO, 2009a). In particular, the review by Hasan *et al.* (2007) includes a global overview (Tacon and Hasan, 2007), regional reviews covering Asia (De Silva and Hasan, 2007), Latin America (Flores-Nava, 2007) and sub-Saharan Africa (Hecht, 2007), and 13 individual country profiles (i.e. Bangladesh, Cameroon, China, Egypt, India, Indonesia, Kenya, Malawi, Nigeria, Philippines, Viet Nam, Thailand and Uganda) concerning aquaculture feed production and ingredient usage.

For the purposes of this paper, feed ingredients can be categorized as follows: (i) animal nutrient sources, (ii) plant nutrient sources and (iii) microbial nutrient sources.

Animal nutrient sources

Aquatic animal protein meals and lipids

The major aquatic animal protein meals and lipids available in the market place can be listed as follows (in order of global production and current market availability):

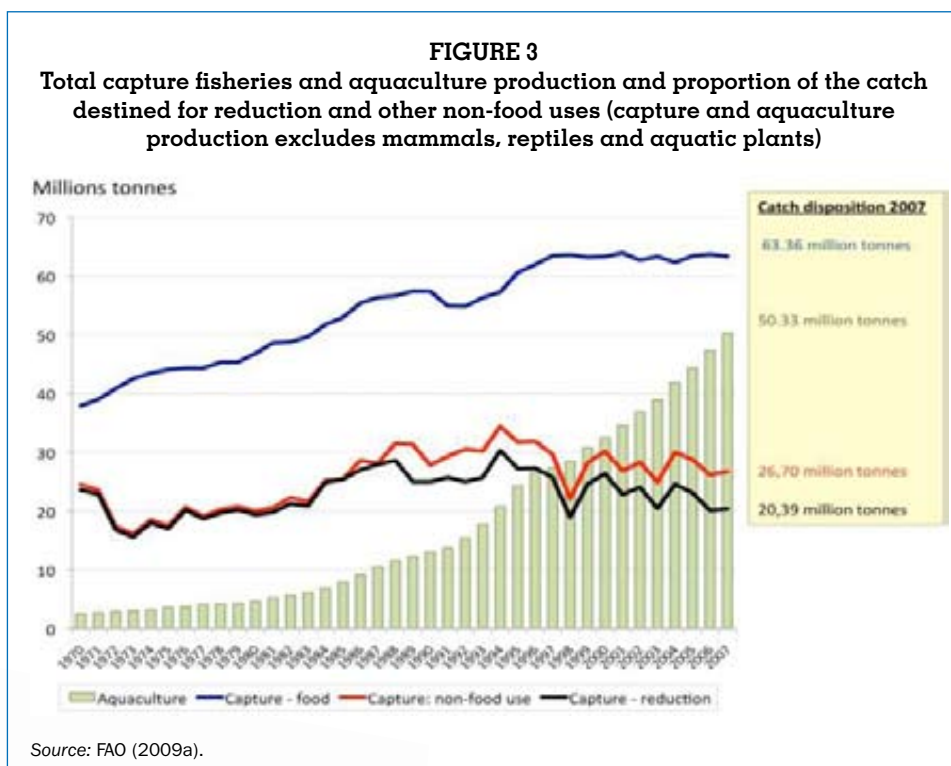
- *Fish/shellfish meals and oils*: produced from wild-harvested whole fish and macro-invertebrate animals, including by-catch.
- *Fish/shellfish by-product meals and oils*: produced from seafood and/or aquaculture processing waste.
- *Zooplankton meals and oils*: produced from wild harvested marine invertebrates.
- *Fish/shellfish hydrolysates, silages and fermentation products*: produced from harvested whole fish, macro-invertebrates, zooplankton and/or seafood processing wastes.

- *Marine polychaete meals*: produced from wild-harvested and/or cultured annelid worms.

Fish/shellfish meals and oils from wild fisheries

Fishmeals and oils derived from wild-harvested whole fish currently constitute the major aquatic protein and lipid source available within the animal feed market place. Despite the growth of the aquaculture sector, the proportion of the global fisheries catch destined for reduction into fishmeal and fish oil has remained relatively static (20.4 million tonnes in 2007; Figure 3), with modest reductions in global fishmeal and fish oil production (1.7 percent per year and 2.6 percent per year since 1995, respectively).

Predictions suggest that total volumes of fishmeal and fish oil from all sources are likely to remain at around 5 million and 1 million tonnes, respectively (except in El Niño years, when volumes are expected to be reduced). Indeed with the increasing demand for the whole fish to go for direct human consumption and with no new fisheries sources to be exploited, there is the likelihood that volumes of fishmeal and fish oil from whole fish will decrease. This reduction might be partially offset by increased volumes of meals and oils from processing by-products (see next section), but the overall trend is likely to be downward.



As with production, the largest exporter of fishmeal and fish oil in 2007 was Peru, exporting 41 percent and 30.6 percent of total world fishmeal and fish oil exports, respectively (FAO, 2009a). However, as for total global production, fishmeal and fish oil exports decreased at an average annual rate of 3.1 percent and 0.7 percent from 1995, respectively (FAO, 2009a). Fishmeal and fish oil imports continue to be dominated by China and Norway, who imported 29.6 percent (969 832 tonnes) and 25.8 percent (231 264 tonnes) of total fishmeal and fish oil imports in 2007, respectively. Moreover, in line with global production and exports, the quantity of fishmeal and fish oil available for export decreased at average annual rates of 2.8 percent and 1.8 percent since 1995, respectively (FAO, 2009a). However, recent data suggest that China's consumption continues to increase, with fishmeal imports increasing to 1 348 676 tonnes in 2008 (Peru 65.0 percent, Chile 17.7 percent, United States of America 5.7 percent), and 1 225 295 tonnes for the first ten months of 2009 (Peru 58.7 percent, Chile 26.0 percent, United States of America 5.5 percent) (Beckman, Wu and Han, 2009).

Fish/shellfish by-product meals and oils

At present, no statistical information is available from the Food and Agriculture Organization of the United Nations (FAO) concerning the total global production of fishmeals and oils produced from seafood and/or aquaculture processing waste. Despite this, it has been estimated that about 6 million tonnes of trimmings and rejects from food fish are currently used for fishmeal and fish oil production (SEAFISH, 2009a). For example, according to SEAFISH (2009b), 38 percent of the fishmeal consumed in the United Kingdom (UK) was produced from trimmings in 2008 (trade estimates). The same authors quoted 2006 trade estimates that 33 percent of the fishmeal produced within the European Union (EU) was manufactured from trimmings/offal from food fish processing plants, and that globally, this figure was about 24 percent. Similarly, the International Fishmeal and Fish Oil Organisation (IFFO) now estimates that about 25 percent of the total global production of fishmeal is being derived from fisheries by-products (Jackson, 2009).

In the case of fishmeals and oils produced from aquaculture processing wastes, it has been estimated that in Chile the production of 600 000 tonnes of salmon yielded 270 000 tonnes of processing waste and farm mortalities, which in turn resulted in the production of 48 600 tonnes of salmon oil and 43 200 tonnes of salmon meal (Anon, 2006).

Zooplankton meals and oils

Major marine zooplankton species which have potential and/or have been considered for use as feed ingredients include the Arctic amphipod *Themisto libellula*, the copepod *Calanus finmarchicus* and the Antarctic krill, *Euphausia superba*. Of these, commercial operations currently only exist for the Antarctic krill, where total landings were reported as 118 124 tonnes in 2007 (FAO,

2009a). As with other shrimp and crustacean meals, no information is currently available concerning the total global production and market availability of krill meal and krill oil. Despite this, krill meal and krill oil are available in the market place (see, for example, www.akerbiomarine.com; www.aquaticceco.com/subcategories/1148/Krill-Meal).

Others

At present, little or no information is available concerning the global production and market availability of fish/shellfish hydrolysates, silages and fermentation products, or concerning the production of wild-harvested and/or cultured marine polychaete worms. However, numerous fish hydrolysates, fermentation products and wild-harvested/cultured polychaetes are currently available in the market place (for example, salmon protein hydrolysate – www.rossyew.co.uk/salmon_pro.htm; farmed polychaetes and polychaete products – www.dragonfeeds.com).

Land animal protein meals and fats

The major land animal protein meals and lipids available in the market place can be listed as follows (in order of global production and current market availability):

- *Meat by-product meals and fats*: produced from slaughtered farmed livestock (cattle, pig, sheep, etc.), and includes meat and bone meal, meat meal, meat solubles and lard/tallow.
- *Poultry by-product meals and fats*: produced from slaughtered farmed poultry, and includes poultry by-product meal, turkey meal, feather meal, chick hatchery waste and poultry fat.
- *Blood by-product meals*: produced from slaughtered farmed livestock (ruminant and monogastric), and includes blood meal, haemoglobin meal and dried plasma products.
- *Miscellaneous invertebrate terrestrial products*: produced from wild-harvested and/or cultured annelid worms, insect larvae/pupae, gastropods (e.g. golden apple snail).

Although no published statistical information exists concerning the individual global production of the above-listed animal by-product meals, it has been estimated that the global combined production of rendered animal protein meals and fats in 2008 was about 13.0 and 10.2 million tonnes, respectively,³ global production of these animal protein meals being over twice that reported for fishmeal in 2008. At present, these terrestrial animal protein meals and fats represent the largest source of animal protein and fats available to the animal feed compounder.

The largest reported producer of rendered animal protein meals and fats in 2008 was the United States of America at 4 094 237 tonnes and 4 576 429 tonnes,

³ Source: Presentation by K. Swisher on *U.S. industry review*. 76th Annual Convention of the National Renderers Association, San Francisco, USA, October 23, 2009.

respectively, followed by the European Union-27 at 3 870 000 tonnes and 2 687 000 tonnes, South America at 3 970 578 tonnes and 2 278 379 tonnes, Australia at 650 000 tonnes and 470 000 tonnes, New Zealand at 214 300 tonnes and 140 000 tonnes, and Turkey at 185 600 tonnes and 84 179 tonnes, respectively (see footnote 3). Clearly, however, these global estimates are low, as they currently exclude most Asian countries from the analysis.

Total exports of rendered animal protein meals was 1 338 954 tonnes in 2008 or 10.3 percent of total global production. The largest reported country exporters were the EU-27 (340 153 tonnes), followed by the United States of America (298 257 tonnes), Australia (259 903 tonnes), New Zealand (149 405 tonnes), Argentina (73 309 tonnes), Brazil (62 903 tonnes), Uruguay (52 081 tonnes) and Canada (25 709 tonnes) (see footnote 3). The largest importers of rendered animal protein meals in 2008 were Indonesia (309 679 tonnes), followed by Thailand (149 490 tonnes), Viet Nam (114 379 tonnes), Mexico (107 187 tonnes), the United States of America (89 675 tonnes), China (62 905 tonnes), Egypt (62 276 tonnes), Chile (53 141 tonnes), Bangladesh (50 315 tonnes), Philippines (50 054 tonnes), Taiwan Province of China (42 190 tonnes), Russia (38 610 tonnes) and South Africa (35 919 tonnes) (see footnote 3).

Data for global rendered fats and greases are only currently available for tallows, with total global tallow exports and imports reported at 1 878 661 tonnes in 2008. The major tallow exporters were the United States of America (1 040 926 tonnes), Australia (372 532 tonnes), Canada (183 765 tonnes) and New Zealand (148 405 tonnes), and the major tallow importers in 2008 were Mexico (516 266 tonnes), China (365 351 tonnes) and Nigeria (123 567 tonnes) (see footnote 3).

Miscellaneous invertebrate terrestrial products

No statistical information is available concerning the total global production of terrestrial invertebrate animal products, the majority being highly localized and serving as supplementary feed items or for use within farm-made aquafeeds (Hasan *et al.*, 2007).

Plant nutrient sources

The major plant dietary nutrient sources, including meals and oils, available in the market place can be listed as follows (in order of global production and current market availability):

- *Cereals, including by-product meals and oils*: includes milled/processed cereals (maize/corn, wheat, rice, barley, sorghum, oats, rye, millet, triticale, etc.), by-product meals (corn/maize gluten, wheat gluten, dried distillers grains with solubles, rice protein concentrate, rice bran, wheat bran) and extracted oils (corn/maize, rice).
- *Oilseed meals and oils*: includes full-fat (soybean) and solvent-extracted oilseed meals (soybean, rapeseed, cotton, groundnut/peanut, sunflower,

palm kernel, copra), by-product meals (soybean protein concentrates, rapeseed/canola protein concentrate) and extracted oils (palm, soybean, rapeseed, sunflower, linseed, cotton seed, olive).

- *Pulses and protein concentrate meals*: includes milled/processed pulses (peas, lupins) and by-product meals (pea protein concentrate, lupin protein concentrate).

Cereals and by-products

Total global cereal production was 2 525 million tonnes in 2008, up by 33.1 percent from 1 898 million tonnes in 1995, with production growing at an average annual rate of 2.2 percent. Maize production was at 822.7 million tonnes (32.6 percent of the total cereal crop in 2008), followed by wheat at 689.9 million tonnes (27.3 percent), rice paddy at 685.0 million tonnes (27.1 percent), barley at 157.6 million tonnes (6.2 percent) and sorghum at 65.5 million tonnes (2.6 percent). Maize remains the fastest-growing cereal crop, with global production up by 59 percent since 1995 and growing at an annual rate of 3.6 percent (FAO, 2009c).

The largest producer of maize in 2008 was the United States of America at 307.4 million tonnes or 37.5 percent of global production, followed by China (166.0 million tonnes or 20.2 percent), the EU (63.2 million tonnes or 7.7 percent) and Brazil (59.0 million tonnes or 7.2 percent) (FAO, 2009c).

Notwithstanding the above, Asia remains the largest global producer of cereals at 1 188 million tonnes or 47 percent of global production in 2008 (with rice paddy being the main cereal crop at 52.4 percent), followed by the Americas at 646.7 million tonnes or 25.6 percent (with maize being the main cereal crop at 67.8 percent), Europe at 504.4 million tonnes or 20.0 percent (with wheat being the main cereal crop at 49.2 percent), Africa at 151.4 million tonnes or 6.0 percent (with maize being the main cereal crop at 35.1 percent) and Oceania at 34.6 million tonnes or 1.4 percent (with wheat being the main cereal crop at 62.9 percent) (FAO, 2009c).

By country, China maintains the position as the world's top cereal producer at 481 million tonnes (19.0 percent total global production in 2008), followed by the United States of America (403.8 million tonnes or 16.0 percent), the EU (316.2 million tonnes or 12.5 percent), India (266.6 million tonnes or 10.6 percent), Russian Federation (106.4 million tonnes) and Brazil (79.7 million tonnes), these countries accounting for over 65.5 percent of total global cereal production in 2008 (FAO, 2009c).

In marked contrast to cereal production, non-Asian countries currently dominate the cereal export market. For example, the top cereal exporters in 2008 included the United States of America at 80.2 million tonnes, followed by the EU (29.2 million tonnes), Ukraine (24.4 million tonnes), Russian Federation (23.5 million

tonnes), Argentina (22.5 million tonnes), Canada (19.2 million tonnes) and Australia (18.2 million tonnes). The largest cereal exporter in Asia was Thailand (9.3 million tonnes), followed by India (4.0 million tonnes) (FAO, 2009b). Japan continues to be the world's largest cereal importer at over 24.5 million tonnes in 2008, followed by Egypt (15.1 million tonnes), Iran (14.8 million tonnes), the EU (12.5 million tonnes), Mexico (10.2 million tonnes), Saudi Arabia (8.3 million tonnes), Korea Rep. (7.5 million tonnes), Algeria (6.8 million tonnes), Brazil (6.7 million tonnes), Nigeria (5.4 million tonnes), Indonesia (5.3 million tonnes) and Iraq (4.7 million tonnes) (FAO, 2009b).

It is important to mention here that in addition to the above global market overview, the FAO FAOSTAT Agriculture database (www.fao.org/corp/statistics/en) on trade also reports the country exports and imports of specific traded cereal by-product meals and oils, including:

- brans of cereals (buckwheat, barley, fonio, maize, millet, oats, rice, rye, sorghum, wheat);
- cakes of cereals (maize, rice bran);
- flours of cereals (buckwheat, maize, millet, rye, sorghum, wheat);
- germ of cereals (maize, wheat);
- gluten feed and meal (no cereal specified); and
- oils of cereals (maize, rice bran).

Apart from the current absence of statistical information on the total global production of the above-listed cereal by-product meals and oils, the listing currently excludes major wheat by-products (wheat middlings/wheat pollard) and by-products from corn ethanol production. For example, according to the Renewable Fuels Association, ethanol bio-refineries within the United States of America reportedly produced nearly 27 million tonnes of corn cereal by-products for use as animal feed in 2008, including 23 million tonnes of distillers grains (production up ten-fold from 2.3 million tonnes in 1999), 3 million tonnes of corn gluten feed and 600 000 tonnes of corn gluten meal. The estimated market value of feed co-products from ethanol production in 2007/08 was USD3 billion, with an estimated additional USD1.7 billion from the sales of corn oil produced from wet-mill ethanol refineries (Renewable Fuels Association, 2008; Deutscher, 2009).

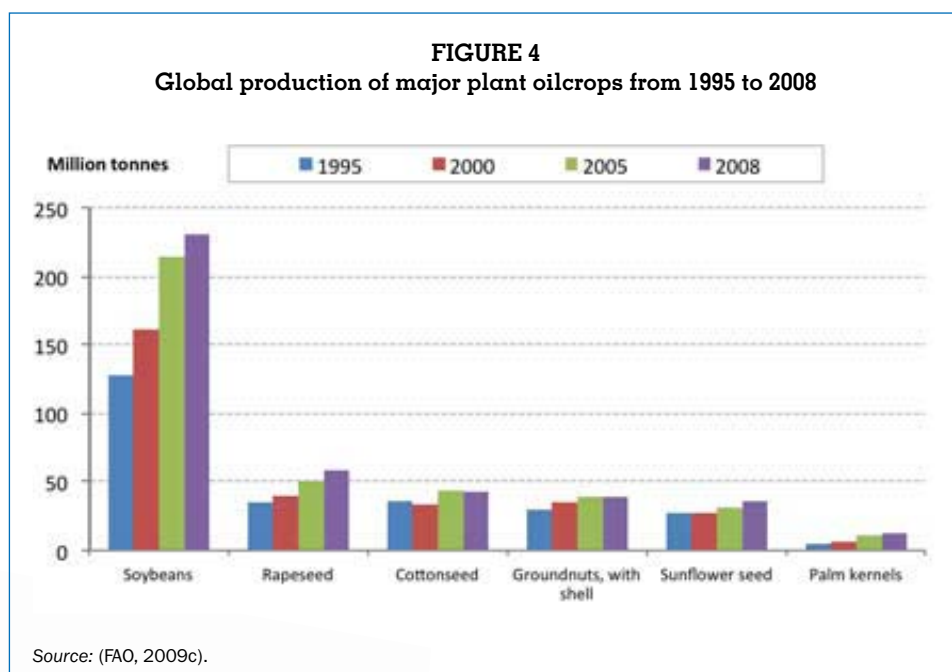
In 2009, distillers grains production was expected to reach 31.5 million tonnes, with exports expected to reach 6.6 million tonnes over the next ten years (Deutscher, 2009). According to the U.S. Grains Council, the United States of America exported over 4.5 million tonnes of dried distillers grains with solubles (DDGS) in 2008, the largest export markets in 2008 being Mexico (1.2 million tonnes or 26.3 percent total exports), followed by Canada (772 000 tonnes or 17.1 percent), Japan (198 000 tonnes or 4.4 percent), Taiwan Province of China (189 000 tonnes or 4.2 percent) and Korea Rep. (185 000 tonnes or 4.1 percent) (Chen, 2009).

Oilseed crops, byproduct meals and oils

According to FAO (2009c), the total global production of oilseeds in 2008 was 427 million tonnes, with production up by 61.1 percent since 1995 and growing at an average annual rate of 3.7 percent (Figure 4). Soybean represented 54.1 percent of the total oilseed crop in 2008, followed by rapeseed (13.5 percent), cottonseed (9.9 percent), groundnut (8.9 percent), sunflower seed (8.4 percent) and palm kernel (2.8 percent).

Soybean continues to be the largest and one of the fastest growing oilseed crops, with global production up by 81.9 percent to 230.9 million tonnes since 1995 and growing at an annual rate of 4.7 percent. The largest producer of soybeans in 2008 was the United States of America at 80.5 million tonnes (54.1 percent of total oilseed production), followed by Brazil (59.9 million tonnes or 25.9 percent), Argentina (46.2 million tonnes or 20.0 percent), China (15.5 million tonnes or 6.7 percent) and India (9.0 million tonnes or 3.9 percent (FAO, 2009c). Other major oilseeds produced in 2008 included rapeseed (57.8 million tonnes), cottonseed (42.3 million tonnes), groundnuts (38.3 million tonnes), sunflower seed (35.6 million tonnes) and palm kernel (11.8 million tonnes) (FAO, 2009c).

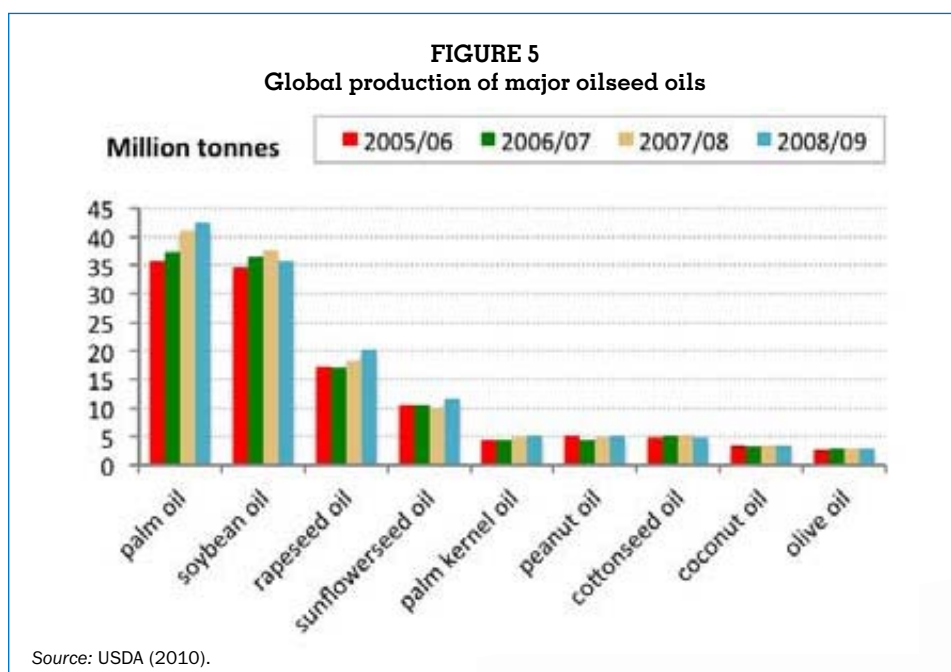
In terms of the total global supply of oilseed protein meals, these follow global oilcrop production, with the largest supply by far being for soybean meal at 151.55 million tonnes in 2008/2009. The largest country producers of soybean meal in 2008/09 were the United States of America (35.47 million tonnes or 23.4 percent), China (32.47 million tonnes or 21.4 percent), Argentina (24.95 million tonnes or 16.5 percent), Brazil (24.33 million tonnes or 16.0 percent),



EU-27 (10.11 million tonnes or 6.7 percent), India (5.98 million tonnes or 3.9 percent) and Mexico (2.73 million tonnes or 1.8 percent) (USDA, 2010).

Other major oilseed protein meals produced in 2008/2009, ranked in order of production volume, included: rapeseed meal (30.76 million tonnes), cottonseed meal (14.44 million tonnes), sunflower seed meal (12.59 million tonnes), palm kernel meal (6.2 million tonnes), groundnut/peanut meal (6.02 million tonnes) and copra/coconut meal (1.90 million tonnes). No published information is currently available for the global production of oilseed protein concentrate meals, including soybean protein concentrate, rapeseed/canola protein concentrate, cottonseed protein concentrate and sunflower seed protein concentrate meals.

In terms of oil supply, palm oil was the top extracted oil produced in 2008/2009 at 42.40 million tonnes (Figure 5), the largest country producers being Indonesia (19.5 million tonnes or 46.0 percent) and Malaysia (17.26 million tonnes or 40.7 percent) (USDA, 2010). The second-largest extracted oil was soybean oil at 35.76 million tonnes, the major producers being the United States of America (8.50 million tonnes), China (7.31 million tonnes), Argentina (6.12 million tonnes), Brazil (6.02 million tonnes), EU-27 (2.31 million tonnes), India (1.34 million tonnes) and Mexico (0.61 million tonnes). Other major oilseed oils produced in 2008/2009, ranked in order of production volume, included: rapeseed oil (20.39 million tonnes), sunflower oil (11.74 million tonnes), palm kernel oil (5.13 million tonnes), peanut/groundnut oil (4.97 million tonnes), cottonseed oil (4.84 million tonnes), copra oil (3.63 million tonnes) and olive oil (2.97 million tonnes) (Figure 5).

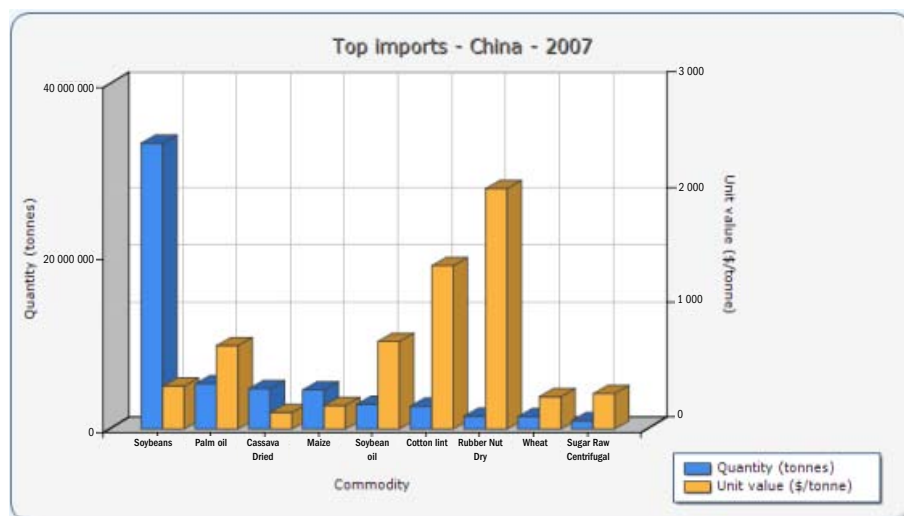


As with the cereals corn/maize and wheat, over 85 percent of global oilcrop exports currently originate from within the Americas (FAO, 2009b), including the United States of America (45.5 percent and 14.8 percent global soybean and soybean meal exports, respectively), Brazil (39.1 percent, 25.0 percent and 21.0 percent of global soybean, soybean meal and soybean oil exports, respectively), Canada (63.7 percent, 54.8 percent and 64.5 percent of global rapeseed, rapeseed meal and rapeseed oil exports, respectively) and Argentina (7.3 percent, 46.0 percent and 52.0 percent total soybean, soybean meal and soybean oil exports, respectively) (USDA, 2010).

China continues to be the world's largest importer of oil crops (46.6 million tonnes or 48.0 percent of global oilcrop imports in 2008/2009 (FAO, 2009b), including 53.7 percent of global soybean imports, 28.1 percent global soybean oil imports, 24.7 percent of global rapeseed imports, 18.4 percent of global rapeseed oil imports, and 18.0 percent of global palm oil imports (Figure 6).

The second largest importer of oilcrops was the EU, which imported 18.6 million tonnes or 19.1 percent of global oil crop imports in 2008/2009, including 57.2 percent of global sunflower seed meal imports, 41.9 percent of global soybean meal imports, 31.7 percent of global sunflower seed imports, 27.2 percent of global rapeseed imports, 26.0 percent of global sunflower seed oil imports and 18.4 percent of global rapeseed oil imports (FAO, 2009b).

FIGURE 6
Top agricultural imports by quantity in China in 2007



Source: FAO (2009b).

Pulses and protein concentrate meals

For the purposes of this paper, only peas and lupins will be considered, as their protein concentrate meals are commercially available for use within compounded animal feeds, including aquaculture feeds.

The total global production of dry peas was 9.8 million tonnes in 2008, with production down by 14.2 percent from 1995. The major country producers in 2008 included Canada (3.57 million tonnes or 36.3 percent of global production), followed by the Russian Federation (1.25 million tonnes or 12.8 percent of global production), China (900 000 tonnes), India (800 000 tonnes), the United States of America (556 560 tonnes), Ukraine (454 900 tonnes), France (446 850 tonnes), Australia (252 000 tonnes) and Ethiopia (231 934 tonnes) (FAO, 2009c).

The total global production of lupins was 789 617 tonnes in 2008, with production down by 54 percent from 1995. The major country producers in 2008 included Australia (484 000 tonnes or 61.3 percent of global production), followed by Belarus (81 314 tonnes), Germany (50 000 tonnes), Poland (39 686 tonnes), Chile (31 623 tonnes) and the Russian Federation (21 840 tonnes) (FAO, 2009c). At present no information is available concerning the global production of pea and/or lupin protein concentrates.

Microbial ingredient sources

Microbial-derived feed ingredient sources include the use of mass-produced harvested/extracted algae, thraustochytrids, yeasts, fungi, bacteria and/or mixed bacterial/microbial single cell protein (SCP) sources. At present, apart from the limited market availability of algal and thraustochytrid products, the only microbial ingredient sources available in commercial quantities globally are yeast-derived products, including brewer's yeast and extracted fermented yeast products (Tacon, Metian and Hasan, 2010). However, at present no information is available concerning the total global production and market availability of these products.

Current levels of feed ingredient usage and constraints

Based on the results of the global survey concerning feed ingredient usage within compound aquafeeds for the major cultivated finfish and crustacean species, the following trends are evident and are discussed individually in the sections which follow:

- Continued use of fishmeal and fish oil as major dietary animal protein and lipid sources.
- Increased use of terrestrial animal protein meals and oils as dietary nutrient sources.
- Continued and increased use of plant protein meals and oils as dietary nutrient sources.

- Ingredient competition with other users.
- Continued growing importance of feed and food safety.

Continued use of fishmeal and fish oil as major dietary animal protein and lipid sources

Fishmeal and fish oil continue to be the major sources of dietary protein and lipid within compound aquafeeds for the higher-trophic-level fish and crustacean species, e.g. eel (fishmeal: 55–65 percent, fish oil: 3–18 percent, total: 58–83 percent), marine finfish (fishmeal: 20–65 percent, fish oil: 5–20 percent, total: 25–85 percent), salmon (fishmeal: 25–40 percent, fish oil: 10–25 percent, total: 35–65 percent), trout (fishmeal: 18–40, fish oil: 5–25 percent, total: 23–65 percent), shrimp (fishmeal: 5–40 percent, fish oil: 1–9 percent, total: 6–49 percent) and freshwater prawn (fishmeal: 20–65 percent, fish oil: 0–7 percent, total: 20–72 percent).

However, in total usage terms, the largest consumers of fishmeal in 2007 (average species levels based in-part on the results of the global survey) were shrimp (964 000 tonnes or 25.1 percent of total fishmeal used in compound aquafeeds), followed by marine fish (811 000 tonnes or 21.1 percent), salmon (568 000 tonnes or 14.8 percent), freshwater crustaceans (264 000 tonnes or 6.9 percent), trout (253 000 tonnes or 6.6 percent), fed carps (247 000 tonnes), eel (208 000 tonnes 5.4 percent), catfish (196 000 tonnes or 5.1 percent), tilapia (175 000 tonnes or 4.5 percent) and miscellaneous freshwater fish (130 000 tonnes or 3.4 percent). On a global basis, it is estimated that the aquaculture sector consumed 3 843 000 tonnes of fishmeal in 2007 or about 68.4 percent of total reported global fishmeal production for that year.

Similarly, in total usage terms, the largest consumers of fish oil in 2007 were salmon (325 000 tonnes or 39.5 percent total fish oil used in compound aquafeeds), followed by marine fish (203 000 tonnes or 24.7 percent), trout (135 000 tonnes or 16.4 percent), shrimp (96 000 tonnes or 11.7 percent), eels (21 000 tonnes or 2.5 percent), freshwater crustaceans (20 000 tonnes or 2.4 percent) and miscellaneous freshwater fish (18 000 tonnes or 2.2 percent). On a global basis, it is estimated that the aquaculture sector consumed 823 000 tonnes of fish oil in 2007 or about 81.3 percent of total reported global fish oil production for that year.

Despite the continued high dependence of fed aquaculture species production upon the use of fishmeal and fish oil (the aquaculture sector consumed over 4 666 000 tonnes of fishmeal and fish oil or about 70.3 percent of the total global production of these finite ingredients in 2007), there was a wide variation in fishmeal and fish oil usage between major producing countries for individual species. This variation mainly reflects differences between countries concerning the selection and use of fishmeal and fish oil replacers, including the increased use of land animal proteins and fats within feeds for high-trophic-level fish

species and crustaceans within the Americas and Australia due to the absence of government and/or consumer restrictions concerning their use, and the differences in ingredient cost and availability between countries.

It is expected that the total use of fishmeal by the aquaculture sector will decrease in the long term, i.e. from a high of 4 225 000 tonnes in 2005 to 3 843 000 tonnes in 2007 (or 14.2 percent of total aquafeeds by weight) and decrease further to 3 689 000 tonnes by 2020 (or 5.2 percent of total aquafeeds for that year). This decrease is primarily due to the reducing volumes of fishmeal as more of the raw materials are likely to be used for direct human consumption, and the increased use of more cost-effective dietary fishmeal replacers (Davis and Sookying, 2009; Hardy, 2009; Nates *et al.*, 2009; Quintero *et al.*, 2010).

There will continue to be a strong demand for fish oil in aquaculture diets, but as already discussed, production volumes are likely to remain static or indeed fall with a reduction in raw material. Also, there is a growing demand for fish oil for direct use in human supplements and pharmaceutical medicines. This market is likely to be able to pay a premium for oil, resulting in aquaculture having to reduce its usage. This, combined with the growth in aquaculture, would mean a considerable reduction in the dietary inclusion levels. This would not have any deleterious effect on the health of the farmed organisms but would reduce the health-giving benefits of the final products imparted by the long-chain highly unsaturated fatty acids, including eicosapentaenoic acid (EPA; 20:5n-3) and docosahexaenoic acid (DHA; 22:6n-3) (Turchini *et al.*, 2009; Wang, 2009).

Alternative lipid sources to fish oil are being used in greater amounts (Turchini, Torstensen and Ng, 2009). Key alternatives include vegetable oils (preferably those with high omega-3 content) and poultry oil. Oils from farmed fish offal are also potential omega-3 sources for other farmed fish. The production of marine microalgae or bacteria with very high content of highly unsaturated fatty acids (HUFA) is currently expensive for use in most aquaculture feeds, but as production methods become more cost-efficient, the situation is likely to change.

Increased use of terrestrial animal protein meals and oils as dietary nutrient sources

The use (within non-European countries) of terrestrial animal protein meals (poultry by-product meal – PBM, hydrolyzed feather meal – HFM, blood meal – BM, meat meal – MM, meat and bone meal – MBM) and lipids (poultry oil – PO) is increasing within compound aquafeeds for both high and low-trophic-level species, e.g.:

- Salmon (PBM 10–30 percent, HFM 5–12 percent, BM 1–8 percent, MM 10–30 percent, PO 1–15)
- Trout (PBM 5–30 percent, HFM 5–20 percent, BM 1–8 percent, MM 10–30 percent, PO 1–15 percent)
- Marine finfish (PBM 10–30 percent, BM 1–10 percent, MM 10–30 percent, PO 1–10 percent)

- Shrimp (PBM 2–30 percent, HFM 5–10 percent, MM 2–30 percent)
- Catfish (PBM 2–4 percent)
- Tilapia (MBM 5–10 percent, PO 2–4 percent)
- Freshwater crayfish (MM 10–30 percent, MBM 10–30 percent)
- Carp (MBM 5–10 percent)
- Grey mullet (MBM 5–10 percent).

The fact that non-European feed manufacturers are able to utilize this largely untapped dietary nutrient source allows them to be less reliant on the use of fishmeal and fish oil as dietary nutrient sources, and by virtue of greater availability and lower cost of these terrestrial meals and oils, makes them more economically competitive than their European counterparts. For example, salmon feeds in Chile currently contain about 10–20 percent terrestrial animal by-products and only 20–25 percent fishmeal and 12–15 percent fish oil, whereas in the UK salmon feeds contain 35 percent fishmeal, 25 percent fish oil and 0 percent terrestrial animal by-products. Despite the above, it is estimated that the total direct usage of terrestrial animal by-product meals and oils within compound aquafeeds is currently only between 150 000 tonnes (lower range limit) and 300 000 tonnes (upper range limit) or less than 1 percent of total global compound aquafeed feed production. Clearly, there is considerable room for further growth and expansion (Nates *et al.*, 2009).

According to the European Commission, the only animal by-products (ABP) which can be used within aquafeeds are Category 3 ABP (European Commission Regulation No. 1774/2002 and No. 999/2001), namely those animal by-products or parts of slaughtered animals which are fit for human consumption in accordance with Community legislation but are not intended for human consumption for commercial reasons, including:

- Fishmeal (with restrictions – intra-species recycling is prohibited, see Regulation EC 999/2001)
- Dicalcium phosphate and tricalcium phosphate of animal origin (with restrictions)
- Non-ruminant blood meal and blood products (with restrictions)
- Milk, milk-based products and colostrums (without restriction)
- Eggs and egg products (without restriction)
- Hydrolyzed protein from ruminant hides/skin (without restriction)
- Hydrolyzed protein from non-ruminants (without restriction)
- Gelatine from non-ruminants (without restriction)
- Animal fats (without restriction)
- Collagen from non-ruminants (without restriction).

Continued and increased use of plant protein meals and oils as dietary nutrient sources

Plant proteins (soybean meal – SBM, wheat gluten meal – WGM, corn gluten meal – CGM, rapeseed/canola meal – R/CM, cottonseed meal – CSM, canola

protein concentrate – CPC, sunflower seed meal – SSM, groundnut/peanut meal – G/PM, mustard seed cake – MC, lupin kernel meal – LKM, faba bean meal – FBM, field pea meal – FPM) and oils (rapeseed/canola oil – R/CO, soybean oil – SO) represent the major dietary protein and lipid sources, respectively, used within feeds for lower-trophic-level fish species (e.g. tilapia, carp, catfish) and the second major sources of dietary protein and lipid after fishmeal and fish oil within shrimp feeds and European high-trophic-level fish species, e.g.:

- Tilapia (SBM 20–60 percent, CGM 5–10 percent, R/CM 20–40 percent, CSM 1–25 percent, SO 1–8 percent)
- Carp (SBM 5–25 percent, R/CM 20–40 percent, G/PM 30 percent, MC 10 percent)
- Shrimp (SBM 5–40 percent, WGM 2–10 percent, CGM 2–4 percent, R/CM 3–20 percent, LKM 5–15 percent)
- Marine fishes (SBM 10–25 percent, SO 3–6 percent, WGM 2–13 percent, CGM 4–18 percent, SSM 5–8 percent, R/CM 7–20 percent, CPC 10–15 percent)
- Trout (SBM 3–35 percent, WGM 2–10 percent, SSM 5–9 percent, CGM 3–40 percent, R/CM 2–10 percent, LKM 5–15 percent, FBM 8 percent, FPM 3–10 percent, R/CO 5–15 percent, SO 5–10 percent)
- Salmon (SBM 3–12 percent, WGM 2–10 percent, SSM 5–9 percent, CGM 10–40 percent, R/CM 3–10 percent, LKM 5–15 percent, FBM 5 percent, FPM 3 percent, R/CO 5–15 percent, SO 5–10 percent)
- Milkfish (SBM 35–40 percent)
- Grey mullet (SBM 20–25 percent)
- Freshwater prawns (SBM 15–25 percent)
- Colossoma (SBM 13 percent, CGM 6 percent)
- Freshwater crayfish (WGM 2–10 percent, LKM 5–30 percent)
- Eel (SBM 8–10 percent).

Soybean meal is currently the most common source of plant protein used in compound aquafeeds and the most prominent protein ingredient substitute for fishmeal in aquaculture feeds⁴, with feeds for herbivorous and omnivorous fish species and crustaceans usually containing (depending upon species, country, price and availability) from 15 to 45 percent soybean meal, with a mean of 25 percent in 2008. In global usage terms and based on a total compound aquafeed production of 27.1 million tonnes in 2007, it is estimated that the aquaculture feed sector is currently consuming about 6.8 million tonnes of soybean meal; China alone, currently consuming an estimated 6.0 million tonnes of soybean meal within compound aquafeeds (Mike Cremer, personal communication, American Soybean Association 2009).

⁴ Source: Paper presented by L. Manomaitis. *Improving Southeast Asian aquaculture through feeds and technology*. 17th Annual ASAIM SEA Feed Technology and Nutrition Workshop, Imperial Hotel, Hue, Vietnam, June 15–19, 2009 (see www.asaimsea.com/download_doc.php?file=FTNW09-Lukas.pdf).

At present, plant protein/oil choice and selection is based upon a combination of local market availability and cost, and the nutritional profile (including antinutrient content and level) of the protein meal and/or plant oil in question (Davis and Sookying, 2009; Gatlin *et al.*, 2007; Lim, Webster and Lee, 2008; Krogdahl *et al.*, 2010). However, there is no doubt that with the continued rise in the price of fishmeal, plant protein concentrates will be increasingly preferred over regular plant protein meals in aquafeeds for high-trophic-level cultured species and crustaceans (includes soybean protein concentrate, canola protein concentrate, pea protein concentrate, corn/wheat gluten meals, etc.; for review see Tacon, Metian and Hasan, 2010). For example, according to L. Manomaitis (see footnote 5) the forecast demand for soybean protein concentrates within aquafeeds is expected to be over 2.8 million tonnes by 2020.

Ingredient competition with other users

Aquaculture, like any other animal production system, has to compete with other users for nutrient inputs, including specific feed ingredients and fresh food items.

Competition with livestock

Livestock are an integral part of the agricultural food production process within all of the countries where aquaculture is practiced and are an important food provider in the form of nutrient-rich meat, eggs, milk and other dairy produce. It follows therefore that livestock are also a major consumer of feed ingredients and feeds. Total global livestock and animal feed production is estimated at 708 million tonnes in 2009 (poultry – 41.5 percent, pig –30.0 percent, ruminant – 25 percent), with total global feed production up by 20 percent since 1995 and growing at an average annual compound rate of 1.3 percent since 1995 (Best, 2010b).

Although aquaculture's contribution to global animal feed production is currently less than 4 percent by volume, it has emerged as a major competitor and consumer for several key ingredient sources, including fishmeal and fish oil. As mentioned previously, it is estimated that the aquaculture sector consumed over 4.7 million tonnes of fishmeal and fish oil or about 70.3 percent of the total global production of these commodities in 2007. Despite this, in China (the world's largest global producer of pigs and aquaculture products), the largest consumer of fishmeal remains the livestock and poultry sector (52 percent of total Chinese fishmeal demand in 2008), the estimated demand for fishmeal within pig starter/piglet diets alone being 612 000 tonnes (Wang, 2009). For example, according to Wang, (2009), animal feed production in China during the first half of 2009 was reported as follows: total national feed production – 64.63 million tonnes (down by 5.4 percent from the previous year), pig feed – 23.3 million tonnes (up 1.8 percent), poultry feed (meat) – 18.5 million tonnes (down 12 percent), poultry feed (egg) – 11.12 million tonnes (down 15.8 percent), aquatic feed – 7.85 million tonnes (up 17.3 percent), ruminant feed –

2.15 million tonnes (down 24.6 percent) and others – 1.6 million tonnes (up 5.7 percent). According to J. Shepherd⁵, the major consumers of fishmeal in China in 2008 were aquaculture – 58.8 percent, pig – 30.9 percent and poultry – 9.1 percent. For fish oil, the 2010 estimates for major consumers were aquaculture – 80 percent, refined edible – 12 percent and industrial – 7 percent. In contrast, aquaculture currently uses 760 000 tonnes of fishmeal, accounting for 76 percent of Europe’s fishmeal consumption⁶.

Competition with pet food

The pet food industry represents a relatively new and rapidly growing non-food animal sector, with dog and cat feed sales totalling USD9 billion in 2008 (Gianni Carniglia, GyB Ltd., Chile, personal communication, 2009). The dog and cat feed sector is currently one of the largest consumers of terrestrial animal protein meals and fats, including poultry by-product meal and meat and bone meal, the petfood industry representing 45 percent of the PAP’s outlets in the EU⁷ and 9 percent of rendered meal usage in Australia⁸. Moreover, compared with the other conventional animal feed sectors (including the aquaculture sector), the high-value and lucrative pet food sector is willing to pay top dollar for “pet food grade” low ash poultry by-product meals, which results in many of these products being out of the economic grasp of other users, including aquatic feed producers (for review, see Aldrich, 2006). A similar situation exists for the competition for fresh fish and aquaculture by-product meals for use within tinned cat foods and dog foods (De Silva and Turchini, 2008).

Competition with biofuels

Increasing petroleum costs, concern for the climate and the need to reduce greenhouse gas emissions have focussed efforts on the identification of alternative, renewable sources of energy, including conventional food grains and oilseeds, plant/animal oils and by-products, and low-value cellulosic wastes as substrates for the production of biofuels, including ethanol and biodiesel. Notwithstanding the ecological, environmental, economical and ethical problems involved in the use of some of these products for biofuel production, it is sufficient to note that many countries/governments have now adopted biofuel production as a national priority, with the sector in some countries enjoying a variety of government subsidies and incentives (for review, see FAO, 2008a).

Most concerning is the diversion of potential existing food grains and crops (including the land and resources used to produce them) from direct human

⁵ Source: Presentation by J. Shepherd on *Past and present priorities*. Annual Conference of the International Fishmeal and Fish Organization, 5–8 October 2009, Vienna, Austria.

⁶ Source: Presentation by M. Thomsen on *Fishmeal Europe 2009*. Annual Conference of the International Fishmeal and Fish Organization, 5–8 October 2009, Vienna, Austria.

⁷ Source: Presentation by N.C.L. Nielsen on *Updates Europe*. 76th Annual Convention of the National Renderers Association, San Francisco, USA, October 23, 2009.

⁸ Source: Presentation by C. Palmer on *Australian rendering industry update*. 76th Annual Convention of the National Renderers Association, San Francisco, USA, October 23, 2009.

consumption to more profitable biofuel production for use as a “greener” petroleum substitute. Often this market advantage is artificial because of government subsidies and incentives, but regardless, it leads to less grains and crops being available for direct human consumption and increased demand for these commodities and consequent increased food prices (for review, see Swisher, 2009). On the positive side, as mentioned previously, a variety of new feed by-product meals will be produced and be available from ethanol biorefineries, including distillers grains, corn gluten feed and corn gluten meal.

Competition with humans

Last but not least, there is the direct competition between the use of fish for aquafeeds and the use of the same resources as a direct food for humans. This includes competition for fresh or frozen fish used as a direct feed source (estimated usage by Chinese aquaculture being between 6 and 8 million tonnes in 2008), or for fish used in production of fishmeal and fish oil (for review, see FAO, 2008b; Funge-Smith, Lindebo and Staples, 2005; Hasan and Halwart, 2009; Tacon and Metian, 2008a, 2009a,b).

Continued growing importance of feed and food safety

Food safety risks associated with the use of aquaculture feeds may result from the possible presence of unwanted contaminants, either within the feed ingredients used or from the external contamination of the finished feed during prolonged storage. For example, major animal feed contaminants reported to date have included salmonellae, mycotoxins, veterinary drug residues, persistent organic pollutants, agricultural and other chemicals (solvent residues, melamine), heavy metals (i.e. mercury, lead, cadmium) and excess mineral salts (i.e. arsenic, hexavalent chromium, selenium, flourine) and possible transmissible spongiform encephalopathies (TSE). Apart from the direct negative effect of these possible contaminants on the health of the cultured target species, there is also a risk that some of these feed contaminants may be passed along the food chain, via contaminated aquaculture produce, to consumers.

In recent years, public concern regarding food safety has increased as a consequence of the increasing prevalence of antibiotic residues, persistent organic pollutants and chemicals in farmed seafood (for review, see Berntssen and Lundebye, 2008; Karunasagar, 2009; Lie, 2008; Lightner *et al.*, 2009; Tacon and Metian, 2008b).

Conclusions and recommendations

Reduce country dependence upon imported feed ingredient sources

On the basis of the results obtained from the feed ingredient survey conducted for this paper, it is apparent that many aquaculture-producing countries are currently highly dependent upon imports for sourcing the feed ingredients used

in their aquaculture feeds. Although the results of this survey should be treated with caution (as the results indicate the best estimates of individual country respondents rather than official government statistics), they do indicate some significant findings, as follows:

- Countries that reportedly import less than 25 percent of their feed ingredients used in compound aquafeeds include: Argentina (0–10 percent), Brazil (0–10 percent) and the United States of America (5–10 percent).
- Countries that reportedly import 25 to 50 percent of their feed ingredients used in compound aquafeeds include: Australia (25–35 percent), Canada (40 percent), Denmark (30 percent), India (0–44 percent) and Mexico (20–45 percent). In the case of India, feed ingredient imports can vary from 0 percent for freshwater Indian major carp feeds using locally available feed ingredient sources to as high as 44 percent for shrimp feeds.

For example, according to a recent survey concerning the animal feed manufacturing sector in Mexico (CONAFAB, 2008), Mexico was ranked fourth in the world in terms of total animal feed production (26.2 million tonnes in 2008, with aquaculture representing less than 1 percent of total feed production or 230 000 tonnes). The country imported over 55 percent of all the ingredients used within the animal feed sector, including over 90 percent of all plant oilseeds.

- Countries who reportedly import 50 to 75 percent of their feed ingredients used in compound aquafeeds include: Chile (30–80 percent), China (>50 percent), Ecuador (60–70 percent), Egypt (54–75 percent), France (50–78 percent), Italy (70–75 percent), Turkey (70 percent), the United Kingdom (60–90 percent) and Viet Nam (30–70 percent).
- Countries who reportedly import 75 to 100 percent of their feed ingredients used in compound aquafeeds include: Greece (90 percent), Korea Rep. (90–100 percent), Norway (80–90 percent), Peru (70–90 percent), Taiwan Province of China (50–100 percent), Tahiti (100 percent) and the United Kingdom (60–90 percent).
- Although no information was forthcoming from several other major aquaculture producers in Asia (including Bangladesh, Indonesia, Japan, Philippines and Thailand), published information suggests that in the Philippines 40–60 percent and 85–95 percent of the feed ingredients used for fish feeds and shrimp feeds are imported, respectively (Sevilla, 2007). A similar situation is expected to exist in Indonesia, Malaysia and Thailand (see SES, 2009a,b,c).
- The current dependence of aquaculture-producing countries upon the importation of major protein ingredient sources and lipids (i.e. fishmeal, soybean meal, fish oil) is strongest within those countries where production focus is on exports and/or the production of high-trophic-level fish and shrimp (SES, 2009a).

- In general, the demand for imported feed ingredient sources is highest within those developing countries with a strong commercial animal feed manufacturing sector and dominated by larger integrated farms and larger independent farms (SES, 2009c).
- In-country feed ingredient availability and usage within most developing countries is usually biased toward energy-rich rather than protein-rich ingredient sources, with greatest usage of local non-imported ingredients being within compound feeds intended for the production of freshwater and brackishwater fish feeds targeted for domestic consumption (SES, 2009a,b) and within farm-made aquafeeds produced by small-holder farmers (SES, 2009c).
- Many governments will continue to actively promote reduction of the current dependency of their national animal feed manufacturing industries upon imported feed ingredient sources by developing more competitive protein and energy sources from locally available agricultural products, including cassava, rice, oil palm, copra, etc. (SES, 2009a,d).

Select feed ingredients that can be sustainably produced and can grow with the sector

As mentioned at the outset of this paper, if finfish and crustacean fed aquaculture production is to maintain its current average annual growth rate of 8 to 10 percent to 2025, then the external supply of nutrients and therefore feed ingredient sources will also have to grow at similar rates.

Included within these ingredient sources are:

- fishery by-products and aquaculture by-product meals and oils;
- invertebrate fishery by-product meals and oils;
- terrestrial animal by-product meals and fats;
- cereals, including by-product meals and oils;
- oilseed meals and oils;
- pulses and protein concentrate meals; and
- microbial ingredient sources.

It follows from the above that ingredient choice should be based not only on nutrient level, digestibility and cost, but also upon other criteria such as sustainability and environmental impact of production, and fish in: fish out ratio (FIFO) (Naylor *et al.*, 2009; Jackson, 2010; Kaushik and Troell, 2010).

The limited supply of fishmeal and fish oil from wild fisheries and the continued strong demand for these products have led to concerns about the long-term sustainability of the fisheries and their level of responsible management. It is therefore important that care is taken to ensure that any fishmeal and fish oil made from whole wild fish comes from fisheries that have been managed according to the *FAO Code of Conduct for Responsible Fisheries* (FAO, 1995).

Minimize environmental and ecosystem impact of feeds and feeding regimes

As mentioned above, major criteria for ingredient selection are nutrient density and digestibility. It follows, therefore, that the higher the nutrient digestibility of a particular ingredient (or complete feed containing the ingredient), the higher its nutrient utilization efficiency and consequent resultant growth of the target species. Moreover, by using highly digestible feed ingredient sources and feeds, nutrient loss and feed wastage are kept to a minimum, thereby also minimizing any possible negative environmental and ecosystem impacts.

In addition to the direct selection of highly digestible feed ingredient sources, nutrient loss and nutrient impacts from feeds can also be negated by integrating production with other cultured species which can benefit from these nutrient waste streams (Duarte *et al.*, 2009; Soto, 2009) or by culturing the species under closed biofloc-based zero-water exchange culture conditions (Avnimelech, 2009).

Of particular note is the ability of biofloc-based zero-exchange production systems to essentially change the nutrition of the target species (usually either marine shrimp or tilapia) from that of a purely monogastric animal dependent upon the external supply of a nutritionally complete diet, to an animal cultured within a nutrient-rich microbial soup capable of supplying nutrients to the cultured species (both shrimp and tilapia are able to filter out these microbial flocs) in addition to the diet being fed, with consequent feed cost savings and ability to better utilize ingredient sources with inherent nutrient deficiencies or imbalances (Tacon *et al.*, 2002, 2006).

Give special attention to small-scale farmers using farm-made aquafeeds

It is widely recognized that small-scale farmers still form the backbone of Asian aquaculture, in particular, for the production of freshwater fish species for domestic consumption. One of the hallmarks of this sector is the use of farm-made aquafeeds. However, apart from the general absence of statistical information on the size and extent of this sector, little or no attention is given to helping farmers better formulate and manage their feeds. To a large extent, this has been due to the thrust by government agencies and feed manufacturers to move the sector away from the use of farm-made feeds to the purchase of commercially manufactured aquafeeds.

Despite the relative merits and demerits of using farm-made aquafeeds (New, Tacon and Csavas, 1995; Hasan *et al.*, 2007), there is an urgent need to better assist the generally resource-poor farmers using farm-made aquafeeds, not only by improving feed formulation, minimizing the use of unnecessary feed additives and chemicals (including antibiotics), but by improving on-farm feed management and thereby reducing feed wastage and potential deleterious environmental impacts.

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