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Challenges and Opportunities in Finfish Nutrition

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Abstract.—Much of the criticism leveled at aquaculture (e.g., dependency on animal-derived feedstuffs, nutrient-laden effluent discharges, and increased organic contamination in edible products) can be traced to the feeds in use. Accordingly, finfish nutritionists are being challenged to formulate feeds that not only meet the nutritional requirements of livestock but also minimize production costs, limit environmental impacts, and enhance product quality. These challenges not only add considerable complexity to finfish nutrition but also afford opportunities to avoid some of the mistakes made by other industries in the past. From a review of the current status of finfish nutrition with respect to major nutrient classes, we comment on future opportunities and promising avenues of research. Alternative protein sources, specifically those derived from marine bycatch, plants, and microbes, are discussed, as well as methods to facilitate their implementation in finfish feeds. Dietary lipid, its role in fish bioenergetics and physiology, and quality of aquaculture products is reviewed with special emphasis on alternative lipid sources and finishing diets. Carbohydrates and fiber are discussed in terms of nutrient-sparing, least-cost diet formulation and digestive physiology. Micronutrients are reviewed in terms of current knowledge of requirements and, along with other dietary immunostimulants, are given further consideration in a review of nutriceuticals and application in finfish feeds. The status of nutritional research in new aquaculture species is also outlined. By integrating classical approaches with emerging technologies, dietary formulations, and species, finfish nutritionists may identify means to increase production efficiency and sustainability and provide for the continued success of aquaculture.

Identifying diets that meet the nutritional needs of organisms is requisite to their successful culture. Commercial production often evolves from high-priced, niche marketing to commodity status when complete diets have been formulated and produced for the target species. Profit margins are typically narrow in animal production, particularly for maturing markets; any method that minimizes production costs is welcome progress (Riepe et al. 1992). Feed costs are the largest expenditure for finfish producers, and here lies the greatest opportunity for improvement. Formulating diets well suited to target species will overcome financial challenges, contributing to the long-term sustainability of aquaculture. Moreover, diets can be formulated to reduce effluents (Gatlin and Hardy 2002) and dependence on resources not renewable in the short term (i.e., fish meal). Progressive nutrition can reduce environmental and ecological costs, as well as the tangible price of feed. We review the current status of finfish nutrition with respect to the major nutrient classes, identify recurring problems, and suggest potential solutions and promising avenues of research. As aquaculturists, we are faced with both challenges and opportunities; our purpose here is to provide impetus for the development of avant-garde feeds and feeding strategies that will allow the industry to meet the challenges ahead and expand current opportunities into future success.

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Finfish as Unique Livestock

Finfish nutrition is limited by several constraints associated with the aquatic environment and the adaptations finfish have acquired to inhabit it. Diversity in nutritional needs and limited direct interaction between terrestrial culturists and aquatic livestock limits feeds and feed delivery methods. These constraints are foreign to other livestock production industries but are prevalent throughout aquaculture production.

Finfish have evolved to exploit virtually every conceivable niche, feeding strategy, trophic level, and habitat. To optimize production, however, livestock producers attempt to simplify the complexities of the natural environment, eschewing diversity and stochasticism for control and predictability. The immense variety of cultured finfish species hampers efforts to simplify production industrywide. Approximately 170 taxa are currently cultured, including carnivores, herbivores, planktivores, and omnivores, each posing its own set of nutritional demands (FAO 1999). Finfish nutrition is made exceedingly complex by the great diversity in form and function imparted by the variability of the natural environment.

Other aspects of aquatic life further complicate nutrition in ways that are foreign to terrestrial livestock

production. Fish are poikilothermic (generally), which maximizes energetic efficiency in an environment where maintaining thermal control is particularly difficult. However, changing body temperatures dramatically affect entire bioenergetic regimes, and thus, nutritional demands vary with culture conditions (Yamamoto et al. 2001). Poultry, swine, cattle, and other homeotherms digest and metabolize nutrients within a relatively narrow homeostatic temperature range, whereas feeding and nutrition of finfish is subject to considerable temperature fluxes.

Another consideration for finfish nutritionists is the method of feed delivery. First, is live or prepared feed more appropriate? Certainly prepared feeds are ideal for simplifying feed management and eliminating a potential pathogen vector, though incomplete information regarding nutrient requirements may lead to ineffective or detrimental diets. Moreover, prepared feeds may have issues of palatability, particularly for wild captures or larval fish. Manufacturers of prepared feeds must also consider the water stability, size, and density (floating or sinking) of pellets. Pelleted feeds must be appropriately sized to allow for easy acquisition and consumption and remain intact despite water saturation. Dietary content is paramount, but manufacturing, processing, and mode of delivery are also critical factors in finfish nutrition.

Recurring Challenges

Dietary Protein and Essential Amino Acids

Protein represents the largest single component of finfish diets and is also the most costly. High demand and expense of high-protein feedstuffs keeps protein at the forefront of finfish nutritional research. In most vertebrates, the requirement for dietary protein is inversely correlated with age, however, as indeterminant growers, finfish exhibit high protein requirements regardless of life stage. Protein requirements for growing finfish are typically 20–55% of total dietary intake (Table 1), whereas crude protein intakes are currently 17–22% of the dry diet for swine and 14–23% for poultry (NRC 1994; NRC 1998). Requirements for other growing vertebrates range from 15% to 20%. Poikilothermy and reduced gravity lower energetic needs of finfish, further increasing the demand for protein relative to other dietary components (Mommsen 1998). Satisfying the dietary protein requirement cost-effectively is a major concern in feed formulation.

TABLE 1.—Protein requirements of finfish used in large-scale aquaculture production; adapted from Wilson 2002 (reprinted with permission).

Species	Protein source used	Requirement (%)
Atlantic salmon *Salmo salar*	Fish meal	55
Channel catfish *Ictalurus punctatus*	Whole egg protein	32–36
Common carp *Cyprinus carpio*	Casein	31
Hybrid striped bass[a]	Fish meal, casein	35
Nile tilapia *Oreochromis niloticus*	Casein	30
Rainbow trout *Oncorhynchus mykiss*	Casein, gelatin	40
Red seabream *Pagrus major*	Casein	55

[a]Striped bass *Morone saxatilis* × white bass *M. chrysops*.

Historically, feed manufacturers used large quantities of fish meal (primarily clupeids and scombroids; FAO 1986) as an inexpensive, protein-dense feedstuff (NRC 1993; Tacon 1993). Fish meal has proven to be an excellent dietary protein source for finfish, leading to its description as an "ideal protein." The ideal protein concept is based on the premise that if the amino acid profile of the feed mimics the whole-body amino acid profile of the animal being fed, protein utilization and growth should be maximized. In this way, the amino acid profile of fish meal produced from the aforementioned species approximates an ideal protein for most cultured finfish species. Fish meal can be considered the first ideal protein feedstuff, and feed manufacturers continue to strive to match the efficacy of this product in finfish nutrition applications.

Fish meal production has remained essentially static since the late 1980s, at approximately 6 million metric tons per annum (FAO 2004). Supply has apparently stabilized; however, demand and competition for this resource continues to increase. This is due, in part, to increased production among all industrial consumers of fish meal, and reduced usage of other meat and bone meals in response to bovine spongiform encephalopathy (BSE or mad cow disease). Although relatively recent analyses of oilmeal market structure indicated that fish meal usage was driven by lower cost per unit protein (Asche and Tvetervás 2004), fish meal is projected to increase in price and diverge from the general oilmeal market as a unique product (Delgado et al. 2003). This specific demand for fish meal further exacerbates the supply–demand issue. Currently, poultry, swine, and aquaculture are equal consumers of fish meal, each using roughly 2×10^6 metric tons annually (New 1997; FAO 1999; Figure 1). Although future fluctuations in annual landings may restore the recent production declines in reductive fisheries landings, it is unlikely that the non-food-use fisheries will be able to meet the 9×10^6 metric ton demand predicted for 2015 (FAO 2004). Clearly, fish meal is a finite resource that could limit continued growth in aquaculture and other livestock production. Further, inherent variability in fish meal composition due to species, season, geographic origin, and processing has led to variation in quality (Bimbo 1990a, 1990b; Sargent et al. 2002; Opstvedt et al. 2003; Bragadóttir et al. 2004). Marine animal-derived feedstuffs have also

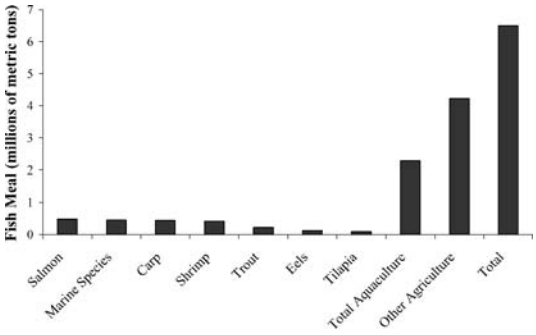

FIGURE 1.—Annual fish meal consumption in aquaculture and other agricultural production sectors (FAO 1999).

been implicated as vectors of contamination, raising levels of PCBs, dioxin, and other harmful chemicals in farm-raised finfish (Hites et al. 2004). Although the validity and conclusions of this particular study have been questioned (Hardy 2004), the interdisciplinary consensus is additional dietary protein sources are needed to supplement or replace fish meal in aquacultural feeds.

The search for novel protein sources is hampered by difficulties in determining the needs of individual species. Finfish do not have a dietary crude protein requirement per se, but they do require the same 10 essential amino acids (EAA) as most terrestrial vertebrates, specifically arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. Quantitatively determining the dietary EAA requirements usually involves utilization of purified proteins or crystalline amino acids, a process that is both costly and time-consuming (NRC 1993). Attempts to simplify this process have been only partially successful (Brown 1995; Alam et al. 2002; Twibell et al. 2003). It has been argued that the EAA requirements do not differ significantly among species and that variation in laboratory practices, growth rates, statistical applications, and response variables are responsible for the different amino acid requirements that have been established (Cowey 1994; Cowey 1995; Hauler and Carter 2001; Wilson 2002). Along these lines, Hauler and Carter (2001) proposed amino acid requirements be listed as ratios to feed efficiency. Preliminary investigations applying this method to existing data sets have produced encouraging results, though current studies using this approach are lacking. Development of efficient methods and full standardization across laboratories is needed before application of EAA requirements will have maximal effects on finfish nutrition and diet formulation.

Quantitative EAA requirements are lacking for most finfish species, and as a result, many nutritional studies focus instead on addressing crude protein requirements. As a consequence, several protein-rich commercial diets have been produced and applied to a broad spectrum of finfish species, regardless of the nutritional needs of the species. Although these nutrient-dense feeds are effective, this approach fails to maximize existing resources. That is, protein or amino acids that are not needed for tissue synthesis may be catabolized for energy or lost in effluents that contribute to nutrient loading in the environment. Diet formulation aimed toward meeting EAA requirements instead of overwhelming them with excess protein would conserve protein resources, increase the efficiency of finfish production, and reduce effluents. Together, these effects would greatly improve the economic viability and public acceptance of aquaculture.

Until a reliable method of determining EAA requirements of finfish is developed, inexpensive sources of crude protein will continue to be of great importance to finfish culture. Fisheries bycatch is one potential source of protein. Considering the volume of bycatch associated with fishing endeavors, products like fish protein concentrates, hydrosylates, and meals created from bycatch processing have received relatively little attention (El-Sayed 1998; Li et al. 2004). Bycatch and discards from the fisheries capture and processing industries represents 25% of total catch, or approximately 20×10^6 tons (Meyers 1986; FAO 1999). Silage produced from fish processing waste was found to be an effective replacement for fish meal in rainbow trout (Hardy et al. 1984; Stone and Hardy 1989; Stone et al. 1989). Although these products would be subject to similar concerns as other animal-based feedstuffs, they represent a potential source of protein for aquacultural feeds.

One obvious solution to problems of animal-derived feedstuffs is using plant-based diets. Plant feedstuffs are less expensive than animal products but present their own challenges in that they often lack EAA, are rich in complex carbohydrates, and may contain antinutritional compounds (NRC 1993). Soybeans are a prime example of these somewhat problematic feedstuffs. Soybeans contain sufficient crude protein, possess an agreeable amino acid profile, and are readily available at low cost. Soybeans have been demonstrated as effective protein sources for omnivorous and herbivorous finfishes (Adelizi et al. 1998; Boonyaratpalin et al. 1998; Quartararo et al. 1998; Arndt et al. 1999; Elangovan and Shim 2000; Refstie et al. 2001); however, low lysine and methionine levels, high fiber content, and antinutritional factors including protease inhibitors, lectins, phytic acid, saponins, phytoestrogens, antivitamins, and allergens (Francis et al. 2001) limit inclusion rates of soybeans as protein sources for

some finfish diets, particularly those formulated for carnivores (Krogdahl 1990; Rumsey 1993; Kikuchi 1999; Krogdahl et al. 2003). Soy-derived trypsin inhibitors, for example, have been shown to negatively affect growth and feed utilization in rainbow trout (Sandholm et al. 1976) and grass carp *Ctenopharyngodon idella* (Dabrowski and Kozak 1979), whereas weight gain in channel catfish was unaffected by these compounds (Wilson and Poe 1985). Phytate, also present in soybeans, has been shown to bind minerals, thereby limiting mineral availability (Erdman 1979; Richardson et al. 1985; Satoh et al. 1989). Reduced mineral availability due to phytate binding has been shown to affect weight gain, feed efficiency, and mineral bioavailability, as well as cause cataract formation in finfish (Spinelli et al. 1983; Richardson et al. 1985; McClain and Gatlin 1988; Gatlin and Phillips 1989; Satoh et al. 1989; Gifford and Clydesdale 1990; Papatryphon et al. 1999). It is possible to compensate for the phytate–mineral interaction by increasing the dietary mineral content, although research is limited. Gatlin and Wilson (1984) found that Zn at 150 mg/kg of diet (dry weight basis) was necessary to overcome the binding of Zn by phytic acid in channel catfish. An approximate seven-fold increase in dietary macro-mineral concentrations was required to overcome this effect in sunshine bass (female white bass *Morone chrysops* × male striped bass *M. saxatilis*) fed 50% soybean diets (C. Kasper and P. Brown, Purdue University, unpublished data). Decreased mineral availability is a nutritional concern, but as with amino acids, poor uptake is also a waste-management concern because reduced uptake rates in vivo result in higher mineral concentrations in effluents. Phosphorus is particularly troublesome in this respect because phosphorus-laden wastewater can cause eutrophication receiving waters, which is generally undesirable.

Several means of avoiding antinutritional effects of plant-derived protein sources have been suggested, including processing treatments to destroy antinutritional compounds, dietary incorporation of enzymes to break down phytate, and the use of genetically improved grains and oilseeds. Processing modifications (heat treatments and extraction procedures) successfully reduce the antinutritional effects of trypsin inhibitors in soybean and other plant-derived products (Mwachireya et al. 1999; El-Sayed et al. 2000; Cheng and Hardy 2003); however, this may be coupled with decreased protein solubility (Arndt et al. 1999) and mineral availability (Cheng and Hardy 2003). Adding enzymes to fish feeds has received considerable attention for a variety of applications (Hardy 2000), including increasing phosphorus availability in plant-derived feedstuffs. Use of phytase supplements in fish feeds has significantly improved phosphorus availability and retention (Papatryphon et al. 1999; Vielma et al. 2000; Sugiura et al. 2001), as well as weight gain, growth rate, and nutrient digestibility (Debnath et al. 2005). A recent review of phytase research lists expanding usage of exogenous enzymes in aquaculture feeds as a primary step toward providing lower cost agricultural products (Mullaney et al. 2000). Genetically modified plants currently being developed may provide the ultimate solution to the antinutritional factor issue. Low-phytate strains of maize, barley, rice, and soybean are currently being raised and contain 5–50% of traditional seed phytic acid levels (Raboy 2002). These feedstuffs are beginning to be investigated in fish nutrition (Sugiura et al. 1999; Tudor et al. 2004) and may be the key to economical, nutritionally superior, and low-polluting protein sources for finfish feeds.

Other recent advances in protein production have stemmed from new grain processing techniques. Common commodities such as canola and barley may yield highly valuable, protein-rich feedstuffs when processed via fractionation or concentration. Rainbow trout exhibited growth similar to control fish fed diets containing canola protein concentrate (Teskeredzic et al. 1995); however, this was not observed in gilthead seabream *Sparus auratus* (also known as gilthead bream) fed diets containing a similar feedstuff at high levels of inclusion (Kissil et al. 2000). Similarly, canola protein concentrates were reasonably digestible for red seabream, but nutrient availability varied considerably among the processing techniques (Glencross et al. 2004). Reduced efficacy may be due to the poor palatability often associated with these protein concentrates. Flavor additives such as betaine, glycine, or other amino acids may offset this effect, making these feedstuffs more amenable to finfish production. If palatability issues can be overcome, plant-based protein concentrates may prove invaluable to the aquaculture industry.

The hazards of direct replacement of animal-based protein with feedstuffs like soybeans are evident, but the benefit of reducing dependence on animal-based protein is great and continues to provide momentum for this research. For example, Kaushik et al. (2004) investigated plant-derived protein sources in diets for European bass (also known as sea bass) *Dicentrarchus labrax* and found that, if limiting dietary factors (lysine and phosphorus in this case) were compensated for, near-complete replacement of fish meal was possible without negative effects on production criteria, feed cost, or waste output. Although there are disadvantages to plant-based feedstuffs, this should not dissuade nutritionists from investigating these alternative feedstuffs.

Harnessing microbes for the production of single-cell protein (SCP) has also garnered interest among finfish nutritionists. Methanotropic bacteria produced in this manner are similar to fish meal in amino acid profile (Skrede et al. 1998). Although SCP research is limited in carnivorous species (Skrede et al. 1998), research with tilapia *Oreochromis* spp. has continued throughout the last decade (Moriarty and Moriarty 1973; Avnimelech and Mokady 1988; Chamberlain and Hopkins 1994; Dempster et al. 1995). As a result, several commercially available SCP products have been successfully used as partial fish meal replacements (up to 50% of dietary protein content) in diets fed to tilapia (Viola and Zohar 1984; Davies and Wareham 1988; Chow and Woo 1990; Schneider et al. 2004). Although this line of research shows great promise as a protein source, it is still in its infancy, and its full potential has yet to be realized.

Lipids and Fatty Acids

Lipids, fatty acids, and their derivatives play a role in virtually every physiological process that occurs in vivo, and for this reason dietary lipid composition and content represent a massive sector of overall nutrition. Nowhere is this more true than in finfish nutrition where lipid can exceed protein in the body composition of finfish, a testament to the physiological and energetic importance of this nutrient class (Tocher 2003). Aside from physiological importance, lipids are indispensable energy sources, especially for finfish, which are not well-adapted to carbohydrate utilization. For these reasons, lipids and fatty acids have received great interest and are perhaps the most widely researched nutrient class in modern finfish nutrition.

Because finfish are, for the most part, intolerant of high dietary carbohydrate content (see Carbohydrates section below), lipids and fatty acids represent the primary sources of metabolic energy. It has been suggested that certain fatty acids are preferentially catabolized for energy, whereas others are reserved for other purposes (Tocher 2003). Fish tissue fatty acid profiles generally reflect high levels of eicosapentaenoic acid (20:5[n-3]; EPA) and docosahexaenoic acid (22:6[n-3]; DHA) relative to feed levels, and this supports the selective catabolism argument, provided the absent fatty acids were catabolized for energy. McKenzie et al. (1998) correlated increased swimming performance with elevated dietary levels of 18-carbon fatty acids, concluding the vigorous response resulted from the relative simplicity of liberating energy from these fatty acids. One must also consider the physiological demand for certain fatty acids and acknowledge that conversion into other necessary products, such as eicosanoids (see below), represents another considerable fatty acid sink. If preferential catabolism occurs, it may be possible to develop "designer" lipid blends that provide the optimal ratio of fatty acids for energy while sparing those needed for biological function.

With the expansion of lipid research in finfish, the relationship of dietary polyunsaturated fatty acid (PUFA) content to physiological competence has become evident. Like all other vertebrates, finfish cannot synthesize linoleic (18:2[n-6]) or linolenic (18:3[n-3]) acid, and these fatty acids are therefore required or essential (Tocher 2003). Other long-chain PUFA, specifically EPA, DHA, and arachidonic acid (20:4[n-6]; ARA), have also emerged as critical dietary constituents. This is especially true for marine finfish, which generally lack the ability to synthesize these compounds de novo in amounts sufficient to meet biological demand. Arachidonic acid and other 20-carbon fatty acids are precursors for eicosanoids, hormone-like cell-signaling compounds that are involved in cardiovascular modulation, immunity and inflammatory response, renal and neural function, and reproduction (Sargent et al. 2002). The n-3 fatty acids are found in great abundance in neural and eye tissues and are critical to proper development and function of these tissues. Dietary provision of these fatty acids is tantamount to biological fitness of cultured finfish.

The ratio of these fatty acids is just as important as their dietary concentration. The specific requirements for essential fatty acids may even vary according to their proportion to one another (March 1993). The ratio of n-3 to n-6 fatty acids has been suggested as an indicator of fish health status (Sargent et al. 1999). Replacement of fish oil with linseed and soybean oils in the diets of gilthead seabream resulted in reduced n-3 : n-6 fatty acid ratio and was associated with increased hepatic lipid deposition (Menoyo et al. 2004). Increasing n-3 : n-6 ratio in diets fed to seabream improved hepatic degradations induced by a soybean-meal-based diet (Robaina et al. 1998). A decreased n-3 : n-6 fatty acid ratio resulting from feeds supplemented with sunflower oil and linseed oil resulted in cardiac lesions in Atlantic salmon (Bell et al. 1993). In these studies, increased n-3 : n-6 fatty acid ratios were beneficial. However, this does not hold across all species or response parameters; n-6 fatty acids are important for egg development in freshwater finfish, and elevated n-3 : n-6 fatty acids can impede proper eicosanoid production (Tocher 2003). Kelly and Kohler (1999) observed significant reductions in cold tolerance and hepatic health of species of *Morone* fed formulated feed versus live food and attributed the differences to differential fatty acid profiles of the dietary treatments. Specifically, ratios of DHA : EPA : ARA in the two diets were significantly

different, ARA levels being higher (lower n-3 : n-6 fatty acid ratio) in the live prey. Here again, designer lipid sources may be possible, but the optimal ratios must be firmly established before such dietary formulations can be applied.

Lipid sources for finfish diets have traditionally been derived from the reduction fisheries (see discussion in Dietary Protein and Essential Amino Acids) in the form of fish oils. Fish oil provides essential fatty acids and acids ideal for energy production, but fish oil carries the same economic and environmental burdens as fish meal. Clearly, replacement of animal-derived lipid sources is as advantageous as replacement of animal-derived protein. Wonnacott et al. (2004) determined that replacing fish oil with canola oil does not significantly affect weight gain, food conversion ratio, or survival of sunshine bass, though changes in fatty acid profile were observed. Comparable results were achieved in Atlantic salmon, using diets based on sunflower oil (Bransden et al. 2003), and in red seabream *Pagellus bogaraveo*, using diets based on refined canola or soybean oil (Glencross et al. 2003). Ng et al. (2004) replaced fish oil with palm fatty acid distillate (PFAD) in the diet of African sharptooth catfish *Clarius gariepinus* and found no deleterious effects on growth, food conversion efficiency, or protein utilization. Rather, replacement of fish oil resulted in significantly improved fillet oxidative stability.

Although complete elimination of animal-derived lipid in finfish diets may not always be possible, partial replacement is often successful. A 25% replacement of fish oil with PFAD resulted in significantly improved weight gain of African catfish (Ng et al. 2004). Replacing two-thirds of total dietary fish oil with canola, soy, or linseed oil did not significantly affect growth or food conversion ratio of barramundi perch (also known as barramundi) *Lates calcarifer* (Raso and Anderson 2003). Caballero et al. (2002) found that replacing 80% of total fish oil with combinations of olive, canola, soybean, and palm oil resulted in satisfactory growth and food conversion efficiency in rainbow trout, though tissue fatty acid profile differed among the treatments. Izquierdo et al. (2003) found similar results in seabream fed diets in which 60% of total fish oil was replaced with soybean, linseed, or canola oil or a combination thereof.

Changes in fatty acid profile, specifically reductions in total highly unsaturated fatty acid (HUFA), EPA, and DHA content, can reduce consumer acceptability (Coello et al. 1999) as well as the nutritional benefit to the consumer. The myriad effects of long-chain HUFA on human health are now widely recognized (Leaf 1990; Arts et al. 2001; Hu et al. 2001; WHO 2002; Calder 2003; Pischon et al. 2003). More specifically, EPA and DHA have been shown to improve cardiac health, reduce blood pressure and risk of stroke, and aid in the management of numerous psychological disorders, including attention deficit and hyperactivity disorder, schizophrenia, and depression (Duo 2003). The nutrition and medical communities have strongly suggested increased consumption of HUFA, especially EPA and DHA, to improve and maintain health of the human population.

Seafood represents the most important source of these beneficial compounds to humans, and reduction in their concentrations is accompanied by reduced nutritive value to the consumer. Fillet fatty acid profile changes predictably following changes in dietary lipid source (Jobling 2003; Robin et al. 2003). Therefore, the negative effects of plant-derived lipid sources on tissue fatty acid profile can be overcome through the use of finishing diets. Turbot *Scophthalmus maximus* fed vegetable oil-based feeds had reduced fillet EPA and DHA concentrations; however, this effect was partially reversed by feeding a fish-oil-based feed for 8 weeks, as was the concomitant effect on fillet sensory profile (Regost et al. 2003a, 2003b). Linseed oil-based diets had similar effects on tissue fatty acid profile of Atlantic salmon, but EPA and DHA were restored to levels exceeding recommended human intake by feeding fish oil-based-diets for 16 weeks (Bell et al. 2004). Clearly, fish-oil-based finishing diets can be used to enhance consumer value at the end of the production cycle, greatly reducing fish oil use.

Fish oil replacement in aquaculture feeds, whether partial or total, reduces feed cost and dependence on capture fisheries but, in the absence of fish-oil-based finishing diets, can lead to an undesirable fillet fatty acid profile. Identifying alternative lipid sources that approximate the nutritional value afforded by fish oil and maintain fillet quality remains a major challenge in finfish nutrition.

Carbohydrates

Although finfish do not require carbohydrates in their diet, incorporation of complex carbohydrates in finfish feeds has a number of distinct advantages, including reduced feed cost and protein-sparing and lipid-sparing effects. Carbohydrates, which are the dominant portion of grains and a considerable constituent of legumes and oilseeds, are an excellent, inexpensive source of chemical energy. However, complex carbohydrates cannot be digested and utilized efficiently by most finfish species, rendering any nutritive value insignificant. Nevertheless, as protein and lipid sources become increasingly scarce and costly, exigency for ways to assuage demand for these

feedstuffs will increase, and advances in carbohydrate processing may lead to increased availability and utilization in aquacultural feeds.

Although many finfish species exhibit appropriate gut morphology and possess abundant intestinal microflora, considerable interspecies variation exists in the ability to process carbohydrates (Stickney and Shumway 1974). A general dichotomy exists in the carbohydrate digestive ability of warmwater omnivores and herbivores versus the inability of coolwater and coldwater carnivores, which lack the appropriate carbohydrase enzymatic suite necessary for digestion of carbohydrates. Although finfish produce amylase and disaccharidase and cellulase and chitinase are present in the digestive tract of some species (Jobling 1995), the low volume or lack of hormonal control over enzyme production prevents significant digestion of complex carbohydrates in species occupying higher trophic levels (Stone 2003). For this reason, diets fed to these fish rarely contain more than 20% complex carbohydrate (Cowey et al. 1975; Hardy 1991; Helland et al. 1991; NRC 1993). Conversely, warmwater omnivores or herbivores (e.g., channel catfish, tilapia, common carp, and white sturgeon *Acipenser transmontanus*) adapt well to diets containing as much as 40% dietary carbohydrate (Luquet 1991; Satoh 1991; Wilson 1991). Omnivory and herbivory necessitate processing of complex carbohydrates in some manner, and these species have evolved the necessary enzymatic processes, or support populations of microflora that do possess carbohydrase ability (Stone 2003).

Carbohydrate origin and the complexity of physical state influence carbohydrate digestibility for finfish, regardless of physiology. The crystalline structure of starch granules varies, wheat starch having one of the smallest grain sizes of any starch (<20 μm) and maize (10–20 μm) and potato starches (20–100 μm) being larger (Stone 2003). Accordingly, wheat and maize starches are more easily digested, probably because of increased granule surface area and enzymatic availability and are more appropriate feedstuffs for aquacultural feeds.

Digestibility of complex carbohydrates can be improved through preconditioning (i.e., gelatinization or enzymatic treatment; Singh and Nose 1967; Hilton et al. 1981; Saad 1989; Schwertner et al. 2003). Heat, pressure, and moisture are typically associated with common feed-manufacturing techniques and gelatinization of carbohydrates, which simplifies molecular structure and increases water solubility and digestibility (Stone 2003). Inclusion of dietary carbohydrases derived from exogenous sources also improves digestibility of carbohydrates. However, care must be taken when selecting specific enzymes to produce the desired end products, and enzymatic stability during diet manufacturing and storage must also be considered (Stone 2003).

Although digestibility of starches can be overcome by processing or using simple sugars (Buhler and Halver 1961; Singh and Nose 1967; Mommsen and Plisetskaya 1991; Cowey and Walton 2002), use of these feedstuffs may still be limited by the carbohydrate (glucose) tolerance of the target species. Feeding diets containing increased levels of digestible carbohydrate resulted in increased liver size and glycogen content in salmonids (Phillips et al. 1948; Hilton and Atkinson 1982), and warmwater species have performed poorly when fed diets in which glucose is the major source of dietary energy (Wilson and Poe 1987; Hung et al. 1989). These adverse effects are related to the hyperglycemic state induced by increased digestible carbohydrate availability. Carnivorous fish fed complex carbohydrate diets exhibit prolonged hyperglycemia similar to diabetic mammals (Shimeno et al. 1977; Brauge et al. 1994; Wilson 1994), followed by hepatic degeneration from glycogen accumulation (Brauge et al. 1994). Although herbivorous and omnivorous finfish experience a similar hyperglycemic affect following ingestion of digestible carbohydrates, the duration is much shorter because of greater clearance rates (Shimeno et al. 1977; Furuichi and Yone 1981; Furuichi 1983; Wilson 1994; Garcia-Riera and Hemre 1996; Peres et al. 1999; Stone et al. 2003). This apparent inability of finfish to regulate blood glucose levels may be due to a combination of several synergistic factors, including low hexokinase activity, an inability to induce glucokinase, and insufficient numbers of insulin receptors (Palmer and Ryman 1972; Ablett et al. 1983; Wilson and Poe 1987). Great strides could be made with the use of genetically modified organisms (GMOs) better suited to glucose regulation. However, developing such strains require considerable allocation of resources, and use of GMOs is still met with considerable opposition in many parts of the world.

Clearly, the potential benefits arising from carbohydrate use in finfish feeds are substantial; however, the equally substantial hurdles to direct application temper innovation in this field of research. Nutritionists must be cautious in their use of carbohydrates in finfish feed, but steadfast pursuit of improved carbohydrate utilization may lead to dramatic changes in finfish nutrition and aquaculture economics.

Fiber

Fiber is defined as indigestible plant material composed chiefly of complex carbohydrates. Some of the more common sources of fiber are cellulose,

TABLE 2.—Vitamin requirements (mg/kg of dry diet unless noted otherwise) for growth of five representative finfish culture species; from Halver 2002 (reprinted with permission). Abbreviations: R = required but level unknown, N = no requirement identified, ? = unknown.

Vitamin	Rainbow trout	Atlantic salmon	Common carp	Channel catfish	Red seabream
Thiamin	10–12	10–15	2–3	1–3	R
Riboflavin	20–30	20–25	7–10	9	R
Pyridoxine	10–15	15–20	5–10	3	5–6
Pantothenate	40–50	40–50	30–40	25–50	R
Niacin	120–150	150–200	30–50	14	R
Folacin	6–10	6–10	N	R	R
Cyanocobalamin (B_{12})	R	0.015–0.02	N	R	R
Myo-inositol	200–300	300–400	200–300	R	300–900
Choline	2,000–4,000	3,000	1,500–2,000	R	R
Biotin	1–1.2	1–1.5	1–1.5	R	N
Ascorbate	100–150	100–150	30–50	60	R
A[a]	2,000–2,500	2,000–2,500	1,000–2,000	1,000–2,000	1,000–2,000
D[a]	2,400	2,400	N	500–1,00	?
E	30	30	80–100	30	?
K	10	10	R	R	?

[a]In international units (IU) rather than milligrams.

hemicellulose, lignin, and petosan. As addressed above, finfish lack the enzymatic mechanisms necessary to digest these compounds, and as a result, the potential usefulness of fiber as a feed component has been disregarded by most finfish nutritionists.

The use of fiber in finfish diets has been associated with decreased gastric retention time, increased fecal output, and reduced nutrient utilization, and consequently the fiber content of finfish feeds is usually 8% or less (NRC 1993). However, dietary inclusion of beet pulp fiber improved fecal pellet stability when fed to carnivorous fishes such as largemouth bass *Micropterus salmoides*, sunshine bass, rainbow trout, and yellow perch *Perca flavescens* (J. E. Wetzel and C.C. Kohler, Southern Illinois University, unpublished data). In this way, dietary fiber may improve filtration efficiency and simplify water quality management. Solids account for much of the debris to be filtered in recirculating aquaculture systems (RAS), and feces compose as much as 80% of all solids (Hinrichs 1994). As use of RAS expands, increasingly complex technologies for water filtration have been developed, requiring commensurate increases in system cost and maintenance requirements (Timmons et al. 2002). Utilization of fiber may prove to be of logistical, if not nutritive advantage.

Micronutrients

Although vitamins and minerals are required in minute amounts compared with protein, lipid, and so forth, they are critically important, and deficiency in one or more of these micronutrients is perhaps the direst of mistakes in diet formulation. Every micronutrient has a deficiency disease associated with it, the effects of which are sometimes irreversible or fatal. For a few vitamins and most minerals, excess can be equally detrimental, resulting in toxicity. We have reproduced tables of known vitamin and mineral requirements for several representative species (Tables 2, 3), but this represents the extent to which we will address specific requirements. Our purpose is not to review the specific knowledge of each micronutrient as it applies to finfish nutrition because several other works of this nature already exist (see Gouillou-Coustans and Guillaume 2001; Lall 2002; Halver 2002). Our focus will, instead, be areas of micro-

TABLE 3.—Mineral requirements of finfish common to aquaculture production; from Halver and Hardy 2002 (reprinted with permission). Abbreviations: R = required in the diet but no quantitative measure published; NR = not able to demonstrate a dietary requirement under experimental conditions.

Species	Calcium (%)	Phosphorus (%)	Magnesium (%)	Iron (mg)	Copper (mg)	Manganese (mg)	Zinc (mg)	Iodine (μg)	Selenium (mg)
Atlantic salmon		0.6	R	30–60	5	10	37–67	R	R
Channel catfish		0.45	0.04	30	5	2.4	20	1.1	0.25
Common carp		0.7	0.05	150	3	13	15–30	R	R
Hybrid striped bass		0.6							
Nile tilapia		0.9	0.06	R	3.5	12	20	R	R
Rainbow trout		0.6	0.05	R	3	13	15–30	1.1	0.15–0.3
Red seabream	0.34	0.7	R	NR	R	R	R	R	R

nutrient research that remain largely unexplored. Although the list of essential vitamins and minerals is considered closed, micronutrient research in finfish nutrition is far from complete, and this somewhat nebulous genre will certainly be a source of both challenges and opportunities for nutritionists.

Vitamins.—Researchers are now learning that dietary incorporation rates that satisfy growth requirements are not necessarily sufficient to maintain reproductive performance, immunocompetence, and so forth, and minimum dietary requirements based on growth alone may be inadequate to optimize overall fitness. Vitamins C, E, and A are noteworthy in this respect, and are given special attention in a later section entitled Nutriceuticals.

Aside from benefiting livestock in vivo, vitamins also play a role in ensuring product quality postslaughter. Riboflavin (Brønstad et al. 2002) and vitamins C and E (Hong et al. 2003) have been implicated as regulators of lipid metabolism in finfish and could potentially be used to modulate dressout percentages and lipid content of the fillet. In terms of fillet stability and quality, elevated vitamin E concentrations have been shown to lengthen shelf life (Gatta et al. 2000; Ruff et al. 2002; Hamre et al. 2004) and maintain fillet color (Scaife et al. 2000; Ruff et al. 2003), firmness, and palatability (Chaiyapechara et al. 2003). Other vitamins may have similar, exploitable roles that should be investigated.

Complete minimum vitamin requirement tables have been established for only a few species and for those that do exist, typically only one life stage is addressed. Significant information gaps exist for larval finfish, broodstock, and emerging culture species. Even delivery methods are in flux because feed manufacturers look for new processes (e.g., low temperature and moisture extrusion, top-dressing, and chemically stabilized sources) to ensure that labile or otherwise vulnerable vitamins survive the manufacturing process. In spite of the appreciable body of literature available, much work remains in the field of vitamin nutrition. Piscine vitamin nutrition offers worthwhile scientific endeavor to those who pursue it and holds great promise for useful industrial application.

Minerals.—Minerals are essential for all life processes. Nearly 90 exist, 29 of these being required by finfish (Lall 2002). Finfish require minerals for ossification of bone and to maintain osmotic balance and acid–base equilibrium. Dietary demand for calcium, phosphorus, potassium, and magnesium, chromium, cobalt, copper, fluorine, iodine, iron, manganese, molybdenum, selenium, and zinc was recognized in early finfish nutrition, but these have since been thoroughly researched (NRC 1993; Lall 2002). Precision and accuracy, however, are difficult to achieve in determining mineral requirements, so many investigators question the validity of the established requirement lists and the essentiality of some minerals in feed supplements. The ability of finfish to absorb minerals from the water column and difficulty in micronutrient detection continue to complicate mineral research.

Despite the complexity involved, mineral research is needed, particularly for trace or microminerals. Microminerals are potentially lethal when present in amounts slightly above or below the requirement, and accurate requirements are therefore imperative for proper diet formulation (NRC 1993). Commensurate with this need is the demand for information regarding the biological function of microminerals in finfish. Complete understanding of function is necessary if accurate micromineral requirements are to be developed.

Like the antioxidant vitamins, selenium may hold promise as a fillet-stabilizing supplement to finfish feeds. Working in conjunction with tocopherols, the enzyme glutathione peroxidase acts to scavenge peroxides and prevent peroxide-induced rancidity in meats. Dietary supplementation with selenium, the primary enzymatic component of selenoproteins, including glutathione peroxidase, has improved production efficiency and meat quality in poultry (Ahn et al. 1998; Bonomi 2001; Surai 2002; Gampule and Manjunatha 2003; Choct and Naylor 2004) and swine (Munoz et al. 1998; Mahan et al. 1999; Bobek et al. 2004) and may also prove useful for finfish production.

Mineral supplements are necessary for the survival of finfish, but their presence also impacts the culture environment. As previously discussed, elevated concentrations of some minerals in effluents can contribute to environmental eutrophication and should be avoided, though moderate concentrations may actually be beneficial. Bacterial cultures necessary for detoxification of wastes also require minerals, and if they are unavailable, minerals can limit biological filtration. Preliminary studies have shown that these microbes require minerals that are often lacking or limiting in the culture environment (J. Alleman, Purdue University, unpublished data). Diets may be a suitable vector to supply these micronutrients and thus stimulate biological filtration.

New Horizons

Nutriceuticals

The term "nutriceutical" or its variant "nutraceutical" denotes an area of research that is currently of great interest in human and animal health and nutrition. A linguistic coupling of nutrition and pharmaceutical, the term was first coined in 1989 by the Foundation for

Innovation in Medicine in response to the growing interest in the role of food or food supplements in human health (Andlauer and Fürst 2002). In recent years, the scope of nutriceutical research has expanded to include veterinary medicine, in terms of both companion animals and livestock. Intensive animal production usually results in stressed, immunologically compromised animals. Increased susceptibility to infection coupled with high animal density make production facilities ideal environments for disease outbreak. Certainly, meeting nutritional requirements is essential for finfish health, but some dietary constituents may exert influence beyond their purely nutritional value (Gatlin 2002). Nutriceutical therapy attempts to stimulate the immune system and compensate for production-related immunosuppression. Nutriceutical research holds great promise for improving health and robustness of livestock without commensurate increases in production cost or animal drug use.

Although an assortment of definitions exist for nutriceuticals, the semantic variants and ongoing research all suggest several common characteristics that separate nutriceuticals from other immunostimulants: (1) a nutriceutical is a naturally occurring substance (though it may be concentrated or purified) that is likely to be found at some level in the natural diet of the organism; (2) a nutriceutical must be administered orally, usually over an extended period of time; and (3) a nutriceutical must have some nutritional value unto itself, aside from immunostimulation. These characteristics make nutriceuticals different from other dietary additives and therapeutants and will make nutriceuticals important in the future of livestock production enterprises, including aquaculture. Several functional categories of nutriceuticals have been investigated in aquaculture nutrition, including probiotics, vitamins, essential fatty acids, and plant derivatives. These are individually discussed below.

The precise definition of a probiotic is difficult to identify; like that of nutriceutical, the meaning of probiotic varies with the source of the definition. Originally, Fuller (1987) defined probiotics narrowly as live microbial dietary supplements, but more recently, Irianto and Austin (2002) defined probiotics broadly as microorganisms (live or dead), cell wall constituents, and other microbially derived products delivered orally, via injection, or by immersion. Limiting discussion to only those products delivered orally does little to restrict research of probiotics, which are the most widely researched nutriceutical in aquaculture. Probiotics are primarily used to maintain balance among the intestinal flora. In finfish nutrition, dietary administration of probiotics such as glucans, gram-negative and gram-positive bacterial cultures, microalgae, and yeasts has been investigated. Results vary among the culture species, though improved appetite, enhanced growth, and reduced need for antimicrobial compounds having been observed in finfish fed diets supplemented with probiotics (Irianto and Austin 2002). Although precise modes of action for probiotics are unclear, a variety of positive functions of probiotics have been suggested: competitive exclusion of pathogenic microbes, stimulation of cellular and humoral immune defenses, improvement in bowel motility, cholesterol-lowering effects, mucosal lining maintenance, breakdown of harmful compounds or otherwise indigestible nutrients, and production of vitamins and digestive enzymes (Holzapfel and Schillinger 2002).

Vitamins were first discovered as treatments for a variety of diseases, including beriberi, pellagra, and scurvy. Perhaps one of the earliest applications of the nutriceutical concept, these so-called preventative factors were prescribed as dietary treatments for these diseases (Halver 2002). Subsequent analysis revealed that the observed afflictions were manifestations of dietary deficiencies, and the preventative factors were required micronutrients. Vitamin deficiency in finfish has been well researched, and minimum dietary requirements for the water-soluble and fat-soluble vitamins have been established for primary culture species. As indicated previously, finfish nutritionists are discovering advantages to exceeding these minimum requirements (super-supplementation) and are taking a nutriceutical approach to vitamin supplementation. Vitamins C and E are certainly the two most avidly researched compounds in this respect. In addition to being cofactors for a variety of enzymatic processes, as antioxidants, vitamins C and E are necessary for preventing free-radical oxidation and tissue damage. Diets super-supplemented with vitamin E have improved nonspecific immune function in rainbow trout (Clerton et al. 2001; Puangkaew et al. 2004) and turbot (Pulsford et al. 1995); enhanced resistance to *Edwardsiella tarda* infection in Indian major carp (also known as rohu) *Labeo rohita* (Sahoo and Mukherjee 2002); compensated for stress-induced reduction of lysozyme activity in seabream (Montero et al. 1999); reduced pro-oxidant stress in juvenile turbot, Atlantic halibut *Hippoglossus hippoglossus*, and seabream (Tocher et al. 2002); and reduced susceptibility to fungal infection in sunshine bass (J.T. Trushenski and C.C. Kohler, Southern Illinois University Carbondale, unpublished data). Increased dietary concentration of vitamin C has been linked to improved, more rapid wound-healing in rainbow trout (Wahli et al. 2003); reduced mortality in mrigal *Cirrhinus mrigala* infected with *Aeromonas hydrophila* (Sobhana et al.

2002); improved growth rates of rainbow trout exposed to normal and hypoxic conditions (Dabrowski et al. 2004); and enhanced complement activity in Atlantic salmon (Hardie et al. 1990; Waagbø et al. 1993), rainbow trout (Verlhac et al. 1993), and channel catfish (Li and Lovell 1985). In combination with one another, vitamins E and C have been shown to increase serum complement level, oxidative burst activity, and lymphocyte proliferation in rainbow trout (Wahli et al. 1998); enhance serum complement and lysozyme activities in European sea bass (Bagni et al. 2000); reduce mortality of rainbow trout experimentally infected (Wahli et al. 1998) with viral hemorrhagic septicemia virus, *Yersinia ruckeri* and *Ichthyophthirius multifiliis*; and were important for assuring gamete quality in milkfish *Chanos chanos* and success of their larvae after numerous spawns (Emata et al. 2000). Although the bulk of nutriceutical vitamin research has been on vitamins C and E, others may emerge as useful nutriceutical supplements. Vitamin A precursors, for example, have been shown to improve some humoral and cellular immune defenses in rainbow trout when provided at concentrations above basal requirements (Amar et al. 2004). Exceeding the minimum dietary requirement of halibut for vitamin A resulted in enhanced intestinal enzymatic activity and proliferation and differentiation of brush-border cells, suggesting enhanced digestive and absorptive ability (Moren et al. 2004). These vitamins have individual and synergistic effects on immunity of finfish, and further research into these compounds as nutriceuticals is warranted.

As noted previously, provision of essential fatty acids, especially n-3 and n-6 series HUFA, is critical to the survival and proper growth of finfish. Proper fatty acid ratios are equally fundamental in maintaining immunity and mounting successful defenses against infection. Balfry and Higgs (2001) postulated three ways in which fatty acid composition of the diet could modulate immune function in finfish: by (1) influencing cell membrane integrity and fluidity, (2) altering signal transduction pathways and sensitivity to chemical signals, and (3) producing immunomodulatory eicosanoids. Compounds, membranes, and tissues formed from different fatty acids have different characteristics that are either beneficial or detrimental to the organism. Montero et al. (2003) found that long-term replacement of fish oil with various vegetable oils (lower in n-3 HUFA) in the diet of seabream resulted in reduced humoral and cellular immunity. Supplementation with n-3 HUFA was demonstrated to improve pathogen resistance in rainbow trout (Kiron et al. 1995). Although traditionally n-3 HUFA were deemed the most important fatty acids for finfish immunity, n-6 HUFA are also imperative for regulating immune function in finfish. Bell and Sargent (2003) reviewed arachidonic acid (ARA) as a supplement in finfish feeds, citing the importance of ARA-derived eicosanoids to proper immune function.

Plants have long been sources of therapeutants for human health, and they may prove equally useful in finfish diet formulation. Mistletoe *Viscum album*, nettle *Urtica dioica*, and ginger *Zingiber officianale* extracts in diets of rainbow trout improved their nonspecific immunity, ginger being especially effective in stimulating leukocyte phagocytosis and extracellular burst activity (Dügenci et al. 2003). A mixture of astragalus root *Radix astragali* and Chinese angelica root *Radix angelicae sinensis* stimulated phagocytosis, serum complement and lysozyme activities, and growth rate of Jian carp (Jian and Wu 2004), a variety of the common carp. Similar results were obtained from yellow croaker *Pseudosciaena crocea* fed diets supplemented with the mixture of astragalus and Chinese angelica; these fish also exhibited enhanced resistance to *Vibrio alginolyticus* infection (Jian and Wu 2003). Aloe *Aloe vera*, well known for its therapeutic effects as a home remedy, enhanced respiratory burst activity and survival of olive flounder *Paralichthys olivaceus* experimentally infected with *Edwardsiella tarda* (Kim et al. 2002). Diets supplemented with maca *Lepidium meyenii* tuber significantly improved growth rate, survival, and feed utilization of rainbow trout (Lee et al. 2004).

Nutriceutical-based diets can have positive effects on disease resistance and general livestock vigor and may be a particularly well suited to aquaculture as an alternative to traditional disease management. In aquaculture, contact with livestock is essentially limited to feeding, which is the reason diets have been used as vectors for disease management tools, such as antibiotic drugs. Using treated feeds after a disease outbreak occurs, however, may be ineffective because diseased finfish typically exhibit reduced feed intake rates. Additionally, the aquaculture industry has received criticism for frequent use of antibiotics: in 1994, the American Society of Microbiologists antibiotic resistance task force cited aquaculture-related antibiotic use as one of its biggest concerns (ASM 1994). Although in recent years, antibiotic usage in aquaculture has declined (MacMillan 2003), through proactive use of innovative feedstuffs, culturists may be able to produce more robust finfish, minimize disease outbreaks, and reduce therapeutant usage even further. Moreover, finfish fed nutriceuticals are essentially value-added products. Increased levels of antioxidants can lengthen product shelf life and, in combination with essential fatty acids, increase nutritional value to the consumer. Although organic labeling is still

TABLE 4.—Finfish species of emerging importance in aquaculture.

Taxon	Reference(s)
Pacu *Piaractus mesopotamicus*	Bock and Padovani (2000); Roubach et al. (2003)
Tambaquí *Colossoma macropomum*	Padilla-Perez et al. (2001); Roubach et al. (2003)
Arapaima[a] *Arapaima gigas*	Rebaza et al. (1999); Imbiriba (2001); Alcantara et al. (2004) Pereira-Filho et al. (2004)
Cobia *Rachycentron canadum*	Kaiser and Holt (2004)
Groupers Serranidae	Bell and Gervis (1999); Tucker (2003)
Flounders *Paralichthys* spp.	Bengtson (1999); Rosas et al. (1999); Conklin et al. (2003)
Brill *Colistium nudipinnus*	Tait and Hickman (2001)
Paddlefish *Polyodon spathula*	Mims (2001)
Red drum *Sciaenops ocellatus*	Lutz (1999)
Mangrove red snapper *Lutjanus argentimaculatus*	Ogata et al. (2004)
Rabbitfishes *Siganus* spp.	
Coral trout *Plectropomus leopardus*	
Yellowspotted trevally[b] *Caranx fulvoguttatus*	
Wolffishes *Anarhichas* spp.	Le François et al. (2002)
Arctic char *Salvelinus alpinus*	
Atlantic cod *Gadus morhua*	Le François et al. (2002); Brown et al. (2003)

[a]Also known as pirarucu.
[b]Also known as striped jack.

controversial in aquaculture, use of nutriceutical therapy in lieu of antibiotic drugs can help producers achieve organic production status and further increase the commercial value of their product. In summary, nutriceutical-based nutrition may be an effective means of controlling disease, reducing production costs, and increasing product value and concurrently build a more ethically sound image for aquaculture ventures.

Emerging Species

Although aquaculture is certainly the most diverse sector of agriculture, only a miniscule percentage of extant finfish species are actively cultured. Undoubtedly other species are equally, if not more amenable to intensive production and these species represent a trove of future opportunity for aquaculturists. However, as we have demonstrated, significant investment of time and resources is implicit in diet formulation. Thus, careful consideration must be given to species suitability before resources are allocated to the development of culture practices, including diet formulation.

Numerous emerging species have shown considerable promise for aquaculture (Table 4), and preliminary research findings are encouraging. Most of the new target species exhibit rapid growth rates, are tolerant of high stocking densities and intensive culture practices, and all are highly regarded for their excellent flesh quality. Although culture practices for these species are relatively well established, they are still new in terms of nutritional research. Although the nutritional requirements of these species are currently being established, investigations of alternative protein sources are already underway for cobia (Chou et al. 2004; Zhou et al. 2004), pacu (Macedo-Veigas et al. 2003), red drum (Li et al. 2004), and tambaquí (Padilla-Perez et al. 2001); similar research with others is surely forthcoming.

Conclusion

Many challenges exist in the formulation of cost-effective, nutritionally adequate aquaculture feeds. Tremendous variation in nutritional demands among species slows progress in formulating diets to meet minimum nutrient requirements. Declining availability and suitability of traditional feedstuffs further complicates the process, forcing finfish nutritionists to use alternative sources of protein, lipid, etc., that present challenges of their own. Today, finfish nutritionists must address nutritional, economic, and environmental concerns by using a restricted repertoire of resources and methods. The challenges to modern finfish nutrition are undoubtedly great, and approaches must be reevaluated and restructured to meet them. Although traditional nutrition has an undeniable role in developing sustainable aquaculture practices, investigation and application of innovative strategies such as those discussed here will ensure the continued relevance of aquaculture to the global community and, ultimately, lead to greater opportunities in the future.

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