REPLACING FISH AND ANIMAL PROTEINS IN AQUACULTURE FEEDS: CHALLENGES AND OPPORTUNITIES

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Global aquaculture production is the fastest growing sector of livestock production, having increased by an annual percentage rate of 10.5% between 1990 and 2000 (Tacon, 2003). Aquaculture production includes finfish, crustaceans, mollusks, amphibians, reptiles and plants; about half of global production of nearly 46 million metric tons (mmt) in 2000 was finfish. In 2002, aquaculture products accounted for 35.2% of total fisheries production, with wild harvest accounting for the remainder. Aside from normal variations in landings from year to year, landings from capture fisheries have not increased for the past 15 years and are not predicted to increase beyond the current range of 89-98 mmt. Of total capture fisheries landings, in 2000 about 61 mmt was used for food production and 36 mmt to produce fish meal and oil (Tacon, 2003). Given the status of many of the world's fisheries as fully or over-harvested, increasing demand for fisheries products can only be met by increased aquaculture production, requiring a significant increase in production of aquaculture feeds.

Approximately 25% of aquaculture production involving over 130 species of fish are classified as filter feeding cyprinids (mainly carp), and the remaining 75% are fed pelleted feeds (Tacon, 2003). Of the species fed pelleted feeds, 62% are classified as omnivores/herbivores and 13% as carnivores. Omnivorous fish species include several species of carp, catfish, tilapia, and milkfish. These fish thrive when fed diets containing 25-32% crude protein, supplied primarily from ingredients derived from plants (oilseeds and grains). In contrast, carnivorous fish species, such as salmon, trout, eel, sea bream sea bass, halibut, cod, striped bass, yellowtail and other marine species thrive when fed diets containing 38-48% crude protein supplied primarily from fish meal or other animal protein sources. Fry and fingerlings of most omnivorous fish species are actually carnivorous; in nature they consume zooplankton, aquatic invertebrates, and larvae of various fish and crustacean species. When they reach the juvenile stage, their digestive systems develop to allow them to thrive on grain and oilseed-based feed formulations.

Although fry and fingerling only consume a small fraction of the total amount of feed used in a production cycle, production numbers for these species is staggering and collectively, they consume a surprising amount of the fish meal used in aquafeeds, about 400,000 mt in 2002. This amount is expected to double by 2010 (Pike and Barlow, 2003). The top five species of farmed fish in 2000 were carp. Tilapia were number 6 in total global production of fish. Production of the top 15 farmed fish species was 128,523,582 mt, 80% of global production (Table 1).

Carnivorous species of farmed fish are generally high-value species. Although production of these species accounts for only 7% of total global production of farmed finfish, together they utilize 70% of the total amount of fish meal used in aquaculture feeds. With the exception of salmon and trout, whose production and markets are becoming commodity-like, carnivorous species of farmed fish have high enough market values that, up to the present, the cost of their feeds has generally been immune to normal economic factors. In other words, feed formulations for these species have not changed despite significant increases in the costs of fish meal. However, this situation is beginning to change with the widespread realization that the finite supply of fish meal will be inadequate to support increased aquaculture production over the next decade at its current rate of growth. Beginning about five years ago, significant pressure on production costs of salmon and trout arose due to global competition and high levels of production in Chile where the cost of production is low compared to Norway, Canada, or the UK. As a consequence, there has been a significant reduction in the percentages of fish meal and fish oil in feeds for salmon and trout, supported by research findings on growth, health, and effects on product quality when fish are fed diets containing a high proportion of ingredients derived from oilseeds and grains.

For decades, fish meal has been the protein source of choice in aquafeeds for many reasons, including its high protein content, excellent amino acid profile, high nutrient apparent digestibility coefficients, general lack of antinutrients, relative low price, and its wide availability. Plant-derived feedstuffs all have some characteristics that place them at a disadvantage to fish meal in terms of their suitability for use in aquafeeds (Table 2). However, the economic and nutritional paradigms that up to now have resulted in high use levels of fish meal in aquafeeds are changing, and expectations are that plant-derived protein sources will be increasingly used in aquafeeds in place of fish meal.

Although the growth of global aquafeed production over the past two decades has altered use patterns of fish meal and oil, it has had little effect on total fish meal production or on the annual harvest rates of fish captured to produce fish meal and oil (Pike and Barlow, 2003). Fish meal is used in poultry, swine, ruminant, companion animal, and fish diets. Today's poultry diets used in the United States do not contain fish meal, whereas in the early 1970s, poultry diets contained 3-5% fish meal to supply 'unidentified growth factors' needed for poultry to gain weight to their potential (Scott et al., 1982). During the 1970s, the unidentified growth factors were identified as trace elements, and supplemented into diets as inorganic minerals, resulting in a gradual elimination of fish meal from broiler and hen diets. In other parts of the world where alternate protein ingredients are expensive relative to the price of fish meal, poultry diets still contain fish meal, albeit a small percentage. Over the same period, fish meal use in aquafeed production has increased dramatically as aquaculture production and aquafeed production have grown. In 2002, for example, estimated fish meal use in aquafeeds was 2,217,000 mt (Pike and Barlow, 2003). Average global fish meal production over the period from 1990 to 2000 was 7,047,000 mt, with a high of 7,440,000 mt in 1994, and a low of 5,342,000 mt in 1998 during an El Nino period that reduced catches of anchovies of the coast of Peru (Figure 1). Thus, the percentage of the 11-year average global production of fish meal that was used in aquafeeds in 2002 was 31.46% (Hardy and Tacon, 2002).

Predictions of future fish meal use in aquafeeds are slightly different depending on who is making the prediction. Pike and Barlow (2003) predict that by 2010, aquafeed production will increase from the 2002 level of 15,794,000 mt to 32,378,000 mt (Tables 3 and 4). They also report that in 2002, 2,217,000 mt of fish meal were used, meaning that 14.037% of the total weight of fish diets produced in 2002 was fish meal (Table 5). Using the same percentage of fish meal in diets predicted to be made in 2010 would require 4,601,321 mt of fish meal, or about 65% of the average annual global production of fish meal between 1990 and 2000. However, they also estimate total fish meal use in 2010 to be 2,854,000 mt, or 1,747,321 mt of fish meal less than one would calculate based upon use levels in 2002. Alternate protein sources are expected to supply the difference of 1,747,321 mt of fish meal that will not be used in aquafeeds (Table 6).

Tacon and Forster (2000), in contrast, predicted that fish meal and oil use in fish diets will decrease from 2,190,000 mt and 590,000 mt, respectively, in 2000 to 1,550,000 and 520,000, respectively in 2010. These authors contend that fish meal and oil use by the aquaculture feed industry will decrease because prices for meal and oil will increase at the same time that market prices for farmed fish and shrimp decrease, forcing the fish feed industry to replace portions of fish meal and oil in formulations with less expensive ingredients. Tacon and Forster (2000) further contend that consumers will demand that farmed fish be fed diets produced from contaminant-free ingredients and that retailers and consumers will demand that farmed fish be fed environmentally-sustainable and environmentally-friendly diets. Both of these developments, if they occur, will result in lower percentages of fish meal and fish oil in farmed fish diets than percentages used at present. New (2003) states that aquaculture could conceivably utilize 70% and 100% of the total annual production of fish meal and fish oil, respectively by 2010. However, New (2003) suggests that criticism of fish meal use in aquafeeds and positive research results with diets in which fish meal has been replaced by plant protein concentrates will result in lower use-levels of fish meal and oil than the potential use levels he calculates for 2010. Most likely, economic rather than social factors are likely to determine fish meal use-levels in aquaculture diets over the coming decade. Contaminant issues with fish meal and oil produced from fish harvested in the North Sea and elsewhere could result in lower use levels in aquafeeds, but new technology to lower the levels of organic contaminants, e.g., PCBs, in fish oil are likely to reduce problems associated with organic contaminants. Organic contaminants in fish meal and oil from fish landed in the eastern Pacific are already at very low levels.

To be considered a viable alternative to fish meal in aquafeeds, a candidate ingredient must possess certain characteristics, including wide availability, competitive price, plus ease of handling, shipping, storage and use in feed production. Further, it must possess certain nutritional characteristics, such as low levels of fiber, starch, especially non-soluble carbohydrates, and antinutrients, plus have a relatively high protein content, favorable amino acid content, high nutrient digestibility, and be palatable. Although some plant-derived ingredients, such a soy protein concentrate or wheat gluten meal, possess most of these characteristics, they are currently too expensive relative to fish meal to be used in production aquafeeds (Table 7). It is likely that a combination of plant-derived feed ingredients will be required to replace fish meal, and that feed supplements, such as amino acids, flavorings, and phytase, will be needed to produce aquafeeds lacking fish meal that support growth rates necessary for economic production of farmed fish.

Candidates to replace fish meal

The list of candidate ingredients to replace a significant proportion of the fish meal in feeds for carnivorous species of farmed fish is relatively short, and includes protein concentrates from soybeans, canola (rapeseed), grains, peas and lupins, and also single-cell proteins (bacteria and yeasts) grown on carbon sources such as methane. Each of these candidate ingredients possesses characteristics, including cost, essential nutrient limitations, presence of anti-nutrients, or presence of non-nutritive constituents, that have limited their use (Dong et al., 2000) (Table 2). Research efforts are underway around the world to solve the problems associated with these ingredients, and results are creating optimism that many of the problems associated with alternatives to fish meal can be overcome or mitigated to the extent that increased use of these ingredients and decreased use of fish meal may become a reality for the aquafeed industry. What follows is a description of the status of the major alternative protein sources for fish meal. Rendered products are excluded from this discussion because of decreasing use in all feeds, including aquafeeds.

Soybean products. Soybean production has increased tremendously over the past few decades, and soybean meal is presently used in aquafeeds for many species of farmed fish (Storebakken et al., 2000). Omnivorous species, such as catfish and tilapia, consume feeds in which soybean meal is the primary protein source, similar to poultry feeds. However, the use of soybean meal in feeds for carnivorous species of farmed fish is limited by the presence of anti-nutrients or by the high amounts of non-digestible compounds in soybean meal. Currently, there are two main problems that limit the use of soybean meal in aquafeeds: (1) constituents that cause inflammation in the intestine; and (2) non-soluble carbohydrates, e.g., stachyose and raffinose, that are not digestible by carnivorous fish and influence the water content of feces and rate of passage of feed in the GI tract. The intestinal inflammation problem appears to be a food intolerance resulting in enteritis, with associated negative effects on nutrient assimilation, feed intake, and growth rates of fish, although the etiology is not yet certain (Van den Ingh et al., 1991; Baeverford and Krogdahl, 1996; Bakke-McKellup et al., 2000). It is most commonly seen in salmon and trout. The non-soluble carbohydrate problem limits the amount of soybean meal that can be used in feeds. Soybean meal can contain up to 20% non-soluble carbohydrates, and high inclusion levels of soybean meal constrain feed formulations by limiting dietary energy content. Other problems with soybean meal, e.g., trypsin inhibitor activity, phytic acid, saponins, lectins, can generally be overcome by ingredient processing or use of supplements, such as the microbial enzyme phytase. A long-term solution to the non-soluble carbohydrate problem with conventional soybean meal may come about through the efforts of plant breeders. Work is underway to develop varieties of soybean that contain low levels of selected non-soluble carbohydrates.

Soy protein concentrate is an excellent alternative potential substitute for fish meal in aquafeeds, as demonstrated by numerous research studies (Kaushik et al., 1995; Stickney et al., 1996; Mambrini et al., 1999). However, the price of soy protein concentrate prevents high inclusion levels in aquafeeds; it generally costs 2-3 times more than fish meal. If alternative processing methods to produce soy protein concentrate for animal and fish feed use were developed and product was priced lower, inclusion levels in feeds would increase considerable.

Corn products. At present, corn gluten meal is widely used in salmon feeds, albeit at relatively low inclusion levels. Corn gluten meal contains a minimum of 60% crude protein, mainly because other byproducts of corn processing, e.g., fiber, starch overflows, resistant starch attached to fiber and condensed solubles from steep tanks, are added back to the protein fraction by processors. If these byproducts are excluded, the resulting corn gluten meal contains 72-80% crude protein, much more in line with the needs of the fish feed industry. Cost is a potential issue with this approach. Corn gluten meal is, of course, deficient in lysine, making it a natural ingredient which to blend with soy protein (deficient in methionine) to make a more complete amino acid balance.

Wheat and barley. Wheat and barley are similar in terms of nutritional content, but wheat is much more commonly used in aquafeeds than barley due to the relatively high fiber content of regular, hulled barley. Hull-less varieties of barley are much better suited as starting material from which to produce a protein concentrate similar to wheat gluten meal, an existing commodity mainly used as a component of human foods. As such, wheat gluten is too expensive to be considered for use in production aquafeeds, despite its high protein content, high protein digestibility, and other positive attributes. A potential market exists for feed-grade wheat or barley gluten meal, providing it could be produced for a price that was competitive with fish meal.

Canola/Rapeseed products. Canola meal is used in feed formulations at limited levels where it is available. Canola meal contains 35% crude protein, making it too low to be used in high percentages in high-energy, nutrient-dense aquafeeds. Rapeseed protein concentrate has been shown to be an excellent ingredient in feeds for salmonids and certain marine species, but it is not widely available (Teskeredzic et al., 1995; Kissil et al., 1997). Amino acids and palatability enhancing supplements are needed in feeds containing high amounts of rapeseed protein concentrate.

Distillers products. Ethanol production in the USA is increasing rapidly, and this increase is generating large quantities of distillers dried grains. Unfortunately, distillers dried grains contain high levels of fiber as well as 32-35% crude protein, limiting its use in aquafeeds. New developments in ethanol production in which protein, starch and fiber are fractionated prior to ethanol production from the starch fraction provide the opportunity to recover the protein for use in livestock and aquafeeds. At present, this approach is not widely used, but economic analysis suggests that ethanol production requires higher returns from the non-starch fraction of grains, mainly corn, making is likely that future ethanol plants will include some version of recovery of the protein and fiber fraction prior to starch fermentation, rather than after as is now the practice.

Singe-cell protein products. Microorganisms can be grown on a wide array of carbon sources, including methane, and product development is well underway in Norway to produce a protein product in this manner. Feeding trials using feeds in which single-cell protein products have replaced fish meal have been conducted with poultry and salmonids with promising results (Skrede et al., 1998). Commercial products are likely to appear in the next few years and their use in feeds for farmed salmon and other marine species is a certainty.

Peas and lupins. Pea and lupin protein concentrates have been produced on a limited scale for experimental use by air-classification and wet milling-extraction. Feeding trials with these products with salmonids have been promising (Thiessen et al., 2003; Glencross et al., 2004)

Seafood processing waste products. Globally, the quantity of seafood processing waste generated each year is nearly equal to the amount of fish captured to produce fish meal and fish oil (Kilpatrick, 2003). In many parts of the world, processing waste is converted into fish meal and used in livestock and aquafeeds. Alaska generates tremendous quantities of seafood processing waste, and a large proportion of material recovered in land-based factories is converted into fish meal. A lower proportion of processing waste from shipboard processing is utilized. As demand for fish meal increases average prices, the economics of recovery and utilization of seafood processing waste will become more favorable, and much of this material will be used in aquafeeds, not necessarily as a primary protein source, but more likely in product forms designed to augment feeds based primarily on plant-derived feed ingredients (Hardy, 2003). Likely uses are as ingredients to overcome amino acid limitations in plant-derived feed ingredients, palatability enhancing materials, products to enhance growth and immunocompetence, and oil supplements to maintain high levels of omega-3 fatty acids in farmed fish products.

Plankton and Krill. The incredible biomass of copepods, Euphausids (krill) and amphipods in the sea has led to suggestions that this material be harvested to produce feed ingredients for use in aquafeeds (Langmyhr and Mjelde, 2005). Utilization of these resources is likely to stimulate controversy as it amounts to harvesting organisms from lower trophic levels than is presently practiced and may be construed as being detrimental to marine food webs. Products made from plankton and krill are high in protein, essential fatty acids, and astaxanthin, the carotenoid responsible for the pink-red color of salmon muscle. Further, they are likely to be highly palatable and thus suited for use in feeds containing high levels of oilseed proteins that typically are lower in palatability than fish meal-based feeds for farmed marine species.

Shifting paradigm in fish meal use in aquafeeds: Implications

Over the next decade, aquafeeds are certain to contain lower levels of fish meal than at present, and consequently, the role of fish meal in aquafeeds is likely to shift from being a primary source of protein to being a secondary source. Fish meal will continue to be an important source of essential amino acids that are limiting in plant protein sources, and its use in aquafeeds will partially revolve around serving to balance the amino acid of aquafeeds containing high quantities of plant protein sources. The essential amino acids of concern in plant protein-based aquafeeds are lysine (deficient in corn-derived proteins), methionine (deficient in soybean-derived proteins), and possibly arginine or threonine (deficient in small grains). High-protein, low-ash fish meals will be increasingly valuable; processing to reduce bone and indigestible protein levels in fish meal will be required to produce such fish meals, either from whole fish or from the seafood processing waste stream. Synthetic methionine and lysine, modified to reduce leaching from aquafeeds, will increasingly be used to supplement fish diets. Other essential amino acids that cannot be supplemented as feed-grade products will need to be supplied from meals produced from marine products and/or seafood by-products. Diet palatability may become an important consideration in diet formulation, especially when oilseed-derived proteins are added to diets (Medale et al., 1998), and addition of small percentages of krill meal, fish liver or viscera meal, or other marine products can restore feed intake. These two primary uses, e.g., source of essential amino acids and palatability enhancing properties, will define the paradigm shift in use of marine proteins in aquafeeds.

Another important issue associated with lower use levels of fish meal in aquafeeds involves dietary minerals, both levels in diets and bioavailability. Fish meal is an excellent source of many essential minerals, in contrast to plant proteins. Phytate, the storage form of phosphorus in seeds (and their meals) is unavailable to monogastric animals, including fish. Phytate is also known to reduce the availability of zinc, making it necessary to over-fortify diets to ensure adequate dietary zinc intake in fish fed diets containing high levels of phytate, especially in the presence of high dietary calcium levels (Richardson et al., 1985; Gatlin and Phillips, 1989).

The amount of fish meal used in aquafeeds will likely increase to 50% of annual global production, but an increased use of specialty marine products in aquafeeds is also likely. These products will be designed to overcome problems associated with expanded use of plant-derived protein concentrates. This will necessitate the expanded recovery and utilization of seafood processing waste and by-catch, with the additional refinement of partitioning of the seafood waste stream into segments that can be further processed to produce specialty products designed to enhance palatability, enrich diets with limiting amino acids, and to increase dietary efficiency, e.g., retention of dietary nutrients to support fish growth.

Economics will be the principle driver of these changes, although regulations associated with discharges of phosphorus, nitrogen or fecal solids from farms, or concerns about contaminant levels in some fish meals and oil, e.g., those from the North Sea or Baltic Sea, may affect fish meal use patterns in fish diets. Increased emphasis will be placed upon dietary nutrient retention, and this will affect future diet formulations and fish meal use. Increasing dietary nutrient retention will require the use of refined diet ingredients in fish diets, in contrast to ingredients simply produced from raw materials. Examples of this include the use of refined starches in place of ground whole wheat, or marine protein concentrate in place of whole fish meal. This will lower levels of indigestible materials in diets, such as fiber from wheat or connective tissue and skin in fish meal. Overall, the amount of fish meal used in fish diets will increase over the next 15 years, but the rate of increase will be much slower than the rate of increase in fish diet production over the same period. As demand for fish meal increases, the world price of fish meal will also increase, making it profitable to produce specialty diet ingredients from recovered seafood processing waste or from grains, oilseed, legumes, and other agricultural products for use in diets used to in the production of specialty (high-value) aquaculture products.

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Table 1. Top 15 species of farmed fish (mt) in 2000 and percent of total finfish production (from Tacon, 2003)

Common Name/Species	Production 2000	Percent of total finfish
Silver carp (*Hypophthalmichthys molitrix*)	3,473,051	15.1
Grass carp (*Ctenopharyngodon idella*)	3,447,474	14.9
Common carp (*Cyprinio carpio*)	2,718,277	11.8
Bighead carp (*Aristichthys nobilis*)	1,636,623	7.1
Crucian carp (*Carassius carassius*)	1,379,304	5.9
Nile tilapia (*Oreochromis niloticus*)	1,045,100	4.6
Atlantic salmon (*Salmo salar*)	883,558	3.8
Roho (*Roho labeo*)	795,128	3.5
Catla (*Catla catla*)	653,440	2.8
Mrigal carp (*Cirrhinus mrigala*)	573,294	2.5
Milkfish (*Chanos chanos*)	511,750	2.2
Rainbow trout (*Oncorhynchus mykiss*)	461,857	1.9
Channel catfish (*Ictalurus punctatis*)	448,141	1.2
Japanese eel (*Anguilla japonica*)	269,367	1.0
TOTAL TOP 15 Species	**18,523,582**	**80.3**

Table 2. Leading plant-derived protein sources and nutritional problems limiting their use in aquafeeds for carnivorous species of farmed fish

Product	Principle Problem(s)
Soybean meal (48% CP)	Non-soluble carbohydrates, low MET, phytate
Soy protein concentrate	Too expensive, phytate
Corn gluten meal	Non-protein components, low LYS
Wheat gluten meal	Too expensive, low LYS, ARG
Canola meal	Relatively low protein content, high fiber
Rapeseed protein concentrate	Not routinely available, low palatability
Distillers dried grains	Low protein content, low lysine, high fiber
Lupin/Pea protein concentrate	Not routinely available
Single-cell protein	Not routinely available
Seafood processing waste products	Logistics, high ash, not routinely available
Plankton/Krill meal	Not routinely available, price, environmental issues

Table 3. World fish aquafeed (mt) by species groups in 2000 and predicted production in 2010

Species group	Diet Production 2000	Diet Production 2010
Salmon/trout	1,636,000	2,300,000
Shrimp	1,570,000	2,450,000
Catfish	505,000	700,000
Tilapia	776,000	2,497,000
Marine finfish	1,049,000	2,304,000
Cyprinids (carp)	6,991,000	27,000,000
Total[1]	**13,106,000**	**37,226,000**

[1] Total includes other species groups not listed in Table.

Table 4. Estimated past, present[1], and predicted future[1] aquafeed use by various species groups of farmed fish (thousand metric tons)

Year	Salmonids	Shrimp	Catfish	Marine	Cyprinids
1990	650	800	380	200	3000
2000	1976	1783	505	1212	7358
2010	2517	2607	700	2465	14931
2020	2918	3227	900	3289	20866

[1] From Tacon (2003).

Table 5. Estimated use of fish meal in diets for various species groups in 2020 and 2010 (Pike and Barlow, 2003)

Species group	2000 (%)	2010 (%)	2000 (000mt)	2010 (000mt)
Salmon	35	25	455	406
Trout	30	20	180	139
Marine fish	45	40	377	628
Flatfish	55	45	40	145
Shrimp	25	20	487	576
Catfish	2	0	12	0
Carp	4	3	337	602
Other[1]			629	489
Total			2117	2854

[1] Includes eels, milkfish, tilapia, and other carnivorous freshwater species.

Table 6. Predicted fish meal use in aquaculture diets in 2000 and 2010

	Feed production (000mt)	Fish meal (000mt)
2000 (est.)	13098	2115
2010 (with today's diet formulations)	37226	4586
2010 (with lower % fish meal in diets)		2831[1]
Difference		1,755[2]

[1] Barlow (2000).
[2] Fish meal equivalent to be supplied by other protein sources.

Table 7. Prices[1] and price per unit protein (in ascending order) of alternative protein sources compared to menhaden fish meal

Ingredient	Crude protein (%)	Price (mt)	Cost per kg protein
Feather meal	83	$260	$0.313
Soybean meal	48	$175	$0.364
Meat and bone meal (porcine)	51	$230	$0.451
Poultry byproduct meal	60	$285	$0.475
Corn gluten meal	60	$350	$0.583
Blood meal (flash-dried porcine)	89	$660	$0.742
Fish meal (menhaden)	***68***	***$630***	***$0.926***
Soy protein concentrate	76	$1001	$1.317
Wheat gluten	80	$1166	$1.458

[1] From Feedstuffs, August 29, 2005, and Nelson and Sons, Murray, UT. For comparison purposes only.

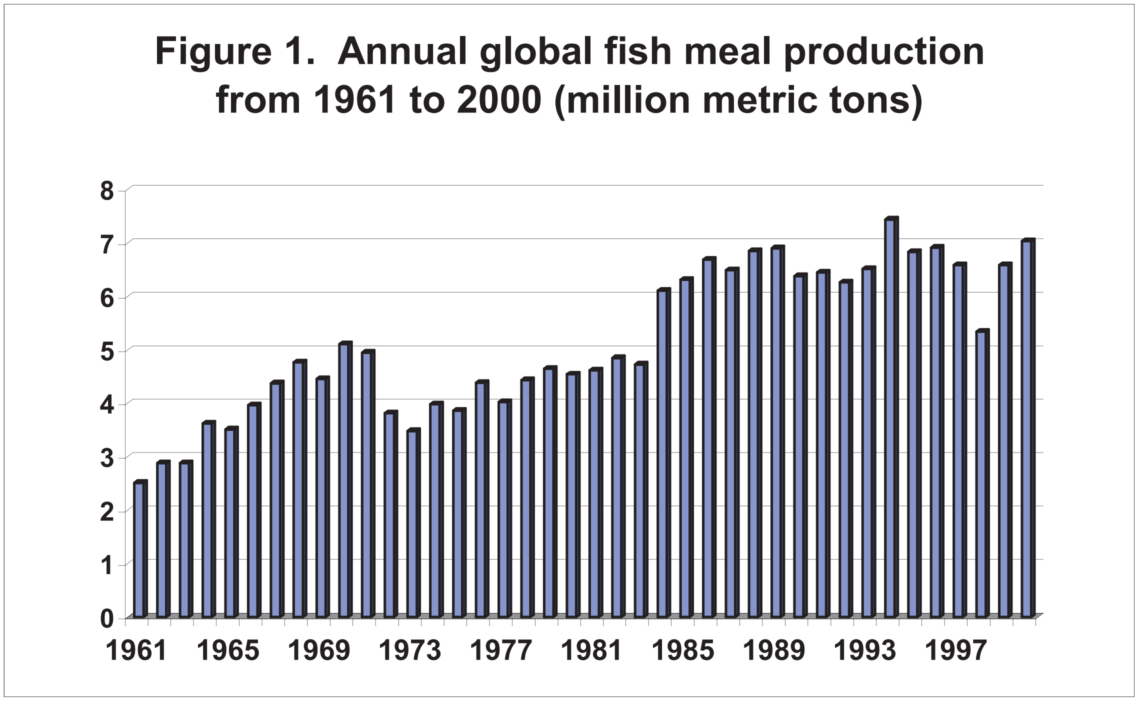
Figure 1. Annual global fish meal production
from 1961 to 2000 (million metric tons)
8
7
6
5
4
3
2
1
0
1961
1965
1969
1973
1977
1981
1985
1989
1993
1997