Role of Aquaculture in Increasing Water Productivity

1 author:

Randall E. Brummett
World Bank

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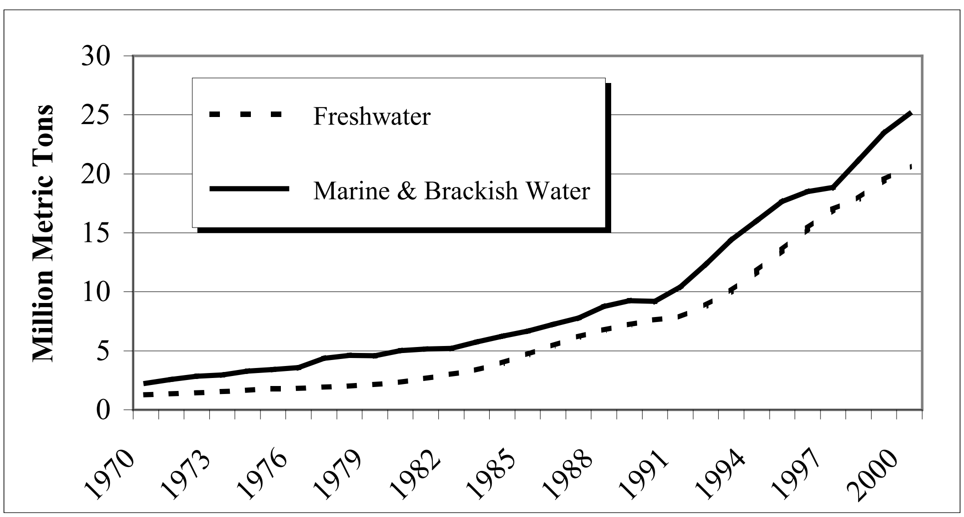
Randall E. Brummett
WorldFish-Cameroon
BP 2008 (messa)
Yaoundé

r.brummett@cgiar.org

Aquaculture, the farming of aquatic animals and plants, is a well-established industry in many parts of the world. Aquaculture has, in fact, replaced inland capture fisheries as the most important source of freshwater fish (Revenga et al. 2000). According to FAO statistics, aquaculture's contribution to global supplies of freshwater and marine species has grown from 3.9 percent of total production by weight in 1970 to 27.3 percent in 2000. Overall, aquaculture has increased at an average compounded rate of 9.2% per year since 1970, compared with only 1.4% for capture fisheries and 2.8% for terrestrial animal production (FAO 2002). In 2000, total aquaculture production reported to FAO was 45.7 million metric tons with a value of $56.5 billion US dollars. Almost half of the total, some 20.2 million metric tons was produced in freshwater (Figure 1).

Figure 1. Global aquaculture production reported to the Food & Agriculture Organization of the United Nations over the period 1970-2000 (FAO 2002).



In terrestrial farming systems, most animal and plant production is based on a limited number of species, compared to the more than 210 different farmed aquatic animal and plant species grown in aquaculture. This diversity reflects the large number of aquatic species adaptable to the wide range of production systems and conditions present in the different countries and regions of the world.

Since 1970, aquaculture production in developing countries has been growing at an average annual rate of approximately 10%. Excluding marine shrimp, the bulk of aquaculture production in developing countries is comprised of omnivorous or herbivorous fish that feed low on the food chain. In contrast, nearly 75% of finfish production in industrialized countries is of carnivorous species, whose feed contains large amounts of fish meal, raising questions of sustainability and efficiency that have attracted the attention of development planners and regulators.

Because of the variety of production systems used (cages suspended in lakes or rivers, earthen ponds, flow-through or recirculating raceways) it is difficult to correlate the increases in production seen over the last three decades with increases in land and/or water use. In addition, most aquaculture has been steadily intensifying through the use of new water, fuel and food conserving technologies. In 2001, the aquaculture industry in Florida, USA was typical of many countries with a diversity of small-scale operators producing a range of species[1] (FASS 2002). Of the 684 operations, 319 (47%) used less than 0.75 ha of land and/or water. Another 150 (22%) used 0.75-1.25 ha. There were only 25 operations using over 10 ha of land and/or water. The overall average is 4.15 ha per aquaculture installation. These farms are somewhat larger than the 1-3 ha land holding typical of tropical developing countries (Hayami & Ruttan 1971), but they are also somewhat smaller than the typical fish farm in Europe and America, 44 ha per catfish farm in the US in 1993, according to Waldrop & Wilson (1996). If the numbers for Florida can be reliably extrapolated, aquaculture globally occupies some 30 million ha of land and/or water surface.

Freshwater use in Aquaculture

The aquaculture sector is composed of production systems that occupy many scales and intensities. Economical carrying capacity of aquaculture farms can vary between 30kg/m^3 for intensive cage or flow-through raceway systems to 0.8 kg/m^3 for static water earthen ponds. Experimental systems have produced as much as 850 kg/m^3 in African catfish (*Clarias gariepinus*) raceways and up to 40 tons/ha in earthen ponds, with water flow requirements of about 2 000 l/kg of fish produced (Hecht et al. 1996, Hecht 1997). Typical production in less industrialized countries ranges from about 5 000 kg/ha in large-scale commercial to 1 100 kg/ha in small-scale artisanal systems.

Table 1. Estimated water requirements to produce 1 kg of common food crops (Piemental et al. 1997).

Crop	Litres/kg
Potatoes	500
Wheat	900
Sorghum	1 110
Corn	1 400
Rice	1 912
Soybeans	2 000
Broiler Chickens	3 500
Beef	100 000

All food production systems require water (Table 1). Fish production, being conducted entirely underwater, would seem to be potentially one of the greater consumers. However, consumptive use of water by aquaculture is, in theory, negligible. Also, aquaculture has the advantage over

[1] In order of economic importance: ornamental fish & plants, clams, penaeid shrimps, alligators, channel catfish, tilapia, hybrid striped bass (*Morone spp*), largemouth bass (*Micropterus salmoides*), bream (*Centrarchidae*), Chinese carps, crawfish (*Procambarus clarkii*), eels, snails, turtles, crabs, frogs, and oysters.

Figure 2. Ponds in the Jordan Valley covered and lined with plastic to prevent evaporative and seepage losses.

rainfed plant crops by being somewhat disconnected from rainfall periodicity. Through the use of recirculating systems and/or integration of aquaculture into other water use schemes, consumptive use of water can be reduced even further to the amount lost to evaporation and leakage, which, in water stressed areas are often controlled with the use of plastic liners and/or greenhouse-like covers (Figure 2).

For example, pond production of channel catfish (*Ictalurus punctatus*) yields an average of around 4 200 kg/ha of fish on a feed input of 5 900 kg/ha (Schwartz & Boyd 1994). Using the figures of Pimentel et al. (1997), it takes approximately 1.54 million liters of water to produce 1 metric ton of typical catfish food, containing 48% soybean meal and 41% corn meal (Lovell 1989). A high estimate of water usage in pond culture of catfish in the Southeastern United States is 17.5 million liters per hectare per year, if all the water from pond draining is lost (Boyd 1995). Adding the amount of water needed for feed production and the amount lost to evaporation and seepage from, and draining of, ponds gives an estimate of 6 300 l of water per kg of channel catfish produced. In the best ponds (i.e., those with low seepage and evaporation rates), and with reuse of pond draining water for irrigation, the figure is 3 350 l/kg, less than the amount needed to produce broiler chickens. Losordo, et al. (2001), extrapolating from total production estimates for the US catfish industry, calculated an average realized water requirement of 3 000 l/kg of catfish.

Figure 3. Kafue Fisheries near Lusaka, Zambia produces 10-12 tons of tilapia per month, primarily on inputs of pig manure.

Tilapia (family Cichlidae) culture in ponds (Figure 4) is growing rapidly. While producing the feed used by commercial growers requires about the same amount of water needed for catfish feeds, tilapia can take advantage of natural food webs fueled by manures and other agricultural by-products in place of feeds for part of the production cycle (Green 1992). If the first two months of tilapia feed is replaced by manures and pond draining water is recycled, the amount of water needed to grow the feed and replace seepage and evaporation losses is 2 800 l per kg of tilapia grown. Tilapia have the added advantage of not requiring particularly fresh water. In fact, they probably do a little better if the water is a bit brackish.

Figure 4. Trout raceways in Zabadani, Syria take advantage of abundant cool freshwater from the Golan Heights.

Another common fish production system is the flowing-water raceway (Figure 4). Production of trout in such systems requires about 600 000 l of water per metric ton of fish per day (Stevenson 1987) and the feed has less water consumptive components than catfish feeds, requiring about 1 million litres per ton of feed. A conservative estimate of time to market size (30-35 cm) is 14 months (Bardach et al. 1972). At a food conversion ratio (FCR) of 1.5, this translates into a water usage of 253 500 l/kg if all the water is discarded. However, because trout raceway water can easily be cleaned and replaced into the watershed, the actual amount of water lost is minimal.

Figure 5. The cages of Lake Harvest, Ltd. in Lake Kariba, Zimbabwe produce 50 kg of tilapia per m^3.

The last major fish production system is cages placed in natural or artificial waterbodies (Figure 5). Because they do not appropriate any water, their consumptive use is virtually nil, but if improperly located cages can contribute to eutrophication and lowering of water quality. Because they are grown at high densities and are isolated from the benthos, fish in cages have limited access to natural foods and thus normally convert feed less efficiently. Relatively poor FCR’s of over 2.0 are not uncommon, but even with an FCR of 3.0 channel catfish from cages use no more water than chickens. If the catfish are replaced with more efficient tilapias, consumptive water use can be further reduced.

Within these categories of production system, variation is huge, depending primarily upon level of intensity (roughly equivalent to energy expenditure), species and temperature (Table 2). Overall, commercial freshwater aquaculture of the types described, probably uses something on the order of 5 m^3 of water per kg of fish produced, which extrapolates to a global total of some 101 thousand million m^3 of freshwater per year, although most of this use is non-consumptive, being either directly usable for other purposes or indirectly usable following settling or biofiltration to remove excessive nutrients and/or suspended solids.

Table 2. Water requirements for various aquaculture systems (Phillips et al. 1991).

Species	**System**	**Country**	**Production (mt/ha)**	**Water Requirements (m^3/mt)**
Clarias batrachus	Intensive, static ponds	Thailand	100-200	50-200
Oreochromis niloticus	Extensive, static ponds		0.05-0.3	3 000 – 5 000
O. niloticus	Sewage, minimal exchange ponds	Thailand	6.8	1 500-2 000
O. niloticus	Intensive, aerated ponds	Taiwan	17.4	21 000
Carp/Tilapia Polyculture	Conventional ponds	Israel	3	12 000
Carp/Tilapia Polyculture	Semi-intensive ponds	Israel	9	5 000
Carp/Tilapia Polyculture	Intensive ponds	Israel	20	2 250
Common Carp	Intensive raceways	Japan	1443	740 000
Channel Catfish	Intensive ponds	USA	3	6 470
Channel Catfish	Intensive raceways	USA		29 000-14 500
Various	Various	Europe		15 768-5 544 029
Rainbow trout	Raceways	USA	150	210 000
Salmonids	Ponds/Tanks	UK		252 000
Salmonids	Cages	Scotland	40-200	2 260 000
Penaeid shrimp	Semi-intensive ponds	Taiwan	4.2-11	11 000-21 430
Penaeid shrimp	Intensive ponds	Taiwan	12.6-27.4	29 000-43 000
Penaeid shrimp	Intensive raceways	Mexico	11.8	55 125

Aquaculture and Society

Increased production, *per se*, may or may not improve the lives of the people who depend on fish for their food and livelihoods. Large-scale industrial aquaculture can tranform local natural resources into food for the already wealthy, often foreign, consumers (Brummett 2003). The aquaculturist, like any other commercial farmer wants to maximize his or her returns, not just profit margin. There are two general strategies for maximizing returns:

1. Produce a relatively small quantity of a high profit margin product (e.g., luxury seafood).
2. Produce a large quantity of a cheap product (i.e., "commodities").

Table 3. Wholesale market value of major aquaculture products grown in 1998 in sub-Saharan Africa (SSA) in million US dollars (FAO 1999).

	MT Grown	Value SSA (USD per MT)	Value Europe (USD per MT)
Cyprinids	2921	1880	591
Salmonids	1769	2830	2898
Tilapias	12238	1706	4001
Other Freshwater Finfish	10860	2170	691
Marine Shrimps	5626	7053	15367
Bivalves	3169	2058	1076
Algae	3153	274	346
Other Mariculture	4	3925	6452

In Africa and South Asia, over 40% of the population lives on less than one US dollar per day; in East Asia and Latin America the figure is about 25% (World Bank 2000). To mass-produce low-value species at the lowest possible cost to feed these people, one would need to use systems based on low-cost inputs. Without chemicals, machinery, electricity and feeds, one could safely anticipate standing stocks of no more than 3 000 – 5 000 kg/ha depending on the species grown. To produce 14 kg of fish per person per year for the 10.5 million people who live in the African country of Malawi, for example, with such a system would require between 28 000 and 46 000 hectares of land. If the 80% of the Malawian population that makes less than 200 USD per household per year were able to spend 10% of total income on fish, a fish farmer could expect to gross about $1 500 per hectare. The same farmer, with the same system but targeting the wealthiest 10% of the population that lives in cities (average annual income of $12 000 per household), could theoretically gross some $60,000 per hectare (World Bank 1996).

This competition with wealthier markets, both locally and internationally, works against the production of cheap fish for the poor (Street and Sullivan 1985). For example, low-tech tilapia production can gross over $8 500 per hectare if the fish are sold in the African wholesale market (Table 3). Exported to Europe, the same fish are worth over twice as much. Producing shrimp for Europe instead of tilapia for Africa could increase gross receipts by over 9 times. It takes a true philanthropist to ignore these figures and the global aquaculture investment pattern shows that philanthropy is taking a back seat to profits, even in situations where people are literally starving to death. In 1998, sub-Saharan African production of difficult-to-grow luxury mariculture products was almost the same, approximately 12 000 metric tons (MT), as that of easy-to-rear tilapias (FAO 1999).

To maximize the benefits accruing to societies that invest in aquaculture development, public and private sectors must develop a strong, interactive relationship. Sometimes employment, food security and environmental considerations must be traded against each other and other development options, in the setting of water use priorities.

Employment in Aquaculture

Aquaculture is already a significant employer and the contribution to global employment is increasing (Table 4). Since 1970, the number of aquaculture workers increased by an annual average of about 7%. Most of the growth of employment in fish farming has occurred in Asia, particularly in China, where the number of people reported engaged in aquaculture has doubled since 1990. Compared to the other major employer in coastal areas, capture fishing, greater economic opportunities derive from commercial aquaculture. For example, in 1999 the average annual income of Japanese households engaged in aquaculture was nearly twice as much as that of households engaged in coastal fishing. While the households engaged in aquaculture derived an average 64% of their income from aquaculture, capture fishing accounted for only 38% of the income of fishing households.

Table 4. Number (thousands) of fish farmers by continent (FAO 2002).

	1990	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Africa				5	6	14	62	55	56	57	75
North & Central America	53	73	101	206	206	176	182	185	191	190	190
South America	16	15	15	20	30	43	44	42	41	42	41
Asia	3 698	3 882	4 292	4 927	5 389	6 003	6 051	6 569	6 758	6 930	7 132
Europe	11	12	13	23	26	18	23	25	25	26	27
Oceania					1	1	4	5	5	5	5
Total	**3 778**	**3 983**	**4 423**	**5 182**	**5 657**	**6 254**	**6 366**	**6 880**	**7 075**	**7 249**	**7 470**

Aquaculture and Food Security

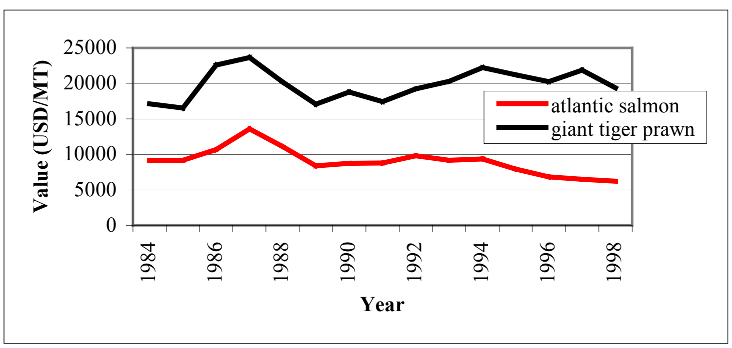
Agriculture in general is different than most businesses because, in addition to generating jobs and income, it produces the food we absolutely must have to survive. Modern agriculture produces enough food to feed the world. The problem is distribution, or more precisely, the inequitable distribution of the financial resources necessary to obtain food.

Although globally fish are one of the most widely consumed sources of animal protein, in industrialized countries seafoods are generally regarded as luxury or specialty products. Prices for salmon, seabass, shrimp, oysters and other such high value commodities can rise or fall and the effects are on producer profit margins. In poorer countries of Africa, Asia and Latin America, fish are often a critically important part of the daily diet and in its absence people suffer from malnutrition, particularly protein deficiencies. Increasing population on these continents, coupled with declines in capture fisheries resulting from over-exploitation and environmental degradation, have rendered these people vulnerable to even minor perturbations in fish supply. Having said that, demand for fish, unlike agriculture of staple crops, is seldom a matter of life or death, but rather an opportunity for profitable aquaculture.

The role of aquaculture in food security has been a major concern of the industry for some time. Bridging the gap between fish supply and demand was the theme of the 1999 World Aquaculture Society annual meeting in Australia. From the point of view of food security, the most important recent trend in aquaculture has been the convergence of production and market value (Figure 6). Overall, the driving force behind the relative increase in production and decline in value appears to be declining prices for luxury (Figure 6a) and commodity (Figure 6b) products as markets are becoming saturated and competition is increasing. However, as the trend for tiger prawn in Figure 6a illustrates, these declines are related to specific market situations. The tiger prawn industry suffered serious technical problems due to self-pollution and disease in the early 1990's that reduced production and forced prices significantly higher, and from which the industry has not yet fully recovered.

Figure 6. Reported value of global aquaculture production in 1998 for luxury seafood products (a) and commodities (b) after FAO (1999).

a.



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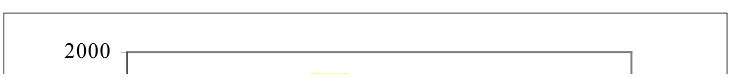
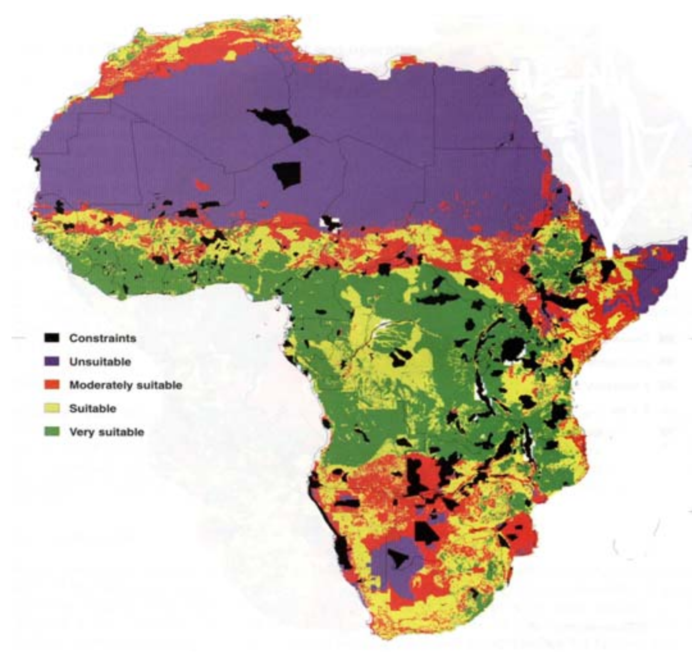


Within the luxury products market, the industry's response to market saturation has been an attempt at species diversification and the production of more specialized products. In a recent survey, Abellan & Basurco (1999) found that Mediterranean countries involved in aquaculture are currently investigating between 5-10 new species each. In addition, new marketing strategies and value added products are under consideration. With the large profits that are potentially possible from production of luxury products for wealthy markets, the scramble for technological advantage and market share will most likely produce further consolidation. However, unavoidable high overheads, such as rental of sites with access to good water, expensive hatchery technology and the cost of high-protein formulated feeds, will keep prices from declining to the point where these products can compete with lower value species in commodity markets for the foreseeable future.

Within the commodity markets, increases in production have brought wholesale prices down to about $1000 per MT. At this price, lower income consumers may be beginning to benefit from commercial fish farming. However, most of these gains have come in China and a few other Asian countries where local demand is high and aquaculture has already become an important part of the food production system. It is worth noting that China, being the single largest producer of lower-priced commodity fish, developed most of it's low-cost aquaculture under the command economy of the early 20th century, and the sustainability of these production systems in a globalised economy is questionable. In any case, the spread of the benefits of through international trade to non-producing countries remain marginal.

In sub-Saharan Africa for example, prices for cyprinids and tilapias remain at about twice the $1000 per MT level, despite high demand. Notwithstanding almost 20 years of structural adjustment, the per capita economic growth rates of all but 6 of the 48 poorest countries remains below the theoretical 3% threshold for poverty reduction (World Bank 2000). This suggests that aquaculture species that are considered as lower priced commodities in some countries, will continue to be available only to a relatively wealthy minority in others: remaining out of reach for the foreseeable future for some sectors of the population with greatest need.

Figure 7. GIS assessment of potential for small-scale aquaculture in Africa (from Aguilar-Mangarrez and Nath 1998).



In the meantime, people need to eat, and since most of the poor people in the world eke a living from small-scale family farms, it seems important to determine in which ways these production systems can be made more productive. Because these farms produce food primarily for the family and only secondarily for sale in the cash economy, small-scale farmers tend to manage for minimal costs and risks, rather than maximum production. Systems that return a profit from locally-marketed fish grown in small ponds fed with agricultural by-products may be attractive to this group of farmers. Cost of production of these fish is low because most inputs are wastes and in most developing countries, where under-employment runs up to 80 percent, there are no realistic opportunities on the labour used for pond construction and feeding (Stewart 1993). In Malawi, Ghana and the Philippines, such systems have been able to double production and treble the cash income of small farms (Brummett & Noble 1995; Prein et al. 1996, Prein et al. 1999).

In Asia and Africa, where an estimated 70 percent of the population is rural (World Bank 2000), the potential impact on food security of integrating these components in household farming systems could be enormous. Using very conservative figures, FAO has recently estimated that 37 percent of sub-Saharan Africa, the continent with the poorest aquaculture and, arguably, the greatest need, is suitable for small-scale fish farming (Figure 7) (Kapetsky 1994, Aguilar-Manjarrez & Nath 1998). If production figures from relatively recent development projects are used (producing 1 300-2 300 kg/ha/yr), 580,000 tons, or 35 percent of Africa's projected increased fish need up to the year 2010 could be met by small-scale fish farmers on only 0.5 percent of the total area potentially available (Kapetsky 1995).

Aquaculture and the Environment

Impacts of the external environmental on aquaculture may be positive or negative (FAO 1997). Nutrient enrichment of water bodies may provide nutrients beneficial to aquaculture production in some extensive culture systems. However, excessive loadings with urban and industrial wastes can have severe consequences for aquaculture. With increasing aquatic pollution and physical degradation of aquatic habitats, aquaculturists face risks of mass mortalities of farmed stock, disease outbreaks, product contamination and reduced availability of wild seed or broodstock (Bardach 1997). Aquaculture has the advantage over capture fisheries of offering opportunities to adapt farming systems and management practices to optimize aquatic food production under sometimes sub-optimal environmental conditions (Bardach 1997).

Impacts of aquaculture on the environment. As recognized in UNCED’s Agenda 21, many types of aquaculture can contribute positively to environmental improvement. Recycling of nutrients and organic matter through integrated farming systems is long recognized as being environmentally sound (Lightfoot & Pullin 1995). Recent developments in Integrated Pest Management have shown how rice-fish culture can help farmers reduce use of environmentally damaging pesticides (dela Cruz 1994). Waste-water-fed freshwater aquaculture and coastal mollusc and seaweed farming can be used to recover excess nutrients, thereby reducing the risk of eutrophication (Chow et al. 2001). In programmes for the restoration and recovery of endangered fish species and stocks, hatcheries and culture systems have been used to provide a temporary sanctuary and to increase numbers of individuals for re-introduction into the wild. Negative impacts have been associated mainly with high-input, high-output intensive systems, the effects of which can include nutrient and organic enrichment of recipient waters resulting in build-up of anoxic sediments, changes in benthic communities and the eutrophication of lakes. For example, intensive shrimp farming loses 63-78% of the nitrogen and 76-86% of the phosphorus in feeds to the environment (Bardach 1997). Large-scale shrimp culture in some areas has resulted in degradation of wetlands,

Table 5. Comparison of channel catfish pond water quality with USEPA* recommended effluent concentration limits (Boyd 1995).

	USEPA Limit (mg/l)	**(%) of Ponds Over Limit**
Suspended solids	30	75
Total phosphorus	0.17	80
Total ammonia nitrogen	1.77	25
Dissolved oxygen	5.0	13

* United States Environmental Protection Agency

localized water pollution and salination problems. Misapplication of chemicals, collection of seed from the wild, introduction of exotic species and overuse of fishery resources as feed inputs, has also raised concern in some locations (Bardach 1997, FAO 1997).

Since most water use in fish culture is non-consumptive, the main environmental concerns a great deal of attention has been paid to the eutrophication of surface waters as a result of the release of water during pond draining (Table 5). While generally perceived as a bad thing where water quality for urban domestic consumption is a major consideration, nutrient enrichment of pond water through fish production presents interesting opportunities for the integration of aquaculture into other farming systems as a means of increasing overall productivity and efficiency.

More than any other human activity, agriculture, including aquaculture, determines what the rural environment will look like. There are many possible scenarios, but at one extreme are relatively small, traditional family farms working land that has been in more or less continuous production for hundreds of years to produce a wide range of products for local markets. At the other end of the spectrum are industrialized, monocropping estates that cover thousands of contiguous hectares and operate on 3-5 year planning horizons to produce bulk products for international markets. In an unregulated market economy, the industrial agriculture end of the spectrum has a clear advantage in terms of profit margins and productivity and this has been reflected in the trend away from family farms. However, human economics is an imperfect distributor of costs and benefits and any form of agriculture which pushes environmental and social limits in order to be profitable, cannot be sustainable in the long term.

For example, thorough cost-benefit analyses of shrimp farms built in mangrove areas show strong negative returns to society (Primavera 1997). Such investments have resulted not only in destruction of sensitive mangrove forests, but also in significant loss of jobs and income, and sometimes even homes and livelihoods. Kautsky et al. (1997) cite a typical example from Thailand where the destruction of 100,000 hectares of mangroves for shrimp ponds caused an estimated loss in capture fisheries production of 800,000 MT over 5 years while only producing 120,000 MT of shrimp.

In countries with the wherewithal to pay, huge subsidies have been made to produce the sort of agriculture that society finds acceptable, such as the traditional farming communities one still sees in much of rural Europe. For the case of the US dust bowl, the federal government took sweeping action to curtail destructive practices and provide high-quality technical expertise to agriculture to prevent future abuses. The US Soil Conservation Service and the Tennessee Valley Authority were created. Land was set aside for hedgerows and barrage ponds to reduce soil erosion. Large investments were made in agricultural education, research and extension to help generate and transfer more productive and sustainable technology.

However, globalisation is working against this system. Increasing competition and the spectre of decreasing protection and/or other subsidies forces farmers to operate on smaller profit margins and larger volume. Often this means increased use of pesticides and chemical fertilizers, and reduction in methods that could limit soil erosion, including hedgerows, water storage reservoirs and fallows. In effect, environmental goods and services, as well as the public health, are the new agriculture subsidies. Rather than paying taxes to support sustainable agriculture, we are now paying higher recreation and medical fees. We may also be mortgaging the land and water resources that future generations will need to feed themselves.

Environmental legislation alone is not a solution to these problems. Harsh penalties for environmental destruction fall disproportionately on smaller, family farms that cannot afford to comply with complex rules nor engage lawyers and lobbyists to fight regulation. As the marginal profitability of small-scale agriculture declines, operators have increasing difficulty buying more expensive and productive technology. In industrialized countries, subsidy programs have been altered to maintain cosmetic compliance with free trade rules, but still help family farms out of this conundrum.

In developing countries that cannot afford lavish subsidies, the situation is somewhat different. Rather than being urban consumers, most of the populations in Africa, Asia and Latin America are rural, smallholding farmers. The bulk of the environmental degradation resulting from bad agriculture on these continents is the fault of people who are, in many cases, struggling less to increase their marginal profits, than to merely survive. Even if governments have the will to legislate against destructive farming practices, low operating budgets for agriculture support agencies mean there is little ability to enforce the law or even explain the problem to farmers in order to seek voluntary compliance. Miniscule public sector support also produces ineffective R&D institutions, which, in consequence, can provide productive and environmentally friendly technology to neither smallholders nor corporate agriculture. In the extreme case, the resulting decreased per capita food production increases political pressure in favour of any type of agriculture, no matter how destructive, just to avoid famine in the short term.

Consequently, examples of unsustainable agriculture are widespread. In Latin America, over 10 million hectares of rainforest have been cut and transformed into very marginally productive cattle ranches (Barbier et al. 1995, McNeely et al. 1995). In Asia, over 30 million hectares of forest have been destroyed to make way for unsustainable shrimp farms (McNeely et al. 1995).

Table 6. Major negative environmental impacts of global aquaculture (Brummett 2003).

Continent	**Major Negative Environmental Impact**
North America	Eutrophication of freshwaters; escape of exotic species
South America	Eutrophication of estuaries receiving shrimp farm effluent; mangrove destruction; escape of exotic species
Asia	Eutrophication of fresh and estuarine waters; extensive mangrove destruction; escape of exotic species
Europe	Eutrophication of freshwaters; sedimentation and fouling of seabed under marine cages; escape of exotic species
Africa	Escape of exotic species
Australia	Escape of exotic species
Oceania	Escape of exotic species

The environmental situation in Asia is so bad that the aquaculture sector alone has auto-polluted itself into estimated annual revenue losses of over $3 billion (ADB/NACA 1996) to say nothing of the destruction of natural aquatic ecosystems. Slash and burn cropping now contributes to the 1 million hectares of deforestation that is estimated to occur each year in Africa. One hundred and forty-two million hectares of rainfed cropland in sub-Saharan Africa have become desertified as a result of agriculture. Salinization of irrigated land affects another 5 million hectares (WRI/IIED 1988). Compared to other agriculture sectors, the contribution of aquaculture to environmental degradation is small, but it may be growing (Table 6).

In an attempt to address these problems without disrupting flows of food and money, farmers with the financial wherewithal will invest in marginal improvements in efficiency that lead to increased competitiveness and decreased environmental impact. The trends that have been identified in recent reviews of the environmental impacts of aquaculture will probably be:

- Decreased reliance upon fishmeal in diets,
- Increased efficiency in feed formulation in terms of pellet stability and nutritional content,
- Containment and recycling of wastes in cages and flow-through systems,
- Increased water and land use efficiency in land-based systems,
- Changes in the type, and reductions in the extent of chemical use,
- Containment and genetic manipulations to minimize the effects of escapees on indigenous fish populations.

An additional step that could be taken to minimize negative environmental impacts and increase the positive image of aquaculture would be to shift away from the luxury products that have heretofore dominated the aquaculture industry outside of some Asian countries, towards fish that feed lower on the food-chain and might be affordable by lower income consumers (Figure 8). The production of such species in integrated farming systems that recycle agricultural by-products through fishponds would further lower costs and increase sustainability (Brummett & Noble 1995, Kautsky et al. 1997).

Figure 8. The use of indigenous species for aquaculture can reduce negative environmental impacts and create more options for low-income producers and consumers.

Another choice that would reduce negative environmental impacts would be to focus on indigenous species for culture. While most successful aquaculture industries are based on local species, many poor countries of Asia, Africa and Latin America have been searching for quick fixes to their aquaculture development problems by importing exotic species from locations where their farming is already established. These fish routinely escape from their culture units, often replacing indigenous species or severely altering local ecosystems (McNeely et al. 1995, Lever 1996). With increasing local and international pressure to safeguard biodiversity, policy-makers should anticipate increased interest in the development of indigenous species for aquaculture as more countries come into compliance with the Code of Conduct for Responsible Fisheries (FAO 1995) and the Convention on Biological Diversity (1994).

Improving Water Productivity in Aquaculture

Fish production per unit land area, per kg of feed input and per unit water volume has been steadily improving over recent decades. In the late 1970's, typical warmwater fish yields averaged about 2 000 kg/ha in intensive, commercial culture (Table 7).

Today, the experimental limits of the 1970's are being routinely surpassed. 1n 1996, average yields on Arkansas channel catfish farms were about 5 500 kg/ha (Heikes et al. 1997) and yields approaching 10 tons/ha in aerated ponds have been reported. The main technologies currently being used to increase yields include:

- Selective breeding & other genetic manipulations (ploidy, gene transfer, hybridization)
- Nutrition, especially animal protein replacement in feeds
- Stock management (e.g., partial harvesting)
- Disease prevention and control

For producers in the tilapia industry (some 178 844 metric tons produced globally in 2000) earthen ponds, the system arguably most likely to be adaptable to new areas in poor African, Asian and Latin American countries, a 10% increase in yield per unit water would result in water savings of 500 l per kg or 90 million m^3 per year.

Water Recycling

Taking advantage of its non-consumptive use of water, aquaculture has been used to add value to sewage treatment facilities (Ferreira & Schoonbee 1983, Gaigher 1983, Edwards 1985, Costa-Pierce 1988) and irrigation systems (Rakocy 1990, Fernando & Halwart 1998, 2000, Huner

2002). Up to 100% removal of nitrogen loading is possible by passing water through aquaculture facilities (Chow et al. 2001). In addition, recirculating systems recycle water back to the fish themselves (Losordo et al. 2001, Sherif et al. 2002). Economically, these systems benefit either from exogenous nutrients (in the case of sewage treatment) or add value to existing infrastructure, in the case of irrigation schemes (Hatch & Hanson 1992). For example, managed freshwater fisheries in three Sri Lankan rice irrigation reservoirs produced over 2 000 tons of fish and added about 18% to total economic returns to water (Renwick 2001).

Figure 9. Tilapia raceways fed with water at the Baobab Fish Farm, Mombassa, Kenya.

Many of the opportunities for integrating aquaculture into water management schemes are idiosyncratic. For example, the Baobab fish farm in Mombassa, Kenya (Figure 9) takes advantage of water pumped to a neighbouring cement plant to grow tilapia in raceways. Heated effluent from a power station has been used to grow heat-loving tilapias in temperate Soweto, South Africa (Ferreira & Schoonbee 1983).

Most irrigation systems are not purpose-built to include fish, but aquaculture embodies a range of very flexible technologies that can often be adapted to unusual circumstances. Sherif et al. (2002) describe how tilapia raised at a density of 6 fish/m^3 in cotton irrigation canals can increase net profits to irrigated cotton by 7%. Putting fish directly into irrigated rice reduces weeds by 30-50% (Cagauan 1991), reducing pesticide application by up to 90% and increasing net profits by some 7-65% (Halwart 1998). Adding the red swamp crayfish (*Procambarus clarkii*) to annual rice field rotations in Louisiana, USA produces an average of 500-700 kg/ha of crayfish without feeding and has led to the creation of a $30 million industry (Huner 2002). The Near East Foundation, working in the Jordan Valley, has developed a system based on small cages placed in irrigation head tanks that provides important additional income to small and medium-scale farmers. Cages placed in irrigation reservoirs are relatively easy to manage and offer important economic opportunities to rural populations or those disenfranchised by dam construction (Costa-Pierce 1997). With an estimated 800 000 dams, nearly 95% of which hold less than 750 000 m^3 of water and are relatively easy to manage (Keller et al. 2000), the opportunities for integrating fish are substantial (Figure 10).

Figure 11. Wastewater-fed cages in Kota Cianjur Indonesia produce 750 tons of carp per year (photo: Barry Costa-Pierce).

Growing fish in wastewater is widespread in Asia and has been shown to reduce biochemical oxygen demand (BOD), while adding substantially to the profitability of sewage treatment (Edwards 1985). For example, stocking the filter-feeding silver carp (*Hypothalmichthys molitrix*) into cooling/recycling reservoirs can produce fish while significantly reducing the need for chemical control of phytoplankton that block intake filters (Ferreira & Schoonbee 1983). The placement of homemade cages into sewage ditches reduces bacterial loads and returns net profits on the order of \$100 per 8 m^3 cage (Costa-Pierce 1988). There are some 5 000 such cages in Kota Cianjur producing an estimated 750 tons of common carp (*Cyprinus carpio*) annually (Figure 11). Horizontal integration, where septage is removed from its point of production into fishponds can produce up to 7 tons of tilapia per hectare per year (Edwards et al. 1987). In Calcutta, India, some 3 000 ha of fishponds utilize an estimated 550 000 m^3 of untreated sewage per day to produce around 13 000 tons of Indian carps (Mara et al. 1993). The water is subsequently used for crop irrigation. Growing fish in such systems presents occupational health hazards, but the fish themselves are safe for human consumption (Cointreau 1987, Mara et al. 1993, Demanou & Brummett 2003).

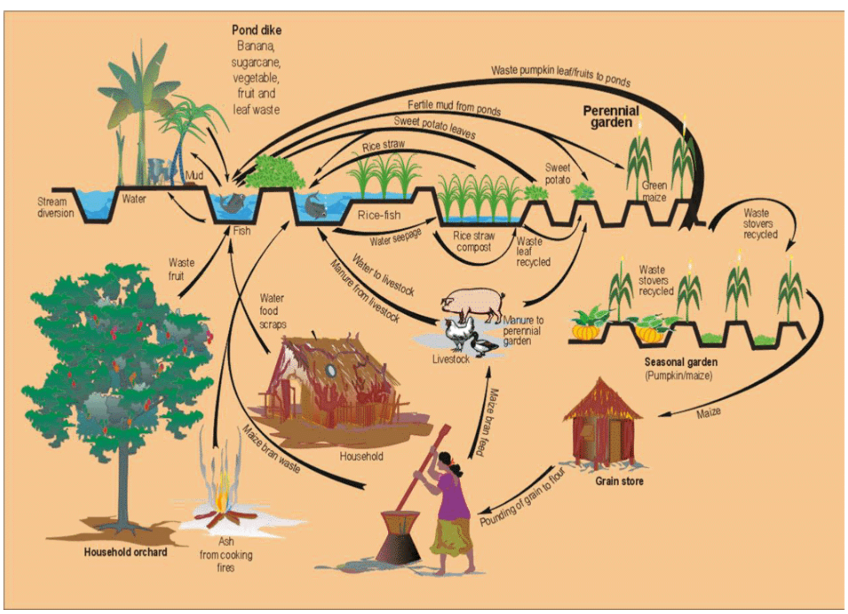
Figure 12. Recirculation systems rely on sophisticated technology, such as this rotating biodisc filter, to reduce water loss.

Hydroponic and recirculating systems that produce fish and/or vegetables under highly controlled conditions can be attractive in either dry or cold climates where electricity is reliable and affordable (Figure 12). Typically, tanks or raceways are connected to a filtration mechanism (e.g., rotating discs, floating beads, mollusc or plant beds, artificial wetlands) are used remove particulate matter and nitrify the ammonia resulting from fish metabolism prior to its being pumped back into the fish culture unit. These systems can produce up to 60 kg of tilapia/m^3 of water (Mires & Anjioni 1997). Some recirculating systems, such as the partitioned aquaculture system (PAS) developed at Clemson University in the US, and the active suspension ponds (ASP) studied at the Israel Institute of Technology are based on similar principles, but use new knowledge of aquatic microbial activity to auto-filter water *in situ* within tanks or small ponds, achieving surprisingly high standing stocks (>9 000 kg/ha) with virtually no loss of water (Goode et al. 2002, Avnimelech 2003).

Recirculating systems are, however, between 20-400% more costly to build and operate than traditional pond-based farms, some $2.50 per kg of tilapia produced in Israel according to Mires & Anjioni (1997), $2.90 per kg in the US Virgin Islands (Rakocy 1990), making them most suitable for locations with access to specialized markets where profit margins can be higher (Losordo et al. 2001) or for hatcheries (Mayo 1991, Head & Watanabe 1995). In Jordan, for example, recirculation systems are used by medium-scale commercial farmers to produce tilapia in the highlands close to urban centers where both water availability and winter temperatures constrain more traditional pond-based systems. Across the river in Israel, the DEKEL system recirculates water between relatively small, covered, aerated tanks and a single large reservoir producing about 9 kg/m^3 (Mires & Anjioni 1997). In the US Virgin Islands, a recirculating system designed by Rakocy (1990) and comprised of one 12.8 m^3 rearing tank, a 1.9 m^3 clarifies, two 2.1 m^3 hydroponic biofilter tanks (containing gravel) and a 1.4 m^3 reservoir produces 400kg of tilapia plus 650 kg of tomatoes or 324 kg of lettuce during a 6-month grow-out cycle. Consumptive water use in this system is only 87 l/kg, but required 8.1 kWH of electricity per kg of fish produced, provided by a 12.5 kW generator (Rakocy 1990).

Integrated Aquaculture – Agriculture (IAA)

Figure 13. Diagrammatic representation of a typical integrated smallholding in Southern Africa (Brummett & Noble 1995).



A special type of integrated aquaculture system is being used by development agencies to encourage increased food production, cash income generation and farming system stability/durability in tropical developing countries (Pullin & Prein 1995). Rather than being a sub-component of large external infrastructure, such as sewage treatment facilities or an irrigation reservoir, these systems, referred to as integrated aquaculture - agriculture (IAA), incorporate a farmpond as the centrepiece of a fully integrated family farm production unit (Figure 13). A farmpond is particularly effective in the role of waste processing unit as it can convert virtually any organic material into fish protein and/or nutrient enriched water and mud without the weed, disease and insect problems associated with terrestrial mulches and green manures.

In IAA, the wastes from each farming activity are recycled into other enterprises, thus raising economic and ecological efficiency overall. The classical image of an integrated farm comes from China where a wide variety of such systems (e.g., duck-fish, rice-fish, mulberry-fish, chicken-pig-fish, etc.) have evolved over a period of nearly 2 000 years (Kangmin & Peizhen 1995). These systems have been shown to be ecologically and economically viable over a wide range of conditions (Hatch & Hanson 1992). For example, modelling nutrient flows on Asian IAA systems showed that nutrient use and economic efficiency can be more than doubled through integration with fish (Dalsgaard & Prein 1999). Reported yields for more intensive Asian IAA systems are in the range of 5 – 8 tons/ha/yr (Prein 2002).

In Africa, average fish productivity of integrated smallholdings is on the order of 1 500 kg/ha in rainfed areas and 1 800 kg/ha in springfed areas. This is 50 to 83 percent more than the average production achieved by the most productive non-integrated small-scale farms, about 900 kg/ha/yr (Chimatiro & Scholz 1995). On integrated farms, ponds are generally located within or next to vegetable gardens, or as often happens, vegetable gardens develop around the fishpond to take advantage of emergency irrigation water and the proximity of garden wastes to feed fish. In water stressed areas, this integrated pond-vegetable garden serves as an economic engine, generating almost three times the annual net income from the staple (maize) and non-farm income combined. The vegetable-fish component contributes, on average, 72% of annual cash income. On a per unit area basis, the vegetable garden/pond resource system generates almost $14 per 100m^2 per year compared with $1 and $2 for the maize crop and homestead, respectively (Brummett & Noble 1995).

Table 8. Natural resource use efficiency of two alternative aquaculture systems, evaluated according to the concept of the "ecological footprint" (Berg et al. 1996). The ecological footprint is the quantity of environmental goods and services consumed by a food production system in the generation of external inputs and the processing of wastes. The integrated pond uses agricultural by-products as inputs to fuel natural processes that generate the bulk of the food for the fish. This converts what are waste products in a cage system into inputs for an integrated system, with consequent reduction in polluting discharge.

To support a 1 m^2 cage raising tilapia, one needs:

21,000 m^2 of ocean to grow fishmeal for inclusion in fish feeds
420 m^2 of cropland to grow grains for inclusion in fish feeds
60 m^2 of green plants to produce oxygen for consumption by fish
115 m^2 of benthic community to assimilate waste phosphorus

Total "Ecological Footprint" = 21,700 m^2 (producing 6 g fish per m^2 of footprint)

To support 1 m^2 of IAA fishpond raising tilapia, one needs:

0.9 m^2 of additional benthic community to assimilate phosphorus
0.9 m^2 of green plants to produce oxygen for consumption by fish

Total "Ecological Footprint" = 1.8 m^2 (producing 264 g fish per m^2 of footprint)

Sustainability

Circumstantial evidence indicates that ponds also have the potential to profoundly affect the stability of small farms. By retaining water on the land, ponds have enabled farms to sustain their food production and to compensate for losses on seasonal croplands. For example, in the 1993-94 drought season in Southern Africa, when only 60 percent of normal rain fell, the average net cash income accruing to a study group of rainfed integrated farms was 18 percent higher than non-integrated farmers in an area with some of the region's severest poverty (Brummett & Chikafumbwa 1995, Noble 1996).

IAA farming systems are more efficient at converting feeds into fish and produce fewer negative environmental impacts than purely commercial fish farms (Table 8). They also have the advantage of not using one human foodstuff to produce another, as is the case with much of aquaculture, particularly as practices in Europe, Japan and the US. Some authors have predicted that the widespread adoption of integrated aquaculture might actually improve local environments by reducing soil erosion and increasing tree cover (Lightfoot et al. 1993, Lightfoot & Pullin 1995), although this remains to be demonstrated on the ground.

Unfortunately, the social, ecological and technical context of small-scale farming systems creates very rigid and not easily modified structures, which encompass many different crops and activities (Harrison et al. 1994). While individual IAA technologies are relatively easy to adopt, the full impact of IAA is only felt with a wholesale farming system transformation to the integrated approach (Lightfoot & Noble 1993). For development agencies, this means that constraints to IAA technology have more to do with its transfer to farmers, than with the technology itself (Lightfoot & Minnick 1991, FAO 2001).

The main users of IAA technology have historically been very poor smallholders with little or no participation in the cash economy. Growth of production on these farms will ultimately be constrained by the lack of inputs. With most of the fish produced being bartered locally in non-cash transactions, there is little likelihood that taxes could be successfully levied to support research and extension services that might help to intensify or expand production. Consequently, the major impacts of this scale of aquaculture will be in local food security, farming systems stability and soil conservation/rehabilitation, rather than in economic growth or national food security. While this group of farmers represents about 70% of African producers and consumers, and subsidies in the form of research and extension support could be very effective, government policy in most tropical developing countries tends to emphasize economic growth and replacement of imported fish (with the associated foreign exchange losses) consumed largely in urban centres.

Aquaculture Research and Policy Recommendations

Compared to crop irrigation, industry and household consumption, fisheries and aquaculture have generally been under-valued and have consequently played a minor role in the debate over allocation of freshwater resources. However, as the data presented above illustrate, fish production has an important, and in some countries critical, role to play in food security and rural economic development, while being a minor terminal user of water resources. Fish consumption and associated demand are rising all over the world (New 1999, Masser 2000, Pedini 2000). Nevertheless, aquaculture will continue to be obliged to seek options for integrating into existing and new water utilization schemes that are seldom designed with fish in mind.

In light of projected shortfalls in supply and large increases in demand for water *and* fish, the further evolution and contribution of aquaculture to human welfare and livelihoods will require that researchers focus on water-efficient technology. However, technology alone will solve nothing if farmers do not use it. Constraints to the adoption and application of technology thus become crucial considerations in determining the way forward (Harrison et al. 1994).

The major constraints to aquaculture development in rural Africa, Asia and Latin America, those places where it could arguably create the most positive contributions to society, are:

- Poor infrastructure, such as bad telephones, bad roads, irregular air service and unreliable electricity (Coche et al. 1994).
- The lack, or volatile prices, of essential inputs such as feeds, fertilizers, chemicals, fuel and spare parts (Williams 1997).
- Political instability (UNDP 1998).
- Poor market development and marketing infrastructure (Hecht 1997, Masser 2000).
- The lack of the necessary R&D to backstop industrial growth (Lazard et al. 1991).

Over recent decades, there has evolved a high degree of uniformity and specialization within specific agroecological zones. States on cold oceans with sufficiently protected areas along their shores produce salmon. Tropical countries with suitable coastal areas produce shrimp. Throughout the Mississippi delta in the US, farmers with bottomland are growing channel catfish. Concomitant with specialization has been a convergence of technology so that systems vary little from place to place. The same will undoubtedly be true of new aquaculture systems that prove successful in the rural economies of Asia, Africa and Latin America. The basic outline of the system that many experts feel will dominate in the medium term already exist (FAO 2000):

- **Species:** tilapias (*Oreochromis spp*) & African catfish (*Clarias gariepinus*)
- **Production System:** earthen ponds & cages in reservoirs or lakes.
- **Feeds:** locally available agriculture products & by-products, either in the form of pelleted diets (cages) or supplemental feeds (ponds).
- **Market:** local with pond-bank wholesaling and/or retailing.

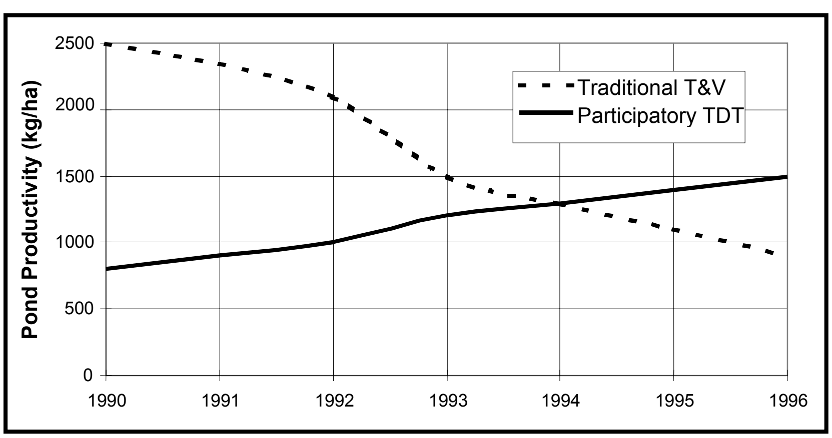
Within this framework, many local adaptations will be necessary, and therein lies the main role for technology research. In the past, attempts were made to directly transfer (through training manuals, technical fliers, etc.) to tropical developing countries aquaculture technologies developed under completely different economic, environmental and cultural conditions. Succes with this approach was generally poor and always patchy. Locally relevant options for fingerling production, feed formulation, pond design and cage management strategy will be extremely important in moving aquaculture forward.

Policy-makers will need to address key concerns about transportation, electricity and communications infrastructure as well as reviewing import duties on equipment and other inputs. Marketing strategies and assistance with gaining access to international markets will also be high-priorities.

The main area of work, however, will rest with those agencies and persons responsible for technology transfer. Unfortunately, the existing government and NGO-based extension services in most tropical developing countries are weak, at best. In many places they are totally dysfunctional in that they have very little in-house technological knowledge and operating capital. Public-private partnerships that link larger aquaculture farms with outreach to small and medium-scale operations will be a key aspect. Fingerling production, processing and marketing by small-scale farmers could be dramatically improved by satellite farming, contractual production or similar arrangements between large and small producers, possibly facilitated by government or other external agencies (e.g., NGOs or IARCs) that could serve as honest brokers and/or suppliers of high quality technical expertise.

In addition, more efficacious relationships need to be established between research and extension. While representing the main body of technical knowledge and expertise, many researchers tend to be overly academic and unconcerned with the application of their research. Job performance and remuneration in most research institutions are correlated with publications rather than farm-level impact. While the role of basic and applied research is crucial in the longer-term, there is a real lack of interest among donor agencies that will probably persist until a larger amount of the knowledge already gained has been adapted to local conditions. This adaptive research, if carried out in participatory, joint-learning exercises with farmers and extension agents, can normally be used within the current institutional structures to facilitate change.

Figure 14. Comparison of productivity over time on farms working with extension through the traditional Training & Visit (T&V) system or with research through a participatory Technology Development & Transfer (TDT) process (Brummett & Williams 2000).



Participatory research has been shown to overcome many of these constraints and can lead to high rates of adoption (Brummett & Noble 1995, Prein 2002). In Malawi, for example, of farmers exposed to a basket of IAA technology options through joint-learning exercises, 86% adopted at least one technology, 76% adopted at least two, and 24% adopted four or more (Brummett & Noble 1995). In Cameroon, participatory research is being used to adapt aquaculture technology to more intensive and commercial farming systems with equally encouraging results.

If done properly, the adoption promoted in this way is sustained and diversified over time, leading to ever-greater levels of integration and production (Figure 14). Once introduced in a rural community, these technologies spread and evolve without further extension support. A survey found that, within six months of a field day in May 1990 explaining the new opportunities, 46 percent of adopters in the target area had learned about it from other farmers. A third of these farmers had adopted two or more technologies from their neighbours. By the end of 1992, almost 80 percent of the farmers practicing integrated farming in Southern Malawi had never participated first-hand any extension exercises (Chikafumbwa 1994). In those areas of Malawi where these transformations have been studied in detail, the original group of 34 farmers undertaking four years of participatory IAA research, has now expanded to more than 225 practicing farmers (Scholz et al. 1997).

While larger, intensive farms offer attractive opportunities for research and extension to have rapid uptake of technology, these users are unlikely to have major economic impact on rural communities. On the other hand, a public-private strategy with the support non-profit technical agencies could be designed to involve a much wider range of producers and consumers. Economic impact at the level of the small and medium scale producer can generate wider economic growth. Delgado et al. (1998) in a review of results from Burkina Faso, Niger, Senegal and Zambia found that "…even small increments to rural incomes that are widely distributed can make large net additions to growth and improve food security." Winkleman (1998) identified interventions that lead to improved incomes at the level of the rural farmer and resource manager as "having a larger impact on countrywide income than increases in any other sector."

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