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Sustainability in Aquaculture: Present Problems and Sustainable Solutions

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I. INTRODUCTION

Aquaculture is the farming of aquatic organisms such as fish, shellfish, and plants in marine, freshwater, or brackish water environments. On a global scale, aquaculture production grew rapidly in the 1980s and 1990s and continues to expand at a slower rate today. In 2010, aquaculture supplied 47 percent of world food fish production for human consumption. World aquaculture is dominated by the Asia-Pacific region which accounted for 89 percent of global production by volume in 2010. This is largely due to China's influence, which alone accounted for more than 60 percent of total production volume in that year.[1]

Traditionally, aquaculture has focused on the farming of species that are low in the food chain, i.e., have a low trophic level. Such species can largely be fed on naturally occurring plankton grown in fertilized ponds or the marine environment and, in some cases, with additional vegetable-based feeds. Species include shellfish and herbivorous (plant-eating) fish such as carp, which still dominate aquaculture today in terms of quantity. About one-third of farmed food fish production is currently achieved without artificial feeding.[2] Cultivation of higher trophic level species such as salmon and marine finfish relies on using wild fish resources as feed ingredients. These species are not a large part of the global aquaculture production but have become economically very profitable due to a ready market in economically developed countries.

The human population is predicted to continually increase in the coming years and while capture fisheries production has remained stable in recent years, and is not expected to increase, aquaculture is expected to expand its output further in order to help feed a growing population.[3] While traditional aquaculture and some modern aquaculture practices are environmentally sustainable, the intensification of aquaculture in recent decades has brought with it serious problems in terms of achieving environmental and social sustainability including: pollution of the surrounding environment with nutrient wastes and harmful chemicals; overuse of antibiotics and development of bacterial resistance; depletion and salinisation of potable water and salinisation of agricultural land; escapes of non-native species; spread of disease to native species; and human rights abuses.[4] Aquaculture will now need to move forward with environmentally and socially sustainable systems that can produce affordable and nutritious fish if it is to make a sustainable contribution to meeting the needs of global food security.

[†] The authors thank P. Johnston (Greenpeace Research Laboratories, UK), P. Trujillo (Greenpeace International, Amsterdam) and A. Quarto (Mangrove Action Project, USA) for their useful comments on the text.

[1] FAO, *World Review of Fisheries and Aquaculture*, (Rome: FAO Fisheries and Aquaculture Department, Food and Agricultural Organization of the United Nations, 2012).

[2] *Id*.

[3] *Id*.

[4] M. Allsopp, R. Page, P. Johnston and D. Santillo, *State of the World's Oceans* (Dordrecht Netherlands: Springer, Springer Science and Business Media B.V, 2009),

This article focuses on two major obstacles that must be overcome to attain environmental and social sustainability in aquaculture: 1) A reduction of the use of wild forage fish as feed for aquaculture is required, and 2) the destruction of important coastal wetland habitats for aquaculture, in particular shrimp farming, has caused many environmental and social problems that must be addressed.

Intensive aquaculture generally uses fishmeal and fish oil in feeds that are derived mainly from wild forage fish. The majorities of fishmeal and fish oil are for cultivation of higher trophic level species including marine finfish and salmon, as well as most shrimp aquaculture.[5] Fishmeal and fish oil in aquafeeds are also sometimes used, but at much lower inclusion rates, in the diet of intensively farmed lower trophic level species such as carp and tilapia species to achieve fast growth to marketable size.[6]

The issue with the heavy reliance on wild forage fish as feed for intensive aquaculture is that these forage fish stocks need to be more effectively managed for their long-term viability and for the integrity of marine ecosystems (see section II). Further, in terms of global food security, we recommend that a large proportion of the catch that can be taken sustainably from some forage fish stocks would be better directed for direct human consumption than for feed for high market value cultured species(see section II). This would represent a supply of cheap, nutritious, and healthy fish for many people. At the same time, aquaculture will need to lessen its reliance on forage fish stocks as aquafeeds and move to alternative sources including plants, animal-by-products, and fish by-products (see section III).

We discuss the importance of coastal wetlands, notably mangroves, and suggest a sustainable way forward for shrimp farming and restoration of mangrove ecosystems (see section IV). Finally, we focus on ways of overcoming other environmental problems in aquaculture by establishing sustainable aquaculture systems (see section V). We recommend that increasing the cultivation of low trophic level species in integrated systems is necessary to improve global food security and lessen the ecological footprint of intensive aquaculture. Such systems are already in place, but there is a vast potential for the further development of aquaculture in this way. For example, expansion of rice-fish culture could significantly improve food security in many countries.

II. CATCHING FISH TO FEED FISH

Introduction

The small pelagic marine fish that are utilized to make fishmeal and fish oil are often called forage fish and include species such as anchovies, sardines, sprats, mackerels, herrings, and sardinellas. In 2010, global marine capture fisheries landed 77.4 million tonnes of fish and, of this, about a quarter (20.2 million tonnes) were fish destined for non-food purposes, 75 percent of which went to reduction to fishmeal and fish oil.[7] Presently, about 63 percent of annual global fishmeal production is utilized for aquafeeds and the majority of the remainder is used for pig and poultry feeds. For fish oil, about 81 percent of the world production is used for aquaculture feeds (68 percent of this to raise salmonids) and the rest is used for direct human consumption and other uses.[8]

The demand for forage fish as ingredients of aquaculture feeds has grown considerably in recent decades along with the growth and intensification of aquaculture, while, over the same period, the use of fishmeal as agricultural feeds and use of fish oil by the margarine industry has declined.

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[5] G. Merino, M. Barange, C. Mullon and L. Rodwell, "Impacts of global environmental change and aquaculture expansion on marine ecosystems," *Global Environmental Change* 20 (2010): 586–596.

[6] C.L.J. Frid and O.A.L. Paramor, "Feeding the World: What role for fisheries?," *ICES Journal of Marine Science* 69, no.2 (2012): 145–150; G. Merino, M. Barange, J.L. Blanchard, J. Harle, R. Holmes, I. Allen, E.H. Allison, M.C. Badjeck, N.K. Dulvy, J. Holt, S. Jennings, C. Mullon and L.D. Rodwell, "Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate?," *Global Environmental Change (*2012), doi: 10.1016/j.gloenvcha.2012.03.003.

[7] FAO, n. 1 above.

[8] A. Chamberlin, "Fishmeal and fish oil – the facts, figures, trends, and IFFO's responsible supply standard," International Fishmeal and Fish Oil Organization, 2012, available online: <http://www.iffo.net>.

Although aquaculture has continued to expand production in more recent years, between 2000 and 2008 the total quantity of fishmeal and fish oil used by the aquaculture sector remained fairly steady. This is because continuing research has enabled the partial substitution of fishmeal in aquafeeds with other proteins, notably soy protein, and of fish oils with vegetable-based oils, mainly rapeseed oil.[9] This is a trend that is expected to continue in the coming years as a consequence of further research and innovation to substitute fish meal and fish oil with other feed products (see section III). In addition, an increasing proportion of fish for the production of fishmeal and fish oil is being derived from reducing trimmings, a by-product of the fish processing industry. Approximately 5 million tonnes of trimmings were reduced to fishmeal and fish oil in 2008. Globally, this represents about 25 percent of annual fishmeal production.[10]

The human population is predicted to continue to increase and aquaculture is expected to expand further in order to meet increased demand for fish protein. It is possible, therefore, that there could also be an increased demand on forage fish stocks for aquaculture feed. However, the total catch of forage fish is expected to remain static or decline due to better management of stocks and to the increased diversion for forage fish for direct human consumption.[11] The challenge for the aquaculture industry will be to decrease its reliance on forage fish as feed to accommodate this (see discussion below).

Other aquafeeds are made from the so-called "low value" marine fish caught in Asia. In 2006, about 30 percent of all aquafeeds were farm-made.[12] The low value fish used to make these feeds include a plethora of species of fish and invertebrates that are of low commercial value by virtue of their low quality, small size, or lack of market demand. Low value fish may be used for human consumption (often processed or preserved) or used for aquaculture or agricultural feeds.[13]

State of Forage Fish Stocks and Ecosystem Impacts of Overfishing

Presently, the management of world marine fish stocks is usually carried out using a single species approach wherein only the target fish stock is considered. Good single stock management is a key first step to effective management of fisheries. However, further improvement is necessary to conserve commercial fish stocks and it is widely recognized that an ecosystem-based approach to fisheries management is a more appropriate form of management. This encompasses consideration of whole ecosystems, rather than just the target stock, and also considers marine protected areas as a management tool.[14] According to an FAO definition, an ecosystem-based approach has to "cater for both human as well as ecosystem well being."[15] The Joint Nature Conservation Committee (statutory adviser to the UK Government) states that "ecosystem-based management is concerned with ensuring that fishery management decisions do not adversely affect ecosystem function and productivity, so that harvesting of target stocks (and resultant economic benefits) is sustainable in the long term."[16] The COMPASS Scientific Consensus Statement, prepared and signed by over 200 scientists and policy experts in 2005 with an aim to provide information on coasts and oceans to U.S. policymakers,

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[9] A. Jackson and J. Shepherd, "The future of fishmeal and fish oil," (International Fishmeal and Fish Oil Organization 2012), in press as the joint Proceedings of FAO/University of Alaska, 2012.
[10] E.A. Bendiksen, C.A. Johnsen, H.J. Olsen and M. Jobling, "Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (*Salmo salar* L.)," *Aquaculture* 314 (2011): 132–139.
[11] Jackson and Shepherd, n. 9 above.
[12] A.G.J. Tacon and M. Metian, "Fishing for feed or fishing for food: Increasing global competition for small pelagic forage fish," *Ambio* 38, (6) (2009): 294–302.
[13] A.G.J. Tacon and M. Metian, "Fishing for aquaculture: Non-food use of small pelagic forage fish – a global perspective," *Reviews in Fisheries Science* 17, (3) (2009): 305–317.
[14] I. Browman and K.I. Stergiou, "Marine Protected Areas as a central element of ecosystem-based management: Defining their location, size and number," *Marine Ecology Progress Series* 274 (2004): 269–303.
[15] *Id*.
[16] Joint Nature Conservation Committee, "The Eco-System based approach," available online: <http://jncc.defra.gov.uk/page-2518>.

stated that "Ecosystem-based management emphasizes the protection of ecosystem structure, functioning and key processes."[17]

Many of the world's marine fisheries currently suffer from overexploitation. For example, the FAO estimated that, in 2010, 29.9 percent of world fisheries were overexploited, and were therefore producing lower yields than their biological and ecological potential and were in need of strict management plans to restore their full and sustainable productivity.[18] Specifically for forage fish, a high proportion of stocks are also overfished. For example, the Sustainable Fisheries Partnership (SFP) recently analysed the management measures for the 28 principal pelagic stocks that are fished for reduction purposes, and revealed that none are currently managed using an ecosystem-based approach.[19] In addition, 29.3 percent of the total catch from these stocks was from fisheries that were particularly badly managed, even from a single-stock perspective (failing on one or more criteria used in the assessment), including having a biomass well below that required to produce the maximum sustainable yield (B_{MSY}). A further 8.3 percent of the catch was from fisheries scoring a basic pass for each criterion, where the biomass was still below B_{MSY} but above a critical limit reference point for the stock.

In conclusion, SFP stated that: "This situation needs to improve significantly. Fisheries that have established a successful single species stock management regime should now be looking to evolve an ecosystem-based approach to ensure sustainability in the future."[20]

Ecosystem-based management is particularly vital in the management of forage fish stocks because these species underpin the food web of marine ecosystems being a critical food source for many other species. Overexploitation of forage fish has resulted in detrimental impacts on other marine species.[21] Recent research is demonstrating that an ecosystem-based approach is crucial in the management of forage fish (see below).

Pinsky et al.[22] analysed the vulnerability of a wide variety of commercial fish stocks to succumb to fisheries-induced collapse. Their study showed that, since 1950, stocks of small, short-lived species such as forage fish have undergone fishery collapses just as often as larger longer-lived species – in contrast to what was previously thought. In conclusion, this study stressed that a "halt to overfishing" was needed across all species, both long- and short-lived. Pinsky et al. also stressed that even temporary collapses of small, low trophic level fishes can have ecosystem-wide impacts by reducing food supply to larger fish, seabirds, and marine mammals. This fact was reiterated through research by the Lenfest Forage Fish Task Force that was formed to provide practical advice on the management of forage fish.[23] Only precautionary management measures protected the forage fish stocks from collapse as well as protecting the predator fish, birds, and marine mammals that depend on them. Similar research by Smith et al.[24] drew the same conclusion: fishing forage fish stocks at conventional MSY levels can have large impacts on other parts of the ecosystem, while halving the exploitation rates would result in much lower impacts on marine ecosystems. Using current fisheries data and statistical models, Pikitch et al.[25] also calculated that leaving twice the amount of forage fish

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[17] COMPASS, "Ecosystem-Based Management Consensus Statement," 2005, available online: <http://www.compassonline.org/science/EBM_CMSP/EBMconsensus>.
[18] FAO, n. 1 above.
[19] Sustainable Fisheries Partnership, "Global sustainability overview of fisheries used for fishmeal and fish oil," June 2012, available online: <http://sfpcms.sustainablefish.org.s3.amazonaws.com/2012/07/06/SFP_Briefing-_Global_Sustainability_Overview_of_Reduction_Fisheries_2012-076caea7.pdf>.
[20] *Id*.
[21] Allsopp et al., n. 4 above.
[22] M.L. Pinsky, O.P. Jensen, D. Ricard and S.R. Palumbi, "Unexpected patterns of fisheries collapse in the world's oceans," *Proceedings of the National Academy of Sciences of the United States of America* 108 (20) (2011):8317–8322.DOI: 10.1073/pnas.1015313108.
[23] E. Pikitch, P.D. Boersma, I.L. Boyd, D.O. Conover, P. Cury, T. Essington, S.S. Heppell, E.D. Houde, M. Mangel, D. Pauly, É. Plagányi, K. Sainsbury and R.S. Steneck, "Little Fish, Big Impact: Managing a Crucial Link in Ocean Food Webs," (Washington, D.C.: Lenfest Ocean Program,2012), 108 pp.
[24] A.D.M. Smith, C.J. Brown, C.M. Bulman, E.A. Fulton, P. Johnson, I.C. Kaplan, H. Lozano-Montes, S. Mackinson, M. Marzloff, L.J. Shannon, Y-J. Shin and J. Tam, "Impacts of fishing low-trophic level species on marine ecosystems," *Science* 333 (2011): 1147–1150.
[25] Pikitch et al., n. 23 above.

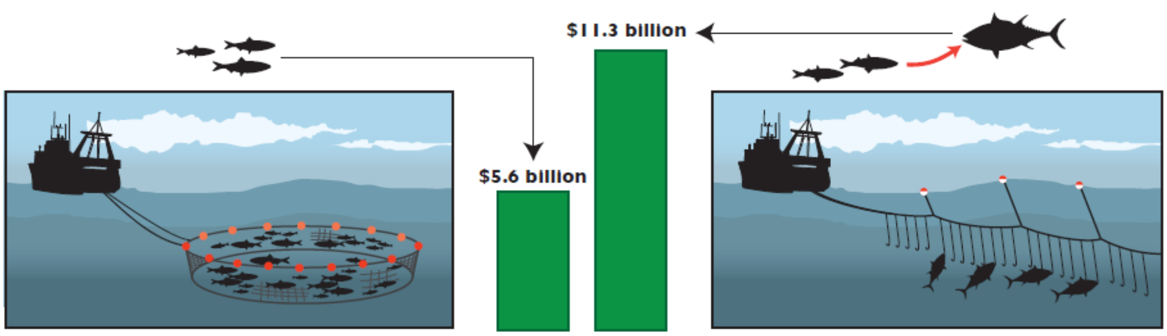
in the water as prey for predators, including commercial fish species, would have an economic advantage due to the positive effects of increasing commercial fish stocks. According to the authors' estimations, this would have supportive economic value of US$11.3 billion from commercial fisheries compared to a direct value of the commercial forage fish alone of US$5.6 billion (see Figure 1). Leaving more forage fish in the water would, of course, also be expected to bring substantial ecological benefits, and for any economic and/or food security gains from associated fisheries to be truly sustainable, it would be vital that measures be emplaced to ensure that these ecological benefits would be properly protected.

Figure 1. Economic importance of forage fish

The total value of forage fish to global commercial fisheries was $16.9 billion (2006 dollars). The value of fisheries supported by forage fish (e.g., cod, striped bass, salmon) was nearly twice the direct value of forage fish.

FORAGE FISH DIRECT VALUE
The commercial catch of forage fish was $5.6 billion.

FORAGE FISH SUPPORTIVE VALUE
Forage fish added $11.3 billion in value to commercial catch of predators.



Food Security and Impacts on Local Communities

There are critical concerns surrounding the use of a large percentage of the global catch of marine fish solely for reduction purposes rather than for direct human consumption. Many species of forage fish are edible and nutritious fish. Malnutrition is still the number one killer and cause of human suffering in the world.[26] The FAO estimated that in 2008, there were 1.02 billion undernourished people in the world. A lack of protein-rich food of animal origin was described as one cause of this problem. Additionally, the demand for fish products is expected to continue to rise in the coming decades.[27]

Further concern arises because some aquaculture practices are net consumers of wild fish, rather than being a net producer of cultivated fish.[28] This is not the most sustainable use of fish protein. For example, it is of concern that marine-based aquaculture in the Mediterranean region is

[26] Tacon and Metian, n. 13 above.

[27] FAO, "The State of World Fisheries and Aquaculture, 2010," (FAO Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, 2010), available online: <http://www.fao.org/docrep/013/i1820e/i1820e.pdf>.

[28] A.G.J. Tacon, and M. Metian, "Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects," *Aquaculture* 285 (2008): 146–158.

now a net fish consumer, not a net producer due to the cultivation of several high trophic level species, in particular the ranching of Bluefin tuna.[29]

The ratio of Fish In-Fish Out(FIFO) is the unit of fish consumed per unit of fish produced,[30] and can thus be defined as the efficiency at which aquaculture converts a weight equivalent unit of wild fish into a unit of cultured fish.[31] The FIFO ratios are particularly high for the cultivated higher trophic level species. For example, based on the global use of fishmeal and fish oil, the FIFO for Atlantic salmon was estimated to be 4.9, and for trout estimated to be 3.4, and for marine fish 2.2.[32] A recent paper by the International Fishmeal and Fish Oil Organisation used a different method of calculation to estimate FIFO ratios, and calculated a FIFO ratio for salmon and trout combined of 1.77.[33]

The FIFO ratios have declined in recent years due to lower inclusion levels in aquafeeds made possible by substitution with vegetable-based products.[34] It is likely that these FIFO ratios will decline further in the future as the industry strives to gain economic benefits by replacing high-priced fishmeal and fish oils with less expensive alternatives and lessen the reliance on a limited global supply of fish oil.[35] This requires ongoing research and technological adaption (see section III).

On a global scale, aquaculture has a FIFO ratio of between 0.66 and 0.7,[36] depending on which method of calculation is used. Thus, the cultivation of lower trophic level species that require little, if any, fishmeal and fish oils in feed has a positive influence on the ratio as a whole.

A recent study sought to answer the question: Can marine fisheries and aquaculture meet fish demand from a growing human population in a changing climate?[37] The study calculated that, to feed the population in a sustainable manner, aquaculture would have to undergo technological adaption to reduce the FIFO ratio by at least 50 percent and fisheries would have to be more effectively managed. It was noted that, "To maximize food production, therefore, small pelagic production would be best used for direct human consumption or directed to the culture of species with lower FIFO rate." Until reliance on fishmeal and fish oil can be considerably reduced for high trophic level species, "it could be argued that salmon aquaculture represents an inefficient use of capture fish production that could otherwise be used directly to meet human food needs, although salmon aquaculture is not driven by food demands but by its economic benefits."[38] The ethics of taking forage fish from the waters of poor communities, primarily to feed the piscivorous farmed fish that are the preference of wealthier nations, must surely be a consideration in reviewing aquaculture practices.

Forage Fisheries in West Africa

The coastal waters of West Africa have become key fishing grounds for trawler fleets of Europe, Asia and Russia. Of these, the pelagic super-trawler fleets are of particular concern. Many stocks in this region are already overfished and the added overcapacity of these foreign fleets has considerable negative impacts on local fishers and communities. This is not an overnight phenomenon but one that has grown in intensity over the last 30 years, fuelled by overcapacity and declining fish stocks in the home-waters of these foreign fleets, fishing subsidies, and the short-sightedness of some West African

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[29] K.I. Stergiou, A.C. Tsikliras and D. Pauly, "Farming up Mediterranean food webs," *Conservation Biology* 23, (1) (2008): 230–232.
[30] O. Torrisen, R.E. Olsen, R. Toresen, G.I. Hemre, A.G.J. Tacon, F. Asche, R. Hardy and S. Lall, "Atlantic salmon (*Salmon salar):*The super-chicken of the sea?," *Reviews in Fisheries Science* 19 (2011): 257–278.
[31] Merino, n. 5 above.
[32] Tacon and Metian, n. 28 above.
[33] Jackson and Shepherd, n. 9 above.
[34] Tacon and Metian, n. 28 above.
[35] Stergiou et al., n. 29 above.
[36] S. Kaushik and M. Troell, "Taking the fish-in fish-out ratio a step further," *Aquaculture Europe* 35 (2010): 15–17; A. Jackson, "Fish in-fish out ratios explained," *Aquaculture Europe* 34 (2009): 5–10; Smith et al., n. 24 above.
[37] Merino et al., n. 5 above.
[38] *Id*.

governments in selling fishing rights to other nations.[39] The example of the environmental and societal problems caused by foreign fisheries in Morocco and Mauritania is discussed below.

Morocco and Mauritania

There are two types of pelagic fleets operating in this region: the fleet that catches fish for human consumption in other parts of West Africa (a large part of the catch of the fleet of the Dutch-based Pelagic Freezer Trawler Association or PFA) and the fleet that catches fish for reduction purposes. Even though the PFA may be supplying local markets with fish for human consumption further south in countries such as Ghana and Nigeria, they are in fact competing directly with local fishers and fishmongers who struggle to catch small pelagic species themselves and this activity is disrupting local markets. The other extensive pelagic fleet operating in the waters of Morocco and Mauritania catches small pelagic species for reduction purposes. The situation in this region is summed up in a recent Greenpeace report:[40]

> "Today, EU vessels catch 235,000 tonnes of small pelagic species annually from the waters of Morocco and Mauritania, the largest EU fishery in foreign waters. Local fishermen see their catches shrinking and their costs and workload rising. They are forced to travel further to catch fish and often have to compete for space with the industrial trawlers in dangerous waters unsuitable for their small boats, increasing the risk of deaths on the open sea".

Furthermore, China recently signed a deal with Mauritania that grants Chinese fishermen access to Mauritanian waters for 25 years; most of the fish caught will be reduced to fishmeal/fish oil. Under conditions such as these, the stocks will only decline further. The FAO has classified all stocks of small pelagic species off Northwest Africa as either fully fished or overfished, with the exception of sardine in one area, and has recommended catch reductions.[41] From an ecological perspective, the species targeted by the pelagic trawlers in West Africa are a food source for larger species, including sharks, turtles, whales and dolphins, and overfishing of their prey will have detrimental impacts.

A study of European pelagic freezer trawlers off Mauritania between 2001 and 2005 reported considerable and unsustainable bycatch of many critically endangered turtles (about 50 annually), as well as manta rays (120–620 annually) and sharks (1,000–2,000 annually), plus the incidental capture of many dolphins and pilot whales.[42] The study stressed the urgency with which this problem needs to be mitigated with the use of excluder devices in the nets. According to researchers familiar with the region, since the study, the management of Mauritanian fisheries has remained poor, and there has been no move to use excluder devices.[43]

Low-value or 'Trash' Fisheries in Asia

Low-value or 'trash' fish fisheries, primarily in East, South, and Southeast Asia, are sourced for aquaculture and/or agriculture feeds from two types of fisheries: fisheries that intentionally target mixed species unsuitable for human consumption (because of size or palatability) and fisheries that target food species, such as shrimp and fish, but with indiscriminate fishing gears that result in a large

[39] O.S. Diouf, F. Obaidullah and E. Partridge, "Empty nets, empty future," (Greenpeace Africa, West Africa Report 2011), available online: <http://www.greenpeace.org/africa/Global/africa/publications/Empty%20nets%20empty%20future.pdf>; Greenpeace "The Price of Plunder," *Ocean Inquirer*, no. 3, February 2012, (Greenpeace Netherlands and Greenpeace UK, 2012), available online: <http://www.greenpeace.org/eu-unit/en/Publications/2012/The-Price-of-Plunder/>.

[40] Diouf et al., n. 39 above.

[41] FAO, "Report of the FAO Working Group on the Assessment of Small Pelagic Fish off Northwest Africa," Nouakchott, Mauritania, 21–30 April 2009, (Food and Agriculture Organization of the United Nations, Rome, 2011), available online: <http://www.fao.org/docrep/014/i2237b/i2237b.pdf>.

[42] J.J. Zeeberg, A. Corten and E. de Graaf, "Bycatch and release of pelagic megafauna in industrial trawler fisheries off Northwest Africa," *Fisheries Research* 78 (2006): 186–195

[43] Dr. Ad Corten, Netherlands Institute for Fisheries Research, pers. comm.

catch of juvenile fish, in particular. In global terms, the landings of low-value fish are vast, perhaps well over 5 million tonnes per year.[44] However, these fisheries are usually unregulated; few if any fisheries data are collected and, without management improvements, such fisheries can be damaging both to ecosystems and to the coastal communities that rely on healthy ecosystems for healthy fisheries.

The lack of data and almost total lack of traceability and transparency in supply chains makes it particularly difficult to determine the sustainability of any aquaculture products fed with low-value 'trash' fish. In this regard, the Sustainable Fisheries Partnership stipulates that "retailers, processors, producers and feed manufacturers in the aquaculture supply chain – and particularly for shrimp and pangasius – should take responsibility for achieving high levels of transparency around the origins of feed ingredients."[45]

Can the Use of Fish in Aquaculture Feeds ever be Sustainable?

The FAO *Code of Conduct for Responsible Fisheries* says that: "States should encourage the use of fish for human consumption and promote consumption of fish whenever appropriate (article 11.1.9). In addition, one of the overall objectives of the Code (2.f) is "To promote the contribution of fisheries to food security and food quality, giving priority to the nutritional needs of local communities." Therefore, adoption of the Code by all countries is imperative both for the sustainable management of fisheries and for human food security. It is clear that a reduction in fishing by highly subsidised foreign trawl fleets is a key first step in bringing fishing under control in many regions.

Some scientists have gone further in their recommendations. Tacon and Metian[46] stipulate that the only way to safeguard and to promote the use of small pelagic forage fish in developing countries for the purpose of food security may be the "imposition of legislative controls by national/local governments" to prohibit the use of potentially food-grade small pelagic forage fisheries for animal feeding, including reduction to fishmeal and fish oil. Jacquet et al.[47] expressed similar ideas in their paper on seafood certification: "One premise of sustainable seafood should be that no fishery that catches fish for the production of animal or feed fish oil should be eco-certified. Instead, groups interested in promoting sustainable seafood should encourage direct human consumption of forage fish."[48]

In Norway there has been a move to directing an increasing proportion of catch of capelin, herring, and blue whiting for direct human consumption, and similarly in Denmark with herring and blue whiting.[49] In South America, there are moves to shift pelagic fish away from fish feeds under two different programs focused on anchovies. In Peru, it has been recognised that more Peruvian anchovy need to be left in the water to support the Humbolt upwelling ecosystem. Furthermore, malnourishment due to poverty is a problem in Peru. With these factors in mind, since 2006, a program has been established to increase the quantity of fish directed to human consumption to alleviate poverty, which in turn provides a better economic return for the anchovy fishery. This has provided the incentive to reduce the anchovy catch, thereby aiding recovery of the ecosystem. The project is meeting with success as the proportion of the catch used for human consumption continues

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44 D. Leadbitter, "New standards drive interest in fish used for fish meal," *AQUA Culture Asia Pacific Magazine*. September/October 2010: 40–41, available online: <http://media.sustainablefish.org/AQUA_CAPM_sep_2010.pdf>.

45 Sustainable fisheries Partnership, "FishSource, reduction fisheries and aquaculture," Sustainable Fisheries Briefing, (Sustainable Fisheries Partnership 2010), available online: <http://sfpcms.sustainablefish.org.s3.amazonaws.com/2011/03/21/SFP_Brief_FS_Reduc-3-193919e6.pdf>.

46 Tacon and Metian, n. 12 above.

47 J. Jacquet, J. Hocevar, S. Lai, P. Majluf, N. Pelletier, T. Pitcher, E. Sala, R. Sumaila and D. Pauly, "Conserving wild fish in a sea of market-based efforts," *The international Journal of Conservation Oryx* 44, no. 1 (2009): 45–56.

48 *Id*.

49 Jackson and Shepherd, n. 9 above.

to increase.[50] In Brazil, new stocks of anchovy were recently discovered off the South East coast of Brazil. An experimental fishery was set up and the anchovy have been successfully used in school meals.[51]

In order to answer the question, can the use of fishmeal and fish oil in aquaculture ever be sustainable?, it is clear that practice and trends in both production and consumption must be considered, now and into the future. We argue that better management of poorly managed forage fish stocks is an essential first step along the road to ecosystem-based management to protect all stocks and the ecosystems they support and to protect future fisheries for human needs. Furthermore, diversion of many forage fish stocks for direct human consumption is necessary to provide affordable and nutritious fish for a growing human population, thereby greatly improving the efficiency of fish protein use. This in turn necessitates that aquaculture production expands into the cultivation of lower trophic level species, rather than increasing production of higher trophic level species. All of the above measures represent steps towards increasing sustainability in aquaculture by reducing dependence on fishmeal and fish oil in aquafeeds.

III. ALTERNATIVE FEEDS FOR AQUACULTURE

The successful substitution of fishmeal and fish oil from reduction fisheries with alternative feeds would allow aquaculture to increase its overall fish production without threatening wild forage fish stocks. A wide variety of studies have attempted to do this with a range of plant sources, animal by-products, and fish by-products, as well as some novel animal proteins (e.g., cultured marine worms), and microbial products, more recently with increasing success.

Fishmeal in aquafeeds has many nutritional advantages, including high protein content, high digestibility, and palatability, and good profiles of essential amino acids and fatty acids, minerals and vitamins. These characteristics make it challenging to substitute with less expensive alternatives without affecting fish performance and fillet quality. The use of alternative plant and animal protein sources in aquafeeds is still being investigated and developed.[52]

Waste Products from Fisheries and Fish Processing

Alleviation of pressure on wild stocks for reduction purposes could come from greater efforts to use fish trimmings from the fish processing industry and from the use of fishery discards. The use of trimmings varies widely between countries; for instance, it is estimated that 80 percent of trimmings from fish processing in Denmark goes to the fishmeal and fish oil industry whereas in Spain the figure is just 10 percent. In the UK, Germany, and France these figures range from 33 to 50 percent. Thus, there is plenty of scope to increase the quantity of trimmings that could be utilized to make fishmeal and fish oil.[53]

Fishery discards are the unwanted bycatch in fisheries. Discards include target species that are over-quota, less valuable commercial species, fish unsuitable for human consumption, or undersized fish. The use of fishery discards for reduction purposes could provide a valuable resource for production of fishmeal. For example, in Europe about 410,000 tonnes of discards are produced annually and this could be made into about 82,000 tonnes of fishmeal that could support aquaculture. Similarly, for the United States there are about 300,000 tonnes of fisheries discards annually that could be converted into fishmeal.[54]

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[50] Pew Charitable Trust, "Peruvian Scientist Patricia Majluf Awarded 2012 Pew Fellowship in Marine Conservation," available online: <http://www.pewenvironment.org/news-room/press-releases/peruvian-scientist-patricia-majluf-awarded-2012-pew-fellowship-in-marine-conservation-85899372521>; Patricia Majluf and the Anchoveta, 2012. You Tube, available online: <http://www.youtube.com/watch?v=UxTLI5QfNsU>

[51] Prof. Lauro Madureira, Instituto de Oceanografia, Universidade Federal de Rio Grande – FURG, pers. comm. (25 April 2012).

[52] F.Y. Ayadi, K.A. Rosentrater and K. Muthukumarappan, "Alternative protein sources for aquaculture feeds," *Journal of Aquaculture Feed Science and Nutrition* 4, (1) (2012): 1–26.

[53] Frid and Paramor, n. 6 above.

[54] *Id*.

The concerns with regard to this option are that fisheries with substantial bycatch need to be better managed to eliminate the bycatch problem and eliminate discarding. Of particular importance is the move towards using more selective fishing methods. Therefore using discards should not provide any economic incentives for continuing bad fishing practices, but rather should simply make use of any current residual bycatch in the interim. The authors suggest that discards should be landed and used, but the fishers should not be reimbursed for this part of the catch; recipients should pay for the fish, but the money could go to fund improvements to the monitoring and control of fisheries, and the provision of scientific data for management advice. Discarding is a topic of considerable debate in the current review of the European Union's Common Fisheries Policy.

Animal Protein Sources

Meat and bone meal is a product of animal rendering produced from waste tissues that are not used for human consumption. This product is commonly included in commercial fish diets but at levels not greater than 20 percent. Other slaughterhouse wastes used to make animal by-products include blood meal, poultry by-product meal, and feather meal. The latter two are already used in aquafeeds. Studies show that all of these animal by-products could partly substitute fishmeal in aquafeeds for some species.[55]

Plant Protein Sources

Several leguminous crops, including peas and beans, have been investigated for their suitability for aquafeeds.[56] Of these, soybean has been the most studied and widely used in aquafeeds. Note, however, that concern has been expressed over the increased area needed to grow crops as alternative aquaculture feed,[57] and it is clear that plant proteins should come from sustainable agriculture in order for the aquaculture operations they support to be considered sustainable. Problems of anti-nutritional factors and unwanted nutrients in plant products may be overcome to some extent by processing to reduce or inactivate anti-nutritional factors, and dehulling to reduce fibre and enhance protein content.[58]

One European project known as Aquamax (Sustainable Aquafeeds to Maximise the Health Benefits of Farmed Fish for Consumers) was initiated to determine whether both fishmeal and fish oil could be replaced simultaneously in the diet of various species and hence reduce the total need for the inclusion of wild fish in aquafeeds.[59] In these studies, fishmeal was partially replaced by vegetable proteins and fish oil was partially substituted with vegetable oils. Complete substitution of fish oil in the diet is not possible with vegetable oils because they do not contain long chain omega-3 polyunsaturated fatty acids, in particular eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), important for human nutrition. Research indicated that both fishmeal and fish oils in feeds can be substantially reduced without affecting the growth performance of the fish and their feed/nutrient utilisation.[60] One study has indicated that, through such partial substitution, Atlantic salmon aquaculture could become a net producer of fish protein rather than net consumer.[61]

Substitution of Fish Oils by Marine Algal Oils

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[55] Ayadi et al., n. 52 above.
[56] *Id*.
[57] Torrisen, et al. n. 30 above.
[58] Ayadi et al., n. 52 above.
[59] Aquamax, "Sustainable Aquafeeds to Maximise the Health Benefits of Farmed Fish for Consumers (Project AquaMax nr: 016249, 2012), available online: <http://www.aquamaxip.eu/files/Aquamax%20Fact%20sheet.pdf>.
[60] Aquamax, "Feed," 2012, available online: <http://www.aquamaxip.eu/content/view/9/14/>.
[61] B.E. Torstensen, M. Espe, M. Sanden, I. Stubhaug, R. Waagbø, G-I. Hemre, R. Fontanillas, U. Nordgarden, E.M. Hevrøy, P. Olsvik and M.H.G. Berntssen, "Novel production of Atlantic salmon (*Salmo salar)* protein based on combined replacement of fish meal and fish oil with plant meal and vegetable oil blends," *Aquaculture* 285 (2008): 193–200.

Aquamax is also working to address the problem of persistent organic pollutants (POPs).[62] Omega-3-containing oils, free from pollutants, have already been successfully produced from marine microalgae and marketed as an alternative to fish oil capsules.

The Aquamax project has recently incorporated DHA- and EPA-rich oils from marine microalgae into the diet of marine finfish.[63] Long-term studies showed that marine micro-algal oils can completely replace fish oils in the diet of Atlantic salmon and gilthead sea bream with only a slightly reduced bodyweight in salmon. Presently, the only drawback of their commercial use in aquafeeds is cost of commercial production,[64] but is likely that micro-algal oils will be used, at least in small amounts, in the near future.[65]

The production of omega oils from genetically engineered crop plants is also being investigated.[66] However, commercialisation of such crops is years away and faces considerable opposition from consumer groups and environmental organisations due to the lack of adequate scientific understanding of the impacts of genetically modified crops, and their products, on the environment and human health.

Bioflocs as Feed Additives and Water Purifiers

Bioflocs consist of algae, bacteria, zooplankton, feed particles, and faecal matter that remain suspended in the water column of an aerated aquaculture system and naturally stick or 'floc' together, forming the particles that give biofloc culture systems their name.[67] The biofloc serves to provide additional food for cultivated species such as shrimp and tilapia.[68] The biofloc is maintained by adding carbohydrates to the system. Biofloc technologies can be applied in ponds, tanks or raceways of different scales.[69]

Biofloc contains nitrifying bacteria that transform toxic ammonia to the relatively non-toxic nitrate. Thus, the maintenance of a biofloc in the aquaculture system means that water quality is more controlled, and consequently the need for water exchange is reduced.[70] Biofloc technology is well suited to cultivating shrimp and tilapia. Intensive, biofloc-based production of shrimp in lined ponds is becoming more common and is rapidly expanding. Biofloc technology is also suited to super-intensive production of shrimp in tanks or raceways.[71]

A recent innovation has been the production of microbial floc meal as a dried feed for cultivation of shrimp.[72] Effluent from a tilapia farm using recirculating aquaculture systems is transferred to a bioreactor. Microbial flocs are produced in the reactor using this nitrogenous waste plus added sugar. The flocs can be harvested, dried, and used as an ingredient for shrimp feed instead of fishmeal or soy protein. Trials with Pacific white shrimp (*Litopenaeus vannamei*) demonstrated

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[62] Aquamax, "PUFAFEED, Substituting fish oil with marine microalgae in fish feed production," Technical Leaflet. Policy-relevant issues in Aquaculture and Fisheries, 2012. Reference No. AA-FI-FEED-03, available online: <http://www.euraquaculture.info/files/eu_projects/pufafeed_web.pdf>.
[63] *Id*.
[64] Bendiksen et al., n. 10 above.
[65] Prof. Gordon Bell, Nutrition Group, Institute of Aquaculture, Stirling University, pers. comm. (22 May 2012).
[66] Bendiksen et al., n. 10 above.
[67] C.L. Browdy and S.M. Moss, "Shrimp culture in urban, super-intensive closed systems," in *Urban Aquaculture,* B. Costa-Pierce, A. Desbonnet, P. Edwards and D. Baker eds., (Wallingford, Oxfordshire: CABI Publishing, 2005), p. 173–186.
[68] P. De Schryver, R. Crab, N. Defoirdt and W. Verstraete, "The basics of bio-flocs technology: The added value for aquaculture," *Aquaculture* 277 (2008): 125–137.
[69] Browdy and Moss, n. 67 above.
[70] *Id*.
[71] *Id*.
[72] D.D. Kuhn, G.D. Boardman, A.L. Lawrence, L. Marsh and G.J. Flick, "Microbial floc meal as a replacement ingredient for fish meal and soybean protein in shrimp feed," *Aquaculture* 296 (2009): 51–57.

that this feed could successfully replace fishmeal and soy protein in the diet and the process is economically viable.[73]

Green-water Microalgae

Several of the leading freshwater aquaculture species feed on 'green-water' plankton in ponds and consume little if any aquafeed.[74] These plankton assemblages are mainly microalgae (phytoplankton) but also include bacteria, protozoa, and zooplankton. The plankton grows in ponds fertilized by different forms of waste from farms and households and, occasionally, chemical fertilizers. Green-water is nutritious for different species of fish that are farmed together in Asian polyculture. Species include silver carp and grass carp, the first and second leading species in world aquaculture production, with a total of 7.9 million tonnes in 2007. Other species that are filter feeders and contribute significantly to aquaculture production include bighead carp, rohu carp, and catla. In total, 10.4 million tonnes of freshwater fish were raised in 2007 without aquafeed in green-water pond systems. Table 1 shows the ten leading cultured freshwater species in world aquaculture in 2007 and their feeding habits, demonstrating that they can be fed mainly on green-water. It has been shown that green-water extensive aquaculture costs less than the more intensive forms of aquaculture and an economic profit can be made from green-water aquaculture. Green-water aquaculture could expand aquaculture and represent a way to cultivate fish and shrimp in a sustainable and economically viable way, without the need for aquafeeds.[75]

Table 1.—Total production of the top ten cultured freshwater fish species in 2007 and their feeding habits.

Common name	**Species**	**Production (million metric tonnes*)**	**Natural feeding**
Silver carp	*Hypophthalmichthys molitrix*	3.66	Microalgae
Grass carp	*Ctenopharyngodon idellus*	3.61	Macrophytes
Common carp	*Cyprinus carpio*	2.87	Omnivores
Gibelioncatla	*Catla catla*	2.27	Zooplankton
Bighead carp	*Hypophthalmichthys nobilis*	2.16	Zooplankton
Nile tilapia	*Oreochromis niloticus*	2.12	Planktonic and benthic algae
Crucian carp	*Carassius carassius*	1.94	Plants, larvae and plankton
Rohu carp	*Labeo rohita*	0.69	Microalgae and zooplankton
White amur bream	*Parabramis pekinensis*	0.58	Plants and detritus
Channel catfish	*Ictalurus punctatus*	0.47	Omnivores

*Fresh weight, as reported to FAO. Source: Neori, see n. 72 above.

[73] D.D. Kuhn, A.L. Lawrence, G.D. Boardman, S. Patnaik, L. Marsh and G.J. Flick, "Evaluation of two types of bioflocs derived from biological treatment of fish effluent as feed ingredients for Pacific white shrimp, *Litopenaeus vannamei*," *Aquaculture* 303 (2010): 28–33.
[74] A. Neori, "Green water" microalgae: The leading sector in world aquaculture," *Journal of Applied Phycology* 23 (2011): 143–149.
[75] *Id*.

IV. SHRIMP FARMING ANDTHE DESTRUCTION OF MANGROVES

Importance of Mangrove Ecosystems

Mangrove forests are comprised of unique plant species that grow in the interface between the land, estuarine, and near-shore marine environments in tropical and subtropical regions.[76] The entire mangrove ecosystem can be defined as the tidally influenced wetland complex, consisting of mangrove forests, but also including tidal flats, salt flats and other associated habitats within the intertidal zone of tropical and subtropical latitudes.[77]

Mangrove ecosystems support rich communities of birds, fish, crustaceans, reptiles, and mammals.[78] They provide a nursery ground for larvae and juveniles of many fish species including commercially important shrimp and crab species and offshore fishes.[79] Mangroves also act to stabilise water quality in the coastal zone by trapping sediments, organic material, and nutrients and their stabilising effect on water quality is necessary for the functioning of nearby coral reefs.[80] Loss of mangroves can cause saltwater intrusion and deterioration of groundwater quality.[81] Mangroves are an essential element in coastline ecology, integrity, and protection. They reduce erosion, protect against floods, and mitigate the impact of severe tropical storms.[82]

Mangrove forests support livelihoods of coastal dwelling communities in tropical and subtropical coasts. A variety of products are harvested on a subsistence level including fish, crabs and shellfish, honey and medicinal plants, fuel wood, timber for construction, and tannins for preservatives and dyes.[83] Mangroves are therefore a very valuable resource for large numbers of people. Polidoro et al.[84] wrote, “Mangrove forests are the economic foundations of many tropical coastal regions providing at least US$1.6 billion per year in ‘ecosystem services’ worldwide.”

Mangrove Losses

Despite their great importance to biodiversity, coastal protection and provision of goods, large-scale destruction of mangrove forests has taken place in recent decades. The conversion of mangroves for commercial aquaculture, agricultural, industrial, and tourist facilities have led to dramatic losses.[85] Throughout the 1980s and 1990s, shrimp farming was heavily supported by World Bank loans. Massive support by governmental and inter-governmental agencies led to rapid and uncontrolled expansion of the shrimp farming industry throughout Southeast Asia and Latin America and consequent widespread mangrove losses.[86] Figures show that, globally, over 50 percent of the original mangrove cover has been lost, with between 20 percent and 35 percent lost since about 1980. Shrimp

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[76] B.A. Polidoro, K.E. Carpenter, L. Collins, N.C. Duke, A.M. Ellison, et al., “The Loss of Species: Mangrove Extinction Risk and Geographic Areas of Global Concern,” *PLoS ONE* 5(4), (2010): e10095. doi:10.1371/journal.pone.0010095.

[77] Dr. Alfredo Quarto, Executive Director, Mangrove Action Project, pers. comm., 2 May 2012.

[78] C.D. Field, “Mangroves,” in: *Seas at the Millennium: An Environmental Evaluation, Global Issues and Processes*, C. Sheppard ed., (Oxford, UK: Pergamon, 2000), Volume III, Ch. 108: pp. 17–30.

[79] M.S. Islam and M. Haque, “The mangrove-based coastal and nearshore fisheries of Bangladesh: Ecology, exploitation and management,” *Reviews in Fish Biology and Fisheries* 14 (2004): 153–180; P.J. Mumby, A.J. Edwards, J.E. Arias-González, K.C. Lindeman, P.G. Blackwell, A. Gall, M.I. Gorczynska, A.R. Harbourne, C.L. Pescod, H. Renken, C.C.C. Wabnitz and G. Llewellyn, “Mangroves enhance the biomass of coral reef fish communities in the Caribbean,” *Nature* 427 (2004): 533–536.

[80] P. Rönnbäck “The ecological basis for economic value of seafood production supported by mangrove ecosystems,” *Ecological Economics* 20 (1999): 235–252.

[81] UNEP-WCMC, “In the front line: Shoreline protection and other ecosystem services from mangroves and coral reefs,” UNEP-WCMC (Cambridge, UK: United Nations Environment Programme – World Conservation Monitoring Centre, 2006), 33 pp.

[82] Field, n. 78 above; UNEP-WCMC, n. 81 above.

[83] UNEP-WCMC, n. 81 above; I. Valiela, J.L. Bowen and J.K. York, “Mangrove forests: One of the world’s threatened major tropical environments,” *Bioscience* 51, no. 10 (2001): 807–815.

[84] Polidoro et al., n. 76 above.

[85] Valiela et al., n. 83 above.

[86] Alfredo Quarto, n. 77 above.

aquaculture alone is estimated to account for 38 percent of global mangrove loss.[87] However, mangroves are by no means ideal environments for shrimp farms. Ponds reclaimed from mangroves become too acidic to support shrimp aquaculture within just a few harvests, leading to a boom and bust cycle and vast areas of abandoned ponds.[88] Despite this, some destruction of mangroves for shrimp farming and other causes is still happening today. Mangrove areas are still disappearing at a rate of about 1 percent per year, with some estimates as high as 2–8 percent per year. Current exploitation rates are predicted to continue unless mangrove forests are protected and conserved as extremely valuable ecosystems and resources.[89]

Continuing Threats to Mangrove Ecosystems from Shrimp Farming

Clearance of mangroves for shrimp ponds is still threatening mangrove forest environments today. It continues to be a major threat to Thailand's remaining mangrove areas,[90] as well as in Sri Lanka and Bangladesh.[91] Presently in Bangladesh, shrimp farming is growing with the backing of international donor agencies and the involvement of multinational corporations. However, this expansion is often unregulated, uncontrolled, and uncoordinated. Both environmental and social problems have arisen. Environmental problems in Bangladesh include the encroachment on mangroves in some areas and pollution from the farms.[92] There are also serious concerns about the impact of saltwater intrusion into surrounding agricultural lands, rendering them unfit for growing crops, and also for the contamination of freshwater supplies with saltwater, creating scarcity of fresh drinking water. Socially, some problems have stemmed from land use changes such as the displacement of previous rice cultivation and livestock production in some parts of the country.[93] As a consequence, the rice yield in Bangladesh has significantly reduced and the decline in grazing land has substantially reduced livestock resources. This is a potential threat to food security. The contribution of shrimp aquaculture to poor people's nutrition can be neglected because most of the farmers cannot afford to eat the high value shrimp.[94]

A recent study estimated the benefits of shrimp farming in Thailand in economic terms versus traditional uses of mangrove areas and the services they provide.[95] The study clearly demonstrated that traditional uses and ecosystem services of mangroves heavily outweighed the short-term gains from shrimp farming. Furthermore, once ponds are no longer fit for use and are abandoned, mangrove ecosystem rehabilitation costs are very high. Rehabilitation of abandoned shrimp farm sites requires considerable investment for treatment and detoxification of the soil, replanting mangrove forests, and maintenance and protection of mangrove seedlings for several years.

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[87] Polidoro et al., n. 76 above.

[88] Robin Lewis, Certified Senior Ecologist, Ecological Society of America, President, Lewis Environmental Service, Florida, USA, pers. comm. (15 May 2012).

[89] Polidoro et al., n. 76 above.

[90] E.B. Barbier, "Wetlands as natural assets," *Hydrological Sciences Journal* 56 (8), (2011): 1360–1373. Special issue: Ecosystem services of wetlands.

[91] M.N. Munasinghe, C. Stephen, P. Abeynayake and I.S. Abeygunawardena, "Shrimp farming practices in the Puttallam District of Sri Lanka: Implications for disease control, industry sustainability, and rural development," *Veterinary Medicine International* 2010, article 679130 (2010): 1–7; B.G. Paul and C.R. Vogl, "Impacts of shrimp farming in Bangladesh: Challenges and alternatives," *Ocean and Coastal Management* 54 (2011): 201–211; P. Saenger, "Mangroves: Sustainable management in Bangladesh," in: *Silviculture in the Tropics, Tropical Forestry*, S. Günter ed., (Berlin/Heidelberg: Springer-Verlag, 2011), chap. 22.

[92] Paul and Vogl, n. 91 above.

[93] N.G. Gregory, P.K. Biswas and S.H. Chowdhury, "Recent concerns about the environment in Bangladesh," *Outlook on Agriculture* 39 no.2 (2010): 115–120.

[94] Paul and Vogl, n. 91 above.

[95] Barbier, n. 90 above.

The Way Forward

Mangrove Conservation and Restoration

As a way forward, measures must be emplaced to protect all mangrove ecosystems from destructive shrimp farming practices and other threatening development pressures. Eleven of the 70 mangrove tree species (16 percent) have been classified by the World Conservation Union (IUCN) as being at an elevated risk of extinction, as are at least 40 percent of mangrove-associated animal species, due to habitat loss.[96] A co-management process involving local government, scientists, NGOs, and indigenous and local communities must be established for effective protection and conservation of mangroves.

Secondly, the restoration of degraded mangroves is required in areas where they have been damaged or destroyed, including re-planting of diverse mangrove species native to the area. Planting monoculture is not recommended. For instance, in northern Vietnam, monocultures were planted and local people argued that these do not provide productive habitats for wild fisheries, clams and crabs. Conversely, in southern Vietnam, mainly species-rich mangroves were replanted that can provide a host of ecological goods and services as well as livelihood benefits.[97]

The non-profit environmental organization Mangrove Action Project (MAP) has promoted a process of "ecological mangrove restoration" to aid in the successful restoration of mangrove ecosystems. MAP puts the rights of local coastal peoples first to ensure the sustainable management of their coastal environment.[98]

Shrimp Farming

For shrimp farming, a sustainable approach to worldwide production is desperately needed. Modern shrimp farming has mainly focused on "open, throughput production systems" that have often resulted in pollution of the local environment with wastes, antibiotics, and chemicals and eventually led to degraded and abandoned ponds. A more recent and more sustainable approach to intensive shrimp farming is the "closed production system." These systems locate ponds out of, and behind the intertidal zone, thereby avoiding alteration of estuarine and mangrove habitats. They employ aeration of pond waters and are less polluting by employing recycling of effluent wastes. Recycling of effluent waters may be achieved by costly water filtration systems or by the establishment of settlement ponds or integrated secondary containment ponds.[99] Recently, effective water recirculation systems have become viable. Closed recirculation aquaculture systems are presently moving from the pilot phase to a more functional, industrial production phase, and are proving suitable for adoption by shrimp producers around the world. These systems can produce a high yield of shrimp and do so in inland facilities not affecting vital intertidal zones. Larger-scale recirculation system facilities are now in operation in Texas, Florida, Virginia, and other states in the US.[100] These systems hold great potential to supply shrimp to importing nations whose markets are currently supplied by largely unsustainable, open-system shrimp farming. Although there are expensive capital costs, it is likely that research and engineering will lead to viable systems of production providing affordable shrimps while being much less polluting and destructive.[101]

Some other systems are also making an effort towards sustainability in shrimp farming. Semi-closed systems utilising integrated aquaculture techniques are particularly promising. Integrated systems culture more than one species so that wastes from fish are used as nutrition by other species

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[96] Polidoro et al., n. 76 above.

[97] N. Powell, M. Osbeck, S.B. Tan and V.C. Toan, "World Resources Report Case Study. Mangrove Restoration and Rehabilitation for Climate Change Adaptation in Vietnam," (Washington, D.C.: World Resources Report 2009), available online: <http://www.worldresourcesreport.org>.

[98] Mangrove Action Project (2012). Sustainable Alternatives of Shrimp Aquaculture, available online: <http://mangroveactionproject.org/issues/shrimp-farming/sustainable-alternatives-of-shrimp-aquaculture>.

[99] *Id*.

[100] Alfredo Quarto, n. 77 above.

[101] E. Stokstad, "Down on the shrimp farm," *Science* 328 (2010): 1504–1505.

(see section V). Also, in Southeast Asia, some shrimp farms use the 'silvo-fisheries' system – an integrated forestry-fishery approach to aquaculture. These farm systems are integrated into intertidal landscapes so that the ecological functions of the mangroves are maintained.[102] Silvo-fisheries systems are a step in the right direction, but can fall short of ensuring that a functional, healthy, and biodiverse mangrove wetland is maintained or established alongside the ponds. Depending on how they are set up, these systems may not provide the services of a healthy mangrove forest because of alterations to the hydrology caused by the pond walls and limited variety of mangrove species able to exist in the area so utilized. Furthermore, the scale of shrimp production is less intense, and thus not as profitable for the shrimp industry in the short term, though these systems can have a much longer operational life span.[103]

Some headway has been made in the development of organic farming systems for shrimp aquaculture. Truly organic farming of shrimp would have advantages in that harmful chemicals and antibiotics would not be used, feed would be derived from sustainable sources, the farms would not be sited in ecologically sensitive areas, and people would not lose rights to their land. In Andhra Pradesh, India, a project has recently been initiated to start organic shrimp farming.[104] In three societies, ponds that were previously abandoned due to viral disease outbreaks have been used again successfully. Networks have been established between the small-scale farmers involved to promote information sharing. The success of the project gives incentives to re-use other abandoned ponds in the region using environmental sustainable methods. While these steps are very positive, it should be remembered that any newly constructed shrimp farming operations should be located out of the intertidal zone in closed or semi-enclosed systems in order to be environmentally sustainable.

According to MAP, certification of organic systems should include the following criteria to ensure that the true definition of organic farming is met in regards to environmental protection:

> 1) No further conversion of mangroves, saltflats, salt marshes and associated inter-tidal wetlands for aquaculture should be sanctioned;
> 2) Certification should abstain from sponsoring activities that displace traditional users, or take away their original customary rights; and
> 3) Certification must be part of a public process in which local communities are fully involved.

V. MOVING TOWARDS SUSTAINABILITY IN MODERN AQUACULTURE

Introduction

Any aquaculture that takes place needs to be sustainable and fair. In this regard, the FAO *Code of Conduct for Responsible Fisheries* contains principles and provisions in support of sustainable aquaculture development.[105] Greenpeace has also made recommendations for the sustainable and equitable development of aquaculture practices.[106] However, in many aquaculture systems today there are still environmental and social problems. Nunes et al. state that, "in many parts of the world the

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[102] S.R. Bush, P.A.M. Zwieten, L. Visser, H. van Dijk, R. Bosma, W.F. de Boer and M. Verdegen, "Scenarios for resilient shrimp aquaculture in tropical coastal areas," *Ecology and Society* 15, no. 2 (2010): 15. <http://www.ecologyandsociety.org/vol15/iss2/art15/>.
[103] Alfredo Quarto, n. 77 above.
[104] N.R. Umesh, A.B. Chandra Mohan, G. Ravibabu, P.A. Padiyar, M.J. Phillips, C.V. Mohan and B.V. Bhat, (2008), "Shrimp farmers in India: Empowering small-scale farmers through a cluster-based approach," in *Success Stories in Asian Aquaculture*, S.S. De Silva and F.B. Davy, eds., (Dordrecht Netherlands: Springer, 2008), 41–66.
[105] FAO, *Code of Conduct for Responsible Fisheries*, Article 9, Aquaculture Development, available online: <http://www.fao.org/docrep/005/v9878e/v9878e00.HTM#9>.
[106] Allsopp, n. 4 above.

blue revolution promises to be anything but green."[107] The costs of such non-sustainable production will be borne locally by future generations and will likely include symptoms such as losses in ecological services, and increased occurrence of harmful algal blooms.

Furthermore, Bert notes that the majority of countries where aquaculture is practiced are located in the world's 25 biodiversity hotspots and they have the most to lose in terms of biodiversity losses.[108] These are losses of world heritage. It is therefore vital that "the world's governments and the aquaculture industry have a continuing collective responsibility to work toward conducting ecologically and genetically sustainable aquaculture for all time, not just for the present."[109]

This considered, some headway towards sustainability has been made in addition to some traditional practices that are inherently more sustainable. For future developments aiming at sustainability, Bert suggests that there is a need to further develop small and medium-scale community-based aquaculture operations in poor areas of the world, particularly in rural areas.[110] Integrated, low-technology aquaculture systems are needed to ensure food security and poverty reduction as well as environmental protection. Consequently, governments must increase their support of small-scale aquaculture. Culturing species low in the food chain rather than carnivorous species is currently more ecologically sound (see section II). Culture of herbivorous species is less expensive both monetarily and environmentally. In addition, aquaculture of native species should be encouraged and financially supported. Culture of alien species should be discouraged, as they have the likelihood of generating adverse environmental effects if they escape or are released. Increasing species diversification in aquaculture is needed, but measures should also be taken to reduce escapes to the environment from all aquaculture facilities to near zero.[111]

We and others[112] therefore have suggested that further expansion of aquaculture should focus on the cultivation of low trophic level species rather than expanding higher trophic level species culture. As discussed in section III, several of the leading freshwater aquaculture species feed on 'green-water' plankton in ponds and consume little, if any, aquafeed and this cultivation could be expanded.[113] Other examples include cultivation of catfish in enclosed ponds in the USA;[114] integrated, organic, polyculture cultivation of carp species in Europe and Asia,[115] and cultivation of tilapia species in ponds and cages where it is native, or in enclosed systems in non-native areas.[116] Further suggestions on the development of aquaculture in a sustainable way are given in the following discussion.

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107 J.P. Nunes, J.G. Ferreira, S.B. Brickjer, B. O'Loan, T. Dabrowski, B. Dallaghan, A.J.S. Hawkins, B. O'Connor and T. Carroll, "Towards an ecosystem approach to aquaculture: Assessment of sustainable shellfish cultivation at different scales of space, time and complexity," *Aquaculture* 315 (2011): 369–383.

108 T.M. Bert, "Environmentally sustainable aquaculture: possibilities and realities," in *Ecological and Genetic Implications of Aquaculture Activities,* T.M. Bert, ed., (Dordrecht, The Netherlands: Springer, 2007), pp. 479–514.

109 Nunes et al., n. 107 above.

110 Bert, n. 108 above.

111 *Id*.

112 Merino et al., n. 5 above.

113 Neori, n. 74 above.

114 T. Ish and K. Doctor, "Channel catfish U.S. Farmed, *Ictalurus punctatus*," Monterrey Bay Aquarium 2005, available online: <http://www.montereybayaquarium.org/cr/cr_seafoodwatch/content/media/MBA_SeafoodWatch_USFarmedCatfishReport.pdf>.

115 European Union, "Fisheries and Aquaculture in Europe," June 2012, available online: <http://ec.europa.eu/fisheries/documentation/magazine/mag56_en.pdf>; Soil Association, "Farming carp," *Organic Farming Magazine*, Summer 2009, p. 38, available online: <http://transitionculture.org/wp-content/uploads/Aquaculture-article.pdf>.

116 I. Tetreault, "Farmed Tilapia, *Oreochromis, Sarotherodon, Tilapia,*" Monterrey Bay Aquarium 2009, available online: <http://www.montereybayaquarium.org/cr/cr_seafoodwatch/content/media/MBA_SeafoodWatch_FarmedTilapiaReport.pdf>.

In 2008, FAO outlined principles for an ecosystem approach to marine aquaculture and freshwater aquaculture.[117] These were:

> *Principle 1:* Marine Aquaculture: Aquaculture should be developed in the context of ecosystem functions and services (including biodiversity) with no degradation of these beyond their residence capacity.
> Freshwater Aquaculture: Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these services to society.
> *Principle 2:* Marine Aquaculture: Aquaculture should improve human well-being and equity for all relevant stakeholders.
> Freshwater Aquaculture: Aquaculture should improve human well-being and equity for all relevant stakeholders especially the more deprived sectors of society.
> *Principle 3:* Marine and Freshwater Aquaculture: Aquaculture should be developed in the context of other sectors and policy goals.

The following section discusses examples of experimental and commercial systems of aquaculture that have encompassed some or all of the above-mentioned requirements for sustainable aquaculture and guiding FAO principles.

Organic Aquaculture

Organic aquaculture aims to address issues of sustainability in the systems it uses. Organic aquaculture is steadily increasing and could help to reduce the ecological footprint of the aquaculture sector.[118] Organic aquaculture aims at producing high quality products by no use of processes harmful to the environment, human, plant, or animal health and animal welfare. Inputs must be organic and no genetically modified organisms are permitted.[119]

Antibiotics are in widespread use in aquaculture to prevent or treat disease outbreaks.[120] Their use in freshwater and marine-based aquaculture has resulted in the emergence of reservoirs of anti-microbial resistant bacteria both in the aquatic environment,[121] and in cultivated fish and shrimp.[122] This could result in adverse ecological and public health effects. Improvements in regulation and management of antibiotics in aquaculture have therefore been recommended.[123]

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[117] B.A. Costa-Pierce, "An ecosystem approach to marine aquaculture: A global review," in *Building an Ecosystem Approach to Aquaculture*, D. Soto, J. Aguilar-Manjarrez and N. Hishamunda, eds., (FAO/Universitat de les Illes Balears Expert Workshop 7–11 May 2007, Palma de Mallorca, Spain 2008), FAO Fisheries and Aquaculture Proceedings, No. 14. FAO, Rome. pp. 81–115; J. Hambrey, P. Edwards and B. Belton, "An ecosystem approach to freshwater aquaculture: A global review," in Sotoet al., *Id*., pp. 117–221.

[118] C. Perdikaris and I. Paschos, "Aquaculture and fisheries crisis within the global crisis," *Interciencia* 36, no.1 (2011): 76–80.

[119] E. Mente, I.T. Karalazos, I.T. Karapanagiotidis and C. Pita, "Nutrition in organic aquaculture: An inquiry and a discourse," *Aquaculture Nutrition* 17; e798–e817.doi (2011): 10.1111/j.1365-2095.2010.00846.x.

[120] O.E. Heuer, H. Kruse, K. Grave, P. Collignon, I. Karunasagar and F.J. Angulo, "Human health consequences of use of antimicrobial agents in aquaculture," *Clinical Infectious Diseases* 49, (8): 1248–1253; A. Sapkota, A.R. Sapkota, M. Kucharski, J. Burke and S. McKenzie, "Aquaculture practices and potential human health risks: Current knowledge and future priorities," *Environment International* 34 (2008): 1215–1226.

[121] Sapkota et al., n. 120 above; L. Nonaka, K. Ikeno and S. Suzuki, "Distribution of tetracycline resistance gene, tet(M), in gram-positive and gram-negative bacteria isolated from sediment and seawater at a coastal aquaculture site in Japan," *Microbes and Environments* 22, (4) (2007): 355–364; Y.B. Zhang, Y. Li and X.L. Sun, "Associated resistance of bacteria isolated from shrimp hatcheries and cultural ponds on Donghai Island, China," *Marine Pollution Bulletin* 62, (11) (2011): 2299–2307.

[122] S. Banjeree, M.C. Ooi, M. Shariff and H. Khatoon, "Antibiotic resistant Salmonella and Vibrio associated with farmed *Litopenaeus vannamei*," *Scientific World Journal* 2012, Article ID 130136, (2012): 1-6; F. Matyar, "Distribution and antimicrobial multiresistance in fram-negative bacteria isolated from Turkish sea bass (*Dicentrarchus labrax* L., 1781) farm," *Annals of Microbiology* 57, (1) (2006): 35–38.

[123] Sapkota et al., n. 120 above.

In organic aquaculture, the prophylactic use of antibiotics is not allowed and, instead, natural veterinary treatments are used such as homeopathic preparations, herbal compounds, minerals, natural immuno-stimulants, and probiotics. Using such substances could play a significant role in disease prevention and cure in future sustainable aquaculture.[124] Defoirdt et al.[125] also discuss other possible methods of disease prevention, currently at the research stage, which may help reduce the use of antibiotics in aquaculture.

Integrated Multi-Trophic Aquaculture

There are two different types of mariculture, 'fed' and 'extractive'. In fed aquaculture, species such as finfish are given feed, whereas in extractive aquaculture, species such as shellfish and seaweed take their nutrients from the surrounding waters. Aquaculture operations in most countries are based on a monoculture system where the fed and extractive species are cultivated in separate bays or regions. For example, in Japan aquaculture is mostly carried out in coastal bays that are individually dedicated to shellfish, fish, or seaweed cultivation.[126] Thus, any potential synergy between the different types of mariculture is lost.[127] A more sensible and environmentally advantageous approach would be to geographically couple the cultivation of fed and extractive species. This would enable the nutrient effluents from finfish cultivation to be taken up as a food source by shellfish or seaweed, effectively converting the culture wastes into growth of another species which itself can be harvested.[128] A further advantage is that the production capacity of an existing site is significantly increased, a necessity in a world with a growing population. This type of mariculture has been termed integrated multi-trophic aquaculture (IMTA). It is not a new concept. For example, Asian marine polyculture in coastal waters uses wastes from caged fish farms to boost nearby rafts of filter-feeding shellfish and nutrient scrubbing seaweeds.[129] However, at present, in most countries monoculture is sadly still the norm.

The IMTA concept is very flexible. It can be used for both open-water and land-based systems and marine and freshwater systems. In Canada, an interdisciplinary team of scientists has been working together to establish an IMTA approach to the cultivation of Atlantic salmon, kelps, and blue mussel in the Bay of Fundy since 2001.[130] Research demonstrated increased growth rate of kelp (46 percent) and mussels (50 percent) cultured adjacent to salmon farms compared with reference sites, a reflection of the increased food source near the cages. Kelp and mussels can be safely harvested as seafood for human consumption.[131] Eight of the 96 cod or salmon finfish sites in south-western New Brunswick practice co-cultivation with mussels and kelp and eight other sites have been amended to develop IMTA.[132]

Examples of IMTA systems that are currently in commercial production include the following:

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[124] Mente et al., n. 119 above.

[125] T. Defoirdt, P. Sorgeloos and P. Bossier, "Alternative to antibiotics for the control of bacterial disease in aquaculture," *Current Opinion in Microbiology* 14 (2011): 251–258.

[126] K. Barrington, T. Chopin and S. Robinson, "Integrated multi-trophic aquaculture (IMTA) in marine temperate waters," in *Integrated Mariculture: A Global Review,* D. Soto ed., (FAO Fisheries and Aquaculture Technical Paper, 2009), No. 529. Rome, FAO), pp. 7–46.

[127] T. Chopin, S.M.C. Robinson, M. Troell, A. Neori, A.H. Buschmann and F. Fang, "Integration for sustainable marine aquaculture," in *Ecological Engineering,* S.E. Jørgensen and B.D. Fath eds., (Oxford: Elsevier, 2008),Vol. 3 of Encyclopaedia and Ecology, 5 vols., pp. 2463–2475.

[128] A. Neori, M. Troell, T. Chopin, C. Yarish, A. Critchley and A.H. Buschmann, "The need for a balanced ecosystem approach to blue revolution aquaculture," *Environment* 49, no. 3 (2007): 36–43.

[129] *Id*.,

[130] Chopin et al., n. 127 above.

[131] Barrington et al., n. 126 above.

[132] T. Chopin, M. Troell, G.K. Reid, D. Knowler, S.M.C. Robinson, A. Neori, A.H. Buschmann and S. Pang, "Integrated multi-trophic aquaculture. Part II. Increasing IMTA adoption," *Global Aquaculture Advocate* November/December (2010): 17–20.

- Barrington et al.[133] give several examples of IMTA systems around the world. These include the cultivation of red algae in tanks that receive seawater from Pacific halibut and sablefish culture; systems where wastewater from shrimp aquaculture is used to feed herbivorous mullet and oyster; and the cultivation of abalone alongside kelp as a feed source for the shellfish. The latter is an on-land integrated culture unit performed in raceways and is seen as a way forward for the industry, in particular because wild kelp beds used as feed for abalone culture are now reaching limits of exploitation.
- In Israel, a commercial IMTA system is used to cultivate abalone, gilthead seabream, and seaweed. The seawater pumped through the tanks is considered to meet all local environmental regulations for point-source discharge and is released to a nearby estuary.[134]
- Aquaponics is an integrated system that links hydroponic production of vegetables/fruits with recirculating aquaculture. Plants are able to utilise the nutrient wastes from fish cultivation for their growth, thus reducing water usage and waste discharge to the environment.[135] Systems can be organic and completely closed so there is no waste output and water is conserved. The size of operations varies from backyard systems to small and large commercial farms supplying local markets. For example**,** SoCal Aquaponics in the US is a commercial operation that grows tilapia, shrimp and vegetables.[136] An Australian company, Aquaponics Solutions, has set up a project to introduce aquaponics to Pacific islands for food security and small business development, as well as a project to introduce large-scale aquaponics to Singapore.[137]

If future aquaculture developments follow the approach typified by IMTA, planning and management could be better integrated, providing for greater food security and reducing the negative ecological and economic impacts of poorly conceived aquaculture practices that have occurred in the past.[138] Regulatory and financial incentives maybe required in order to account for the benefits of biomitigation arising from IMTA systems, which can greatly reduce problems of waste nitrogen, carbon, and phosphorus.[139]

Among the critical steps needed to develop sustainable IMTA systems are the selection of the right combination of species, the use of native species to prevent the risk of release of invasive alien species,[140] and the reduction and prevention of disease transmission within and between aquaculture facilities and to natural aquatic species.[141]

Integrated Rice-Fish Culture

A very promising form of aquaculture with huge potential for sustainable expansion in support of food security is the production of fish in rice fields, known as integrated rice-fish culture. Rice-fish culture in China dates back 2,000 years and is also practiced today in several countries. However, the practice is still marginal in most countries with the exception of China (production of 1.2 million tonnes in 2010), Indonesia (92,000 tonnes in 2010), Egypt (29,000 tonnes in 2010), and Thailand 21,000 tonnes in (2008).[142]

In China, rice-fish culture has grown 13-fold in the last two decades. It has made a substantial contribution to national food security and significantly enhanced the income of rural farmers, as well

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133 Barrington et al., n. 126 above.
134 Chopin et al., n. 127 above.
135 R.V. Tyson, D.D. Treadwell and E.H. Simonne, "Opportunities and challenges to sustainability in aquaponic systems," *HortTechnology* 21 (February 2011): 6–13.
136 SoCal Aquaponics**,** 2012, available online:<http://socalfishfarm.com/fish/>.
137 Aquaponic Solutions, 2012, available online: <http://www.aquaponic.com.au/index.htm>.
138 A.M. Nobre, D. Robertson-Andersson, A. Neori and K. Sankar, "Ecological-economic assessment of aquaculture options: Comparison between abalone monoculture and integrated multi-trophic aquaculture of abalone and seaweeds," *Aquaculture* 306 (2010): 116–126.
139 Chopin et al., n. 127 above.
140 *Id*., Chopin et al., n. 127 above.
141 Soto, n. 126 above.
142 FAO, n. 1 above.

as providing incentives to remain settled in rural areas. Since the late 1990s, development of rice-fish culture focused on moving towards a more environmentally sustainable production of rice because this system reduces the need for herbicides and pesticides and even organic production is possible.[143] Experiments have shown that the incidence of rice diseases and pests are more effectively controlled by the presence of fish.[144] The fish eat weeds that lessen the need for herbicides. Excreta from the fish serve to fertilize the rice, reducing the need for inorganic fertilizers. Fish disease is considerably reduced when compared with pond aquaculture. According to Weimin, in many areas, traditional rice-fish culture has transformed into organic food production systems.[145] Although the fish feed naturally, grains can be added as supplementary feed to achieve higher yields.

In Bangladesh, field studies of rice-fish culture have been successful in culturing significant quantities of fish and gave benefits of weed- and pest insect-control.[146] Rice-fish farming in Bangladesh is not widely practised as yet, though studies have shown that current rice-fish farms in the district of Mymensingh produced a greater quantity of rice than traditional monocultures, and had the further advantage of significant fish production.[147] Ahmed and Garnett stated that, although rice monoculture is still the dominant farming system in rural Bangladesh, rice-fish integration could provide a social, economic, environmental, and nutritionally viable alternative for resource-poor farmers and help meet the ever-increasing demand for rice and fish of a growing population.[148]

Asia provides more than 90 percent of the world rice production and, with some 140 million hectares of rice fields, the potential of future rice-fish culture is immense. Effort and active support by governments and NGOs is essential to demonstrate environmentally sustainable management practices to rice farmers, and actively promote this method of farming with institutional, organizational, and technical support and training.[149]

Optimisation of Water Use

Existing water bodies such as irrigation reservoirs can be used for the sustainable cultivation of fish without causing impediment to their primary use. These culture-based fisheries (CBF) are based mainly or entirely on the recapture of farm-produced 'seed' stocked in water bodies after an adequate growth period. The fish rely on the natural productivity of the water for growth. In Sri Lanka and Northern Vietnam, CBF systems are now in place and have brought improved income generation and food-fish availability to rural communities. This system of aquaculture requires only minimal capital investment, particularly benefits rural communities and contributes to food security. There is potential for its further uptake by other countries.[150]

Urban aquaculture is a term used to describe the use of recirculating aquaculture systems as they can be sited in any suitable location. Recirculating systems, in their simplest form, consist of a fish tank and a water treatment unit. Water is (partially) re-used after undergoing treatment, thus giving an advantage of reducing water usage as well as improving waste management and nutrient recycling.

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143 M. Weimin, "Recent developments in rice-fish culture in China: A holistic approach for livelihood improvement in rural areas," in De Silva and Davy, n. 104 above, pp. 15–40.

144 J. Lu and X. Li, "Review of rice-fish farming systems in China – One of the Globally Important Ingenious Agricultural Heritage Systems (GIAHS),"*Aquaculture* 260 (2006): 106–113.

145 Weimin, n. 143 above.

146 M. Frei, M.A.M. Khan, M.A. Razzak, M.M. Hossain, S. Dewan and K. Becker, "Effects of a mixed culture of common carp, *Cyprinus carpio* L., Nile tilapia, *Oreochromis niloticu*s (L.), on terrestrial arthropod population, benthic fauna, and weed biomass in rice fields in Bangladesh," *Biological Control* 41 (2007): 207–213; M.A. Frei, M.A. Razzak, M.M. Hossain, M. Oehme, S. Dewan and K. Becker, "Performance of common carp, *Cyprinuscarpio* L. and Nile tilapia, *Oreochromis niloticu*s (L.) in integrated rice-fish culture in Bangladesh," *Aquaculture* 262 (2007): 250–259.

147 N. Ahmed and S.T. Garnett, "Integrated rice-fish farming in Bangladesh: Meeting the challenges of food security," *Food Security* 3 (2011): 81–92**.**

148 *Id*.

149 Weimin, n. 143 above; Ahmed and Garnett, n. 147 above.

150 U.S. Amarasinghe and T.T.T. Nguyen, "Enhancing rural farmer income through fish production: Secondary use of water resources in Sri Lanka and elsewhere," in De Silva and Davy, n. 101 above, p. 103–130.

Recirculating systems can be used to farm freshwater and marine fish and can be sited away from the coast and near to markets, lessening the carbon dioxide emissions associated with food transport. In recirculating systems, the food conversion ratio for fish (the ratio reflects the relative efficiency at which fish assimilate feed) can be optimized and yield of fish can be increased.[151]

Despite the potential environmental advantages, the contribution to aquaculture production using recirculating systems is still small due to high initial set-up costs. However, recirculating systems offer the possibility to achieve a high production and improve animal welfare, while creating a minimal environmental impact. Waste can be used in IMTA systems effectively, making nearly closed systems that can be environmentally sustainable.[152] Recirculating systems are one of the current and future platforms that offer a more sustainable method for farming marine and freshwater fish.[153]

Optimisation of Land Use

Rice-fish culture (see above) maximizes utilisation of water resources and agricultural land. Optimisation of land use could also include taking advantage of disused/unviable agricultural land for aquaculture. For example, in Banat, a region of Serbia, research has suggested that about 200,000 ha of land in the vicinity of a canal system that is not suitable for agricultural activity could be used for the organic polyculture cultivation for carp and other species.[154]

Integration of Aquaculture with the Environment

In southern Spain in 1982, a fish farm, Veta La Palma, was established on wetlands that had previously been drained for cattle farming but then re-flooded to introduce aquaculture.[155] The tides are allowed to sweep into the estuary water where a pumping station distributes water into the farm's 45 ponds. The local fish species are fed naturally by microalgae and shrimp coming in with tidal seawater. The area has become a haven for birdlife since the farm was established. Previously there were 50 bird species but now there are 250, including some endangered species. The birds are able to forage in the fish ponds leading to a reduction in production of about 20 percent, which the company allows in order to support the area's biodiversity. The farm business is nevertheless very successful.[156]

V. CONCLUSIONS

This article has focused on two (of several) major obstacles to be overcome in order to achieve sustainable aquaculture and on opportunities for more sustainable practices now and into the future. In this context, the following recommendations are made:

1. The equitable use of fish protein is paramount to human food security. Lessening the dependence of aquaculture on fishmeal and fish oil derived from wild pelagic fish stocks is therefore recommended, along with the diversion of these fish for direct human consumption wherever possible within the limits of sustainability. Because of the importance of these fish

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[151] Y. Tal, H.J. Schreier, K.R. Sowers, J.D. Stubblefield, A.R. Place and Y. Zohar, "Environmentally sustainable land-based marine aquaculture," *Aquaculture* 286 (2009): 28–35.
[152] C.I.M. Martins, E.H. Eding, M.C.J. Verdegem, L.T.N. Heinsbroek, O. Schneider, J.P. Blancheton, E. Roqued'Orbcastel and J.A.J. Verreth, "New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability," *Aquacultural Engineering* 43 (2010): 83–93.
[153] Tal et al., n. 151 above.
[154] Dragana Ljubojević, Research Assistant, University of Novisad, based on Ph.D. thesis pending publication, pers. comm. (28 May 2012).
[155] L. Abend, "Sustainable aquaculture: net profits," *Time* (2009), available online: <http://www.time.com/time/magazine/article/0,9171,1902751,00.html>.
[156] *Id*.; K. Svadlenak-Gomez, Ecoagriculture Snapshot, Biodiversity-friendly aquaculture on the Veta La Palma Estate, Spain, 2010, available online: <http://www.ecoagriculture.org/case_study.php?id=77>.

in marine ecosystems, it is necessary that stocks be managed using an ecosystem approach to achieve environmental sustainability.

2. Increasing rates and extent of conversion to the cultivation of low trophic level species is recommended to optimise food security from aquaculture operations and provide sufficient food for an increasing human population. Establishing integrated multi-trophic aquaculture systems, increasing rice-fish culture and culture-based fisheries could all make significant contributions to this. Organic cultivation in all of these systems represents the most sustainable way forward. Cultivation of native species is recommended where there is a risk of escapes to the environment. Recirculating system technology represents a way of cultivating non-native species and can be located close to markets, lessening the carbon footprint.
3. Substitution of fishmeal and fish oil in the diet of all fed species, as far as possible, with alternative feed sources derived from sources that are themselves sustainable, is recommended, including by the use of fishery by-products, discards, marine algal oils, animal by-products, and plant proteins.
4. Where the intensive cultivation of higher trophic fish is continued, switching to integrated multi-trophic aquaculture systems will improve environmental sustainability. This includes the use of recirculating systems.
5. The conservation of mangrove ecosystems is critical for the many environmental, coastal protection, and human services they provide. Furthermore, ecological restoration of degraded mangroves is necessary in the same regard. It is recommended that any new shrimp farming operations be primarily located out of and behind the intertidal zone. Closed recirculation aquaculture systems represent a more sustainable way forward, particularly using biofloc technology and/or incorporation in integrated multi-trophic aquaculture systems.
6. Where cultivation of shrimp in the coastal zone continues, it is recommended that silvo-fishery systems and organic systems are used, which are sensitive to the wetland habitat and restoration of native mangrove ecosystems in their vicinity is conducted wherever possible.