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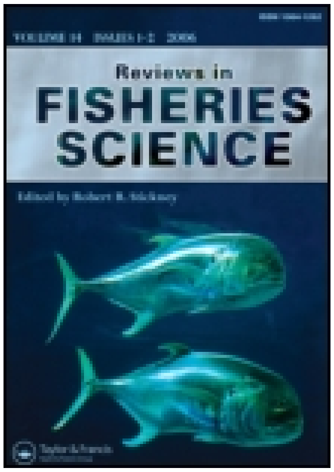

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From Fishing to the Sustainable Farming of Carnivorous Marine Finfish

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From Fishing to the Sustainable Farming of Carnivorous Marine Finfish

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Carnivorous marine finfish aquaculture has been the subject of intense criticism. Because the process consumes more fish biomass in the form of fishmeal and fish oil than it produces, critics argue carnivorous marine finfish aquaculture causes a net loss of living marine resources and is unsustainable given the continued expansion of the industry. While this "fish-in fish-out" critique is factually correct, it fails to capture all the costs and benefits of carnivorous marine finfish aquaculture. Accepted theories on energy and matter flow between trophic levels indicate that carnivorous marine finfish aquaculture appropriates less ocean primary production than commercial fishing and, as we show, it is generally less demanding of agricultural resources and inputs than terrestrial animal husbandry. The basic fish-in fish-out critique also neglects to consider the fishmeal industry with sufficient granularity. The amount of small pelagic fish harvested for reduction has remained stable despite increased carnivorous marine finfish production, largely due to research into alternative ingredients that has decreased fishmeal and fish oil inclusion rates and caused aggregate fishmeal and fish oil consumption by the aquaculture industry to plateau in recent years. Consideration of all the costs and benefits of carnivorous marine finfish aquaculture suggests that the industry is progressing toward sustainability.

Keywords aquaculture, fishmeal, fish oil, sustainability

INTRODUCTION

Aquaculture is set to become the world's dominant system of aquatic organism production. In 2006, aquaculturists produced 51.7 million metric tons (Mt) of aquatic organisms for human consumption, nearly half of the world's total supply (FAO, 2009). If current trends continue, fish farms will produce more than 65% of the world's total supply of aquatic organisms by 2030 (FAO, 2002). Approximately one-third of this production is focused on organisms that utilize fishmeal (FM) and fish oil (FO) in their diets, including carnivorous marine finfish (CMF) (Tacon and Metian, 2009).

CMF aquaculture is a controversial practice with debate focused largely on the use of FM and FO in compounded aquafeeds and the use of whole fish as feed items. Critics point out that several units of wild fish biomass must be consumed as feed in order to produce a single unit of farmed CMF, a pattern of resource consumption they consider unsustainable given the forecasted expansion of the industry (Pauly et al., 2003; Volpe, 2005; Clover, 2006; Stier, 2007; Allsopp et al., 2008; Pauly, 2009). Industry representatives counter that levels of FM and FO in compounded aquafeeds have dropped significantly over the last decade and that aggregate global consumption of FM and FO by the aquaculture industry has leveled off (Jackson, 2010).

Recently published data suggests that both sides of the debate are essentially correct. As the industry has expanded, global "fish-in fish-out" (FIFO) ratios for CMF aquaculture have remained above unity (Tacon and Metian, 2009), meaning that the industry is still a net consumer of marine biomass and will eventually become unsustainable if improvements are not made. On the other hand, sustained research into alternative ingredients is lowering rates of FM and FO inclusion in compounded

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aquafeeds (Naylor et al., 2009) and the CMF aquaculture industry's use of FM and FO has plateaued in recent years while the global FIFO ratio for CMF producers is approaching unity (Tacon and Metian, 2008, 2009).

The FIFO metric, however, is a relatively narrow analytic tool and this narrowness is one of the reasons the debate continues to persist in its current form. More complex techniques are being developed for assessing the environmental impacts of food production including Life Cycle Analysis, Ecological Footprinting, Energy Flow Analysis, Virtual Water Flow Analysis, and Primary Productivity Required, all of which allow for a more sophisticated approach to the environmental questions surrounding CMF aquaculture.

In this article, we draw inspiration from this growing body of research on food production to move beyond the FIFO debate and examine some of the environmental implications of CMF aquaculture from less frequently considered perspectives. We begin by considering the imperatives that have given rise to the modern CMF aquaculture industry and that will likely ensure its continued presence in the world economy. Next, we analyze the merits of CMF production relative to both fishing and terrestrial livestock production. We move on to examine the prospects for creating a more sustainable CMF aquaculture industry and then conclude the article by arguing that a more complete analysis of the costs and benefits of CMF aquaculture suggests that the industry is becoming increasingly sustainable.

THE NECCESSITY OF CMF AQUACULTURE

For much of humanity, the last century has been a time of plenty. Fueled by improved health care and nutrition, human populations have more than quadrupled since 1900, from 1.6 billion at the turn of the last century to almost 6.8 billion today, and many demographers believe that the world's population will rise to almost 9 billion by the year 2050 (United Nations, 2009).

The story is different for world fisheries. Driven by the increasing demand for seafood that has accompanied the boom in human reproductive success, many species of commercially important fish have been harvested to their biological limit (Pauly et al., 2002). Since the mid-1990s, catches from traditional capture fisheries have reached what seems to be a maximum harvest level of 85 to 95 Mt annually, less than 60 Mt of which is used for human consumption (FAO, 2009). Yet today, humans consume approximately 110 Mt of seafood a year, or 16.7 kg per person per year, leaving more than 50 Mt a year to be produced by aquaculturists (FAO, 2009), and the FAO has predicted that as much as 160 Mt of seafood will be needed to meet demand by 2030 (FAO, 2002).

There are two principle alternatives to CMF aquaculture for meeting this demand: commercial fishing and the aquaculture of herbivorous, omnivorous, and/or filter feeding organisms. While these modes of production will undoubtedly supply a great deal of seafood to world markets in the future, neither are likely to be able to meet forecasted demand for seafood in the absence of a vibrant and growing CMF sector, particularly within developed country markets.

Wild-Caught Fish

The first alternative to farmed CMF is wild caught CMF, which is a problematic option. Approximately 19.3 Mt of the world's total aquaculture production (37%) in 2006 was of the sort that depended on small pelagic fisheries through the use of FM- and FO-based compound aquafeeds or the direct feeding of low value "trash" fish (Tacon and Metian, 2009). While it is possible that more effective conservation schemes could increase the output of commercial fisheries enough to replace this sort of aquaculture, a number of factors suggest that these schemes are not likely to emerge anytime in the near future.

To begin with, it isn't clear how many more large wild fish are left to be managed. Myers and Worm (2003) estimated that as many as 90% of all large predatory fish have been lost due to industrialized fishing. At least 51 species of marine fish are known to be functionally extinct over some or all of their former geographical range largely due to commercial fishing (Dulvy et al., 2003), and more than 130 distinct populations of fish have lost more than 80% of their historical biomass (Hutchings and Reynolds, 2004). Given present rates of extraction, Worm et al. (2006) have predicted a complete collapse of all global fisheries by 2048 and it isn't certain that these fish can return. Exhausted stocks tend to have difficulty recovering in the first 15 years after a collapse (Hutchings and Reynolds, 2004), and there is a real possibility that many fisheries have experienced durable "regime shifts" within their environment that will continue to delay their recovery (Bakun and Weeks, 2006).

Where there are fish to manage, the process is difficult and fails as often as not (Hilborn et al., 2004; Daw and Gray, 2005; Rosenberg et al., 2006). The general decline of fisheries in the north Atlantic during the latter half of the 20th century, for example, occurred despite the creation of a host of local, national, and international regulatory agencies intended to protect fish stocks (Pauly and Maclean, 2003). Even where proactive steps to prevent overfishing are taken, enforcing sustainable harvest levels is a challenge. The amount of illegal, unregulated, and unreported (IUU) fish landed worldwide each year has been estimated to be between 10 and 26 Mt a year (Agnew et al., 2009), but no one is certain. Whatever the precise amount, IUU fishing has had devastating effects on a number of supposedly protected fish stocks, including the Bluefin tuna (*Thunnus spp*) (e.g., MacKenzie et al., 2009) and Patagonian toothfish (*Dissostichus eleginoides*) (popularly known as the Chilean seabass) (Lack, 2008) and continues to thwart efforts to rebuild these stocks.

Government subsidy policies are also likely to continue to hinder efforts to end overfishing. Globally, the approximately $85 billion commercial fishing industry runs an annual deficit of \$5 billion (World Bank and FAO, 2008) and takes in as much as \$32 billion per year in subsidies (Khan et al., 2006). Assistance takes many forms, including equity infusions, grants, tax exemptions, loans, loan guarantees, vessel buybacks, price support, insurance underwriting, and other direct and indirect forms of taxpayer-funded financial aid (Schrank, 2003). The artificial inflation of profits that results from these policies discourages conservation because it encourages increased effort regardless of the condition of the fishery and masks the economic signals that indicate it is no longer profitable to fish (Cox, 2004).

"Vegetarian" Fish

The other alternative to CMF aquaculture is to farm herbivorous and omnivorous species, such as carp, tilapia, and filter feeding shellfish, thus avoiding all the problems that arise from FM and FO use. This is an appealing proposal, but this type of aquaculture probably won't supplant CMF production. First, increased production of herbivorous and omnivorous species is unlikely to affect existing demand for farmed CMF. The literature on market interactions between seafood products indicates that farmed CMF do not compete with seafood products generally but only with those species that are very close substitutes (Asche et al., 2001, 2005; Asche and Tveteras, 2005). Thus, for example, farmed salmon compete with wild caught salmon, but not with carp or tilapia. Secondly, the idea of focusing on herbivorous and omnivorous species ignores the potential health benefits of eating CMF (Mozaffarian et al., 2005; Mozaffarian and Rimm, 2006; Lee et al., 2008). CMF, including farmed CMF, generally contains high levels of the n-3 fatty acids thought to promote cardiac health (e.g., Steffens, 1997; Osman et al., 2001). This unique attribute is likely to ensure continued demand for CMF regardless of the availability of alternative products. Finally, increased production of omnivorous and herbivorous fish would come at a considerable cost in land and freshwater resources. Globally, the dominant types of omnivorous and herbivorous fish produced by aquaculturists are freshwater *Cyprinids* (carps). Nearly 22.5 Mt of *Cyprinids* were produced in 2006 (FAO, 2008), mostly in freshwater ponds in Asia (Michielsens et al., 2002; Dey et al., 2005). Yields in these ponds range from 1,000 to more than 15,000 kg ha^{-1} depending on the type of farming system used (Jena et al., 2002). Even assuming that all future carp farms will rely on intensive systems with yields in the vicinity of 15,000 kg ha^{-1}, doubling *Cyprinid* production to 45 Mt would require constructing or finding 1.5×10^6 ha of new fishponds. Furthermore, assuming that each of these ponds would be 1.5 m in depth and would be drained and refilled only once a year, these new fishponds would consume approximately 22.5×10^9 m^3 of freshwater annually. This level of production would not be sufficient to meet even half of the projected 50 Mt increase in global demand for seafood expected to occur by the year 2030 (FAO, 2002). Given the considerable strain global supplies of arable land and freshwater are already under (see below), these sort of resource requirements may prove prohibitively high for the omnivorous and herbivorous finfish aquaculture sector.

THE ENVIRONMENTAL MERITS OF CMF AQUACULTURE

The apparent permanence of CMF aquaculture is potentially troubling because a straightforward FIFO analysis of CMF aquaculture reveals that these farming operations usually consume more fish biomass in the form of FM and FO or whole fish than they produce. Despite this, CMF aquaculture has a number of efficiency advantages relative to other forms of animal protein production that offset its current dependence on FM and FO.

Living Marine Resources

Current theories on trophic energy and matter flows suggest that CMF aquaculture is less demanding of the ocean's living marine resources than is commercial fishing. Additionally, a group of unique and largely unquantifiable externalities associated with fishing but generally avoided by aquaculture help CMF farmers realize living marine resource savings that cannot be captured by analyzing patterns of FM and FO use.

Fish-In Fish-Out

It is generally accepted that energy and matter move between trophic levels with a transfer efficiency of 10% (Pauly and Christensen, 1995). Thus, a hypothetical high-level predator fish feeding on a species one trophic level lower would require approximately 10 units of prey in order to gain 1 unit of biomass resulting in a FIFO ratio of 10:1. Farmed marine fish, on the other hand, consume diets composed of FM and FO supplemented with grains, oilseeds, and other ingredients. This results in the consumption of less forage fish.

Consider a hypothetical farmed salmon fed an industry standard feed with 24% FM and 16% FO inclusion. If this fish is harvested at a market weight of 4 kg and has a feed conversion ratio (FCR) (FCR = ratio of feed consumption to biomass gain) of 1.25 (well within industry norms), it will have consumed 1.2 kg of FM and 0.8 kg of FO during its lifetime. Because the average FM yield of small pelagic fish (22.5%) is much larger than that of FO (5%), FO consumption is the determining variable for calculating FIFO (Tacon and Metian, 2008). Based solely on the 5% yield for FO, production of this hypothetical farmed fish required harvesting 16 kg of small pelagic biomass giving it a FIFO ratio of 4:1, which is 60% lower than wild fish. This example is broadly representative of the efficiencies achieved by CMF aquaculture in general. Many other species of farmed fish convert feed less efficiently but compensate by using feeds with lower average FM and FO inclusion rates. The mean inclusion rates for all farmed marine organisms using FM and FO in their diets, for example, is 15 and 8%, respectively (Tacon and Metian, 2009).

Primary Productivity Required (PPR)

FIFO, however, is a relatively crude measure of ecological efficiency. In the wild, many high-trophic level predator fish (such as salmon) do not feed entirely or even primarily on fish (e.g., Jacobsen and Hansen, 2001). They also consume a great deal of low-trophic level organisms, such as crustaceans, thus, lowering their FIFO ratio and complicating efficiency comparisons. Additionally, feed conversion data from commercial aquaculture operations tends to indicate that the 10:1 FIFO ratio is a simplistic assumption even for purely piscivorous fish. Some species, such as Atlantic Bluefin Tuna (*Thunnus thynuss*) (Ottolenghi, 2008) and Yellowfin tuna (*Thunnus albacares*) (Wexler et al., 2003) kept in captivity and fed an entirely fish-based diet are reported to exhibit FIFO ratios as high as 34:1. Other species kept by the authors, including cobia (*Rachycentron canadum*), greasy grouper (*Epinephelus tauvina*), and barramundi (*Lates calcarifer*) have exhibited FIFO ratios of 6:1, 7:1, and 4:1, respectively, while fed entirely fish-based diets.

To capture this type of variability more accurately, Pauly and Christensen (1995) and Talberth et al. (2006) have developed the "Primary Productivity Required" (PPR) metric. The PPR metric quantifies the amount of oceanic primary productivity (photosynthesis and upwelled nutrients) needed to support the food web that ultimately produces a fish. Higher order predators (tuna, cobia, salmon, etc.) require hundreds or even thousands of units of primary productivity while lower level forage fish often require an order of magnitude less (Pauly and Christensen, 1995; Talberth et al., 2006).

Even using the broader PPR metric, CMF aquaculture appears to be a more efficient consumer of living marine resources than fishing. Consider again the hypothetical farmed fish from the previous example that was produced with a FIFO ratio of 4:1. According to Talberth et al. (2006), the menhaden that were processed to make the FO that was fed to that fish had a PPR of 17.8. Because four units of menhaden were needed to produce one unit of salmon, the PPR for that farmed fish is 71.2 (or 4 × 17.8). Different species of commercially targeted wild fish (salmon, snapper, tuna, etc.), on the other hand, are estimated by Talberth et al. (2006) to have PPRs ranging from 540 to 1,738. Different feeds made from higher PPR fish (herring, for example, are estimated to have a PPR of 141) or cultured species with a higher FCR could make these comparisons less favorable, but usually not so much that catching wild fish becomes more efficient than farming them.

Uncounted Costs

FIFO and PPR analyses, however, are both incomplete because they ignore bait use, bycatch, and habitat destruction, forms of living marine resource consumption unique to commercial fishing. While these externalities are difficult to quantify, there is little doubt that they impute considerable uncounted inefficiencies to the industry and should be considered by anyone attempting to compare the relative demands placed on living marine resources by aquaculture and fishing.

Bait Use. Tacon and Metian (2009) imply that as much as 2.2 Mt of small pelagics and trash fish are used each year as bait by the commercial fishing industry. While there is little reliable data on global bait use, assessments of individual fisheries suggest that this estimate is reasonable. FitzGerald (2004) has estimated that longline fishing vessels require approximately 8 kg of bait to produce a single 30 kg tuna based on a set of generalized assumptions for mean weight per fish, total reported catch, average weight per baitfish, and catch per unit effort. Applying this bait-to-catch ratio to global landings generates an estimate of approximately 146,000 tons of bait used annually by tuna longline fleets. Additionally, trap fisheries for crabs and lobsters use large amounts of bait (O'Malley, 2004). In Maine, for example, Elliot (2006) concluded that 50,000 to 60,000 tons of herring are used each year to produce 35,000 tons of lobster.

Bycatch. Bycatch consumes a greater amount of living resources than does bait use. Alverson et al. (1994) estimated that the world's fishing fleets discarded 27.0 Mt of bycatch every year. More recently, Kelleher (2005) derived a lower estimate of 7.3 Mt of annual global discards but this reduction appears to be due to higher utilization of previously discarded species and targeting of formerly undesirable fish rather than to increased efficiency (Zeller and Pauly, 2005). Bycatch is also a significant problem in the U.S., where more than 22% of the catch is thrown back (Harrington et al., 2005).

Non-fish marine animals are also taken as bycatch. It has been estimated that 653,365 marine mammals (Read et al., 2006), 250,000 loggerhead and leatherback turtles (Lewison et al., 2004), and hundreds of thousands of seabirds (Gilman, 2001; Gilman et al., 2005) are involved in interactions with the commercial fishing fleet every year, many of whom are killed or injured. These populations are especially vulnerable to this sort of pressure because they tend to have a K-selected life strategy characterized by long lifespans, low reproductive rates, and a late age of sexual maturity (Cook, 2001).

Habitat Destruction. Less obviously, fishing is destructive of habitat. Bottom trawlers and dredgers use gears designed to make direct contact with the seafloor, digging deep into the sediment. In addition to causing direct mortality from physical contact, bottom trawling and dredging removes or damages essential habitat (rocks, pebbles, etc.) and habitat forming organisms (such as macroalgae, corals, and sponges) that provide refuge for many commercially valuable fish species (Thrush et al., 1998; Watling and Norse, 1998; Turner et al., 1999; Thrush and Dayton, 2002). Trawling and dredging can also lead to the re-suspension of sediments, which smothers suspension-feeding organisms and alters nutrient supply from the seafloor (Thrush and Dayton, 2002). Benthic ecosystems can take years to recover from fishing-induced disturbances if they are allowed to recover at all. It is estimated that trawl and dredge gear is dragged across an area equivalent to the world's continental shelf every two years, 150 times more submerged land area than the area of terrestrial forest lost each year (Watling and Norse, 1998). More heavily fished parts of the ocean, such as the north Atlantic, are under even greater pressure, being covered by trawls several times a year (Thrush and Dayton, 2002).

The Importance of Efficient Use of Living Marine Resources

The superior living marine resource performance of aquaculture relative to fishing does not, in and of itself, indicate that CMF aquaculture is sustainable from a living marine resource perspective. If a fishery for FM- and FO-grade fish is managed poorly, it will eventually collapse regardless of the efficiency of the downstream use of the resulting FM and FO. If, on the other hand, sustainably produced FM and FO is used, both FIFO and PPR analysis, as well as a qualitative assessment of the unique externalities associated with fishing indicate clearly that aquaculture can be a more efficient use of living marine resources than commercial fishing. Given the already high demands placed on ocean ecosystems by anthropogenic activities (Talberth et al., 2006), any efficiency gains in the world's seafood production systems are likely to be important in the future.

Agricultural Resources and Inputs

CMF aquaculture also compares favorably to terrestrial animal protein production as a user of agricultural resources and inputs. Feeding both terrestrial livestock and marine fish requires the production of grain (e.g., corn) and oilseed (e.g., soybeans). In the case of terrestrial livestock, the animals' diets are largely based on the direct feeding of these products (e.g., Kuhl et al., 2002; Tilman et al., 2002). Marine fish also consume a great deal of agricultural commodities because processed forms of grain and oilseeds (wheat flour, peanut meal, etc.) are key ingredients (along with FM and FO) in compounded aquafeeds (e.g., Mundheim et al., 2004; Zhou et al., 2004).

Grain and oilseed consumption levels, however, are not equivalent between the different species of fed animals. Not only are grain- and oilseed-derived products a smaller proportion of their feeds, farmed marine fish have physiological advantages related to their lower basal metabolic rates that result in generally lower consumption of macronutrients (carbohydrates, fats, and proteins) per unit of weight gain than their terrestrial counterparts (Naylor et al., 2009). Farmed Atlantic salmon (*Salmo salar*), for example, have an industry-wide average FCR of 1.3:1 (Tacon and Metian, 2008), while many other species of commercially cultured fish, such as gilthead sea bream (*Sparus aurata*) (Company et al., 1999), yellowtail flounder (*Limanda ferruginea*) (Dwyer et al., 2002), cobia (*Rachycentron canadum*) (Denlinger, 2007), and cod (*Gadus morhua*) (Rosenlund et al., 2004), are capable of achieving FCRs of less than 1.5:1. Chickens, on the other hand, have an industry-wide FCR of 1.9:1 (Pelletier, 2008), while swine producers can achieve FCRs of 2.8:1 (e.g., DeRouchey et al., 2007), and cattle producers have FCRs ranging from 6 to 9:1 (Smil, 2002), respectively, although the ratio can be higher than 10:1 depending on the type of feed used (e.g., Kuhl et al., 2002). The differences in feed compositions as well as the lower FCRs exhibited in aquaculture operations imply that less grain and oilseeds are required to produce a unit of fish than are required to produce a unit of chicken, swine, or cattle even after grain processing yields are accounted for. This, in turn, implies that aquaculture consumes less of the key agricultural resources and inputs used to produce those grains and oilseeds, especially arable land, irrigation water, nitrogen, and agricultural chemicals.

To demonstrate this, we analyzed commonly accepted livestock diet formulations, FCRs, and meat yields to calculate the amount of feed needed to produce a unit of beef, pork, chicken, and salmon. We then used USDA statistics to determine the amount of unprocessed grain and oilseeds, land, irrigation water, nitrogen, and agricultural chemicals needed to produce that feed, and compared them in order to gauge the intensity of the resource use associated with the production of different types of animals (Figure 1).

These numbers do not demonstrate that CMF aquaculture is environmentally superior to other types of animal protein production. They simply demonstrate that CMF aquaculture is potentially less demanding of a particular basket of agricultural resources and inputs than are other types of animal protein production. The studies that have attempted to quantify the sum of the environmental impacts of CMF aquaculture (especially salmon aquaculture) have reached decidedly mixed results (e.g., Tydemers et al., 2007; Pelletier et al., 2009). The environmental performance of CMF production comes out ahead of terrestrial livestock production in some areas and is scored less well in others. These studies, however, are not focused on specific levels of consumption of a particular resource or input. Instead these studies are concerned with quantifying the aggregate inputs (such as energy or net primary productivity) and impacts (such as greenhouse, acidifying, and eutrophying emissions) of CMF aquaculture.

Still, because resources do not exist in equal abundance, the degree to which they are consumed by different systems of food production is an important consideration. While small pelagic fish are an important global resource, arable land and fresh water are arguably more important to the world's food production system and are becoming increasingly scarce in many of the world's major food producing regions (Tilman et al., 2002). This scarcity is exacerbated by increased production of terrestrial livestock (Smil, 2002; Naylor et al., 2005; Steinfeld et al., 2006; Bourne, 2009). The land shortage has become serious enough that countries, such as China and India, have begun to acquire millions of acres of farmland in Africa (Anonymous, 2009) and water shortages brought on, in part, by the doubling of irrigated agriculture acreage since the 1960s (Howell, 2001; Bourne, 2009) have led some to argue that the earth may lack the fresh water resources needed to feed future populations (Postel, 1998; Brown, 2009).

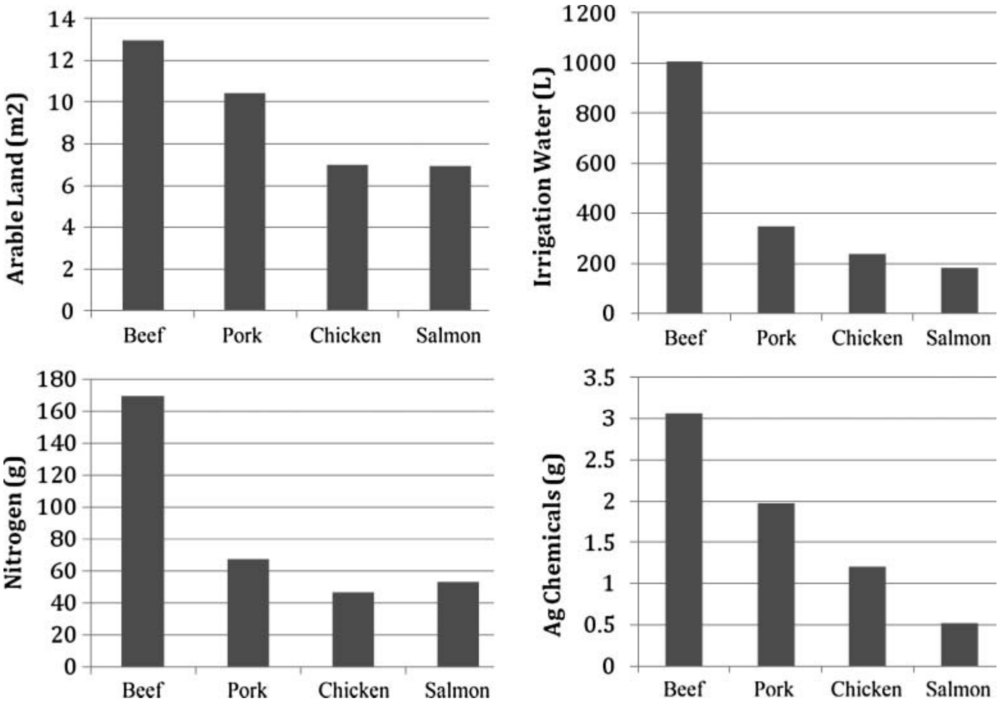

Figure 1 Clockwise from upper left: estimated amount of arable land (m^2), irrigation water (L), nitrogen (g), and agricultural chemicals (g) needed to grow the feeds used for the production of a kilogram of beef, pork, chicken, and salmon. Beef cattle feed requirements were drawn from Kuhl et al. (2002), swine feed requirements were drawn from Walker and Myer (1989), chicken feed requirements were drawn from Pelletier (2008), and the salmon diet requirements were drawn from Mundheim et al. (2004). All diets chosen were broadly representative of industry standards. Meat yields for beef cattle and swine were drawn from Wulf (1999). Meat yields for chickens were drawn from Brickett et al. (2007). Salmon fillet yields were drawn from Einen et al. (1998). Processing yields for the agricultural commodities were drawn from a variety of industry and trade sources. Statistics used for calculating the amount of arable land, irrigation water, nitrogenous fertilizer, and agricultural chemicals needed for producing those feeds were drawn from NASS (2004, 2005, 2008).

Further, the heavy use of fertilizer in agriculture has led to increased losses of nitrogen and phosphorus to the environment via runoff, leaching, and volatilization and has resulted in harmful nutrient over-enrichment of some surface, ground, and coastal waters, developments that threaten both marine and terrestrial ecosystems (Vitousek et al., 1997; Carpenter et al., 1998; Smil, 2001; Tilman et al., 2002; Rabalais et al., 2002; Alexander et al., 2008; Diaz and Rosenberg, 2008). Similarly, the heavy use of agricultural chemicals has given rise to worries about the development of highly resistant crop pathogens (Tilman et al., 2002).

While CMF aquaculture does not solve any of these problems it does allow for increased animal protein production at generally lower land, water, nitrogen, and agricultural chemical costs than can be achieved through terrestrial animal husbandry. This is a virtue that will become increasingly important as world populations and food production needs continue to expand.

THE PROSPECTS FOR SUSTAINABLE CMF AQUACULTURE

The relatively superior efficiencies argued for in the previous section are relevant only so long as the CMF aquaculture industry does not demand more FM and FO than the world's fisheries can sustainably produce. The unique nature of small pelagic fisheries, increasing efficiency of FM and FO use by fish farmers, and the success of ongoing research into alternative feed ingredients suggest that this outcome is possible.

Small Pelagic Fisheries

At the present, the world's small pelagic fisheries are fully (and in some cases, over) exploited (Alder et al., 2008). Nonetheless, large scale fisheries for small pelagics have been operating for more than thirty years, and many, such as Peruvian Anchovy (Gutierrez et al., 2007; Swartzman et al., 2008) and Gulf of Mexico Menhaden (Vaughan et al., 2007) have held up reasonably well. Many of these fisheries suffer from overcapacity but they are not generally unmanaged. The Peruvian anchovy fleet, for example, is overcapitalized by as much as 72%, but the fishery is subject to a total allowable catch that usually limits the fishing season to less than 50 days (Freon et al., 2008) and an individual vessel quota system was recently introduced in an attempt to reduce capacity (Aranda, 2009). While there have been collapses, such as in southern Africa's Benguela current fisheries (Bakun and Weeks, 2006), there have also been recoveries, such as the California sardine fishery (Hill et al., 2005). The reasons for these successes are not entirely clear, but small pelagic fisheries share a few unique characteristics that may help explain their continued resilience.

Most importantly, the life history traits of small pelagics probably make them more suitable for commercial harvest than other types of fish. Most small pelagics fit Pianka's (1970) classic definition of an r-selected species. These fish are modestly sized, have short life spans, grow fast, reach maturity early, and reproduce quickly (e.g., Butler et al., 1993; Lisovenko and Andrianov, 1996; Silva et al., 2006; Vaughan et al., 2007; Cubillos and Claramunt, 2009), all of which are characteristics believed to impart resilience to fish stocks subjected to extractive pressure (Jennings et al., 1998; Fromentin and Fonteneau, 2001; Denney et al., 2002; Dulvy et al., 2003; Hutchings and Reynolds, 2004; Reynolds et al., 2005).

In addition, stocks of small pelagic fish contain large amounts of biomass, making it possible to sustain higher levels of extraction than can be sustained by other fisheries. The biomass of small pelagic fish in South America's Humboldt current ecosystem, for example, is measured in the millions or tens of millions of tons (Bertrand et al., 2004; Gutierrez et al., 2007) and other stocks of small pelagic fish, while less impressive than those in the Humboldt, still contain hundreds of thousands to millions of tons of biomass (e.g., Vaughan et al., 2007; Pajaro et al., 2008). Current estimates of the spawning stock biomass of Atlantic Bluefin Tuna (*Thunnus thynuss*), in contrast, are approximately 20,000 tons (ICCAT, 2008).

Finally, environmental variability seems to affect small pelagic stocks at least as much as directed fishing pressure (Jacobson et al., 2001; Rodriguez-Sanchez et al., 2002; Chavez et al., 2003; Bertrand et al., 2004; Sandweiss et al., 2004). In the Peruvian fisheries there is even some evidence that environmental variability in the form of El-Nino events positively impacts fisheries by periodically "resetting" the ecosystem to a regime more favorable for anchovies and sardines (Bakun and Broad, 2003).

Trends in FM and FO Use

Despite the apparent resilience of small pelagic fisheries, overall use of FM and FO by fish farmers has increased greatly in recent years leading to concerns that the growth of the aquaculture industry could outstrip the productive capacity of nature in the very near future (Naylor et al., 1998, 2000; Naylor and Burke, 2005). In 1994, global consumption of FM and FO for compounded aquafeeds was estimated to be 0.96 and 0.23 Mt, respectively (Tacon, 2005). By 2004, FM use had risen to at least 3.0 Mt and probably as much as 4.3 Mt, while FO use had risen to approximately 0.85 Mt (Jackson, 2006, 2007; Tacon and Metian, 2008).

Nonetheless, the situation is not as dire as the statistics would indicate, largely because the growth of the aquaculture industry has not been predicated upon increased exploitation of reduction fisheries. The amount of fish harvested annually for reduction to FM and FO has remained in a stable range between 20 and 30 Mt for the last 35 years and has yielded a relatively consistent 4.57–7.48 Mt of FM and 0.85–1.67 Mt of FO (Tacon and Metian, 2009), despite steady annual growth of 8.7% in fish farm production (FAO, 2009). In fact, there is no statistical correlation between the growth of the aquaculture industry and the amount of fish harvested for reduction each year (Asche and Tveteras, 2004).

Instead, the increased consumption of FM and FO by the aquaculture industry has come about through market forces. Growing demand from the aquaculture sector for these commodities has not expanded the overall production of FM and FO but has priced other users out of the market or forced them to reduce consumption. As recently as 1988, the poultry industry was the dominant user of the world's FM, consuming about 60% of the available supply, followed by swine producers (20%), aquaculturists (10%), ruminant producers (3%), and others (7%). Today the situation is reversed. Aquaculture feeds consume about 57% of the world's FM supply, followed by swine feeds (21%), poultry feeds (13%), and others (6%) (Tacon and Metian, 2009).

More importantly, it appears that total FM and FO use by the aquaculture industry has begun to plateau. Since 1998, the use of FM in compounded aquafeeds has been significantly lower than predicted (Figure 2) and total consumption of FM and FO has been flat to decreasing in absolute terms since 2005, a trend that is expected to continue for the foreseeable future (Tacon and Metian, 2008). Today, the global fish-in fish-out ratio for externally fed marine finfish is approaching 1:1 (Tacon and Metian, 2009).

Developments in Alternative Feed Ingredients

This reduction in FM and FO use has come about largely because the marine aquaculture community is keenly aware of its current dependence on reduction fisheries and has invested an enormous amount of time and resources investigating substitutes for FM and FO in compounded aquafeeds. Because CMF do not have a requirement for FM and FO per se, but for the suite of essential amino acids and nutrients contained within FM and FO, it has proven possible to substitute a wide variety of alternative feed ingredients into compounded aquafeeds to deliver the needed nutrients to cultured species.

Today, alternative feed ingredients and formulations have been investigated for nearly every species of commercially important fish including, for example, Atlantic salmon (*Salmo salar*) (Olli et al., 1995; Bjerkeng et al., 1997; Bell et al., 2001, 2003, 2004; Opstvedt et al., 2003; Mundheim et al., 2004), red drum (*Sciaenops ocellatus*) (Kureshy et al., 2000), cobia (*Rachycentron canadum*) (Zhou et al., 2004; Lunger et al., 2006; Fraser and Davies, 2009), turbot (*Psetta maxima*) (Regost et al., 2003a; Fournier et al., 2004), European sea bass (*Dicentrarchus labrax*) (Gouveia and Davies, 2000; Tibaldi et al., 2006), gilthead sea bream (*Sparus aurata*) (Izquierdo et al., 2005; Venou et al., 2006), Japanese flounder (*Paralichthys olivaceus*) (Kikuchi, 1999), yellowtail (*Seriola quinqueradiata*) (Maita et al., 2006), and rainbow trout (*Oncorhynchus mykiss*) (Kaushik et al., 1995).

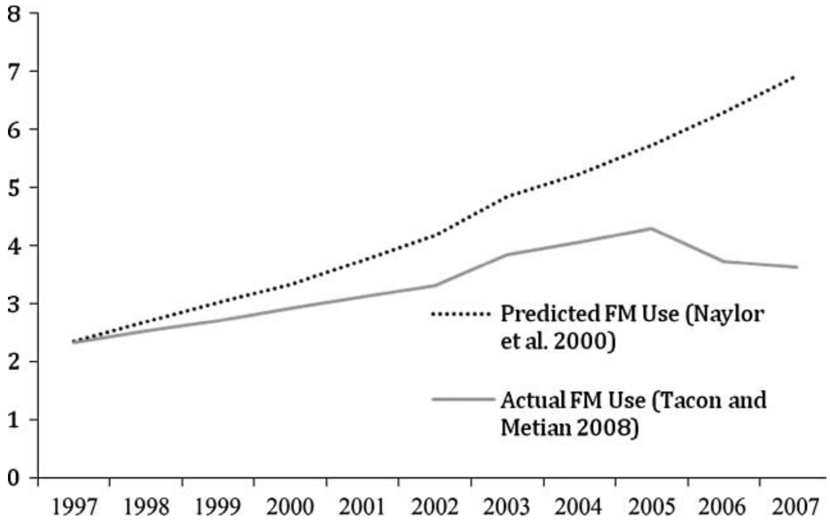

Figure 2 Fishmeal use: past projections and current trends (adapted from Kristofersson and Anderson, 2006).

The result of all this research has been a significant reduction in FM and FO inclusion rates. Between 1995 and 2007, FM and FO inclusion rates dropped across almost all sectors of the industry. Salmon feed FM and FO inclusion, for example, dropped from 45 to 24% and from 25 to 16%, respectively, while marine fish feed FM and FO inclusion rates dropped from 50 to 30% and from 15 to 7%, respectively (Tacon and Metian, 2008).

The downward trend is likely to continue. A growing body of evidence indicates that it is possible to produce CMF with feeds that have extremely low inclusion rates or are entirely devoid of FM and FO. Espe et al. (2006) was able to grow salmon using feeds based on plant protein meal, solubilized fish protein (5%), and squid hydrolysate (3%), although growth was reduced by approximately 15% relative to control diets. In a follow-up trial, Espe et al. (2007) added 5% FM and lysine supplements to the feeds utilized in the 2006 trial and achieved growth only 3% lower than control fish fed a conventional FM-based diet. Most recently, Kousoulaki et al. (2009) showed that salmon fed a diet with 10% FM inclusion and stickwater supplementation grew as well as salmon fed a conventional diet. Similarly promising studies have been performed on rainbow trout. Kaushik et al. (1995) replaced 100% of the FM in trout feeds with soy protein concentrate (SPC) with no effect on growth. Cheng et al. (2003) also managed to grow rainbow trout using a low (16%) FM feed supplemented with lysine without statistically significant reductions in growth, although there was a trend to slightly higher growth in the fish fed conventional FM-based feeds. Richard et al. (2006) showed that FO could be entirely replaced in trout feeds by a blend of vegetable oils with no impact on growth, nutrient utilization, or flesh quality. Finally, Salze et al. (2010) grew cobia on a diet with no marine proteins or lipids. In this study, FM was replaced by SPC and the FO was replaced by a blend of soil oil and docosahexaenoic acid-rich algal meal. The fish in this trial grew as well as control fish fed a conventional FM- and FO-based diet. While producing fish using non-marine lipid sources tends to reduce the level of omega-3 fatty acids in fish flesh, it has been proven possible to raise these levels by switching to feeds with higher levels of FO near the end of the culture cycle (e.g., Bell et al., 2004; Regost et al., 2003b; Izquierdo et al., 2005; Turchini et al., 2009). Additionally, while plant-derived feed components tend to contain anti-nutritional factors that reduce their value to CMF, researchers are learning to neutralize these compounds with specialized processing techniques (Trushenski et al., 2006) or through the addition of enzyme supplements (Hardy, 2000). This trend, coupled with rising prices due to increased demand for small pelagic fish from other sectors (Tacon and Metian, 2009) and increased social pressure for improved sustainability (Marine Aquaculture Task Force, 2007), will probably continue to drive down inclusion levels in the future.

It should also be noted that the amount of seafood processing waste and bycatch produced by the commercial fishing industry annually is probably equal to the amount of small pelagic fish landed for reduction to FM and FO and aquaculture researchers are working to develop these resources as an alternative source of FM and FO (e.g., Hardy, 2000; Li et al., 2004; Naylor et al., 2009). Concerns about the perverse incentives created by the use of bycatch will probably limit its use going forward but processing waste shows great promise. Industry sources estimate that 25% of the world's supply of FM and FO comes from processing waste (Jackson, 2010) and in the EU-15 the percentage is as high as 33% (Tacon and Metian, 2009). The technical and logistical challenges associated with recovering processing waste have slowed the utilization of these resources (Naylor et al., 2009) but the huge amount of available raw material and the conservation benefits that are likely to result will make efforts to further develop these resources worthwhile.

CONCLUSION—TOWARD SUSTAINABLE CMF AQUACULTURE

Aquaculturists have known for years that there is much to be done to ensure a more sustainable future for fish farming (e.g., Hardy, 1999): continued research into alternative feed ingredients (Naylor et al., 2009), development of improved on-farm husbandry practices (Tacon et al., 2010), and better management of small pelagic fisheries (Alder et al., 2008) are all obvious needs. Additionally, the process of manufacturing aquafeeds could be improved. Existing technologies consume large amounts of energy and create significant amounts of pollution (Tydemers et al., 2007). Many are also concerned about the increasing use of low value "trash" fish as a direct feed in the Asia-Pacific region (Tacon and Metian, 2009) as well as the diversion of fish suitable for human consumption to non-food uses (Tacon et al., 2010).

Yet, CMF aquaculture carries with it benefits that justify the consumption of small pelagic fish. It provides consumers with a high quality source of animal protein, generates significant employment and business activity in rural coastal areas (such as in the Chilean salmon industry), and often occurs on small, farmer-owned farms (especially in Asia) (Tacon et al., 2010). CMF aquaculture is also, as we have seen, generally less demanding of a group of important natural resources than is commercial fishing and terrestrial animal husbandry. Finally, as the pattern of falling FIFO ratios and increasing production demonstrates, the CMF aquaculture industry is clearly moving away from its historical dependence on FM and FO.

In sum, CMF aquaculture is progressing towards increased sustainability. While the industry is still tied too closely to marine sources of protein, it has efficiency advantages that tend to offset this dependence relative to other forms of animal production. Most importantly, research efforts aimed at finding sustainable substitutes for FM and FO are showing signs of success, suggesting that improvements in environmental performance will continue to occur as the industry expands.

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