

CHAPTER 3

INDICATORS FOR THE SUSTAINABILITY OF AQUACULTURE

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Abstract: Global demand for fish will probably double in the next 30–50 years. To what extent can aquaculture increase and sustain its contributions to world fish supply without unacceptable environmental impacts? Indicators towards answering this question are suggested here. These are as follows: (1) biological indicators—potential for domestication, with genetic enhancement; trophic level; feed and energy conversion efficiency; (2) ecological indicators—ecological footprint; emissions; escapees and feral populations; (3) intersectoral indicators—sharing water (e.g., with agriculture, fisheries, forestry, water supply, waste treatment); diversity; cycling; stability; and capacity. Back-calculation of FAO fisheries statistics yielded a dataset for aquaculture production from 1950 to 1997. This dataset, and reviews of literature on the sustainability of world food production, suggest that expansion of aquaculture will not result in sustainable and environmentally acceptable systems unless such indicators are used by policymakers and developers.

Key words: aquaculture, biology, ecology, environment, indicators, sustainability

1. INTRODUCTION

World food supply will probably have to double in quantity and to increase in quality over the next 30–50 years, as populations and incomes rise. The demand for fish as food will probably double or increase even more. We use the term “fish” here to mean all aquatic animals.

Would it be a wise investment to attempt to increase the contribution of aquaculture (currently about 20%) to world fish supply? What would be the

environmental implications of such expansion? The extensive literature on aquaculture and the environment (e.g., Pullin et al., 1993; FAO 1997a; New, 1998a, b) does not provide ready answers. Naylor et al. (2000) concluded that aquaculture must reduce its dependency on wild fish for feeding farmed fish and must also adopt “ecologically sound management practices” in order to contribute sustainably to world fish supply. Substantial efforts are indeed being made towards lessening the adverse environmental impacts of aquaculture; for example, through the work of FAO (Barg, 1992, 1997; FAO, 1995, 1997b) and through the aquatic work programs of Parties to the Convention on Biological Diversity (CBD).

We consider here three categories of broad indicators for the sustainability of aquaculture: biological, ecological, and intersectoral. We consider that the economic sustainability of aquaculture is ultimately a product of all of these categories. Moral and ethical aspects and the sharing of benefits from expansion of aquaculture are beyond the scope of this paper.

2. SUSTAINABILITY

Much has been written about the environmental aspects of sustainability (e.g., Becker, 1997) and about its application to aquaculture (e.g., Folke and Kautsky, 1992; Pillay, 1997; Naylor et al., 2000). We follow here the definition of sustainability adopted by the Technical Advisory Committee of the Consultative Group on International Agriculture Research (TAC/CGIAR, 1989): “Successful management of natural resources . . . to satisfy human needs while maintaining or enhancing the quality of the environment and conserving natural resources.”

There is general agreement that sound management of natural resources is the key to sustainability. However, short-term needs and objectives (addressing food and employment deficits and providing quick returns to investment) usually dictate policies and events. Overall, macro-economic factors (e.g., trade and consumption patterns) have been the main controllers of aquaculture production trends (Born et al., 1994). The environmental and social costs of aquaculture development have been inadequately addressed.

Poverty alleviation, sustainability, and the environment are common watchwords in aquaculture research and development, but planning horizons and assessments of impact and success usually relate to only the present generation of humans. Moreover, developers sometimes appropriate lands and water for aquaculture as a temporary front for other developments (e.g., housing, industry, recreation). Consequently, the history of aquaculture, like that of agriculture, has many examples of adverse environmental impacts and unsustainability (e.g., see Pullin et al., 1993).

Such a history cannot continue indefinitely. Non-negotiable, natural laws are already forcing changes against a background of resource depletion, environmental degradation, and increasing conflict, as is happening for many capture fisheries. The productive capacity of the Earth’s lands and waters is finite, as is

the capacity of the ecological services upon which biological productivity and waste processing depend.

We suggest that aquaculture needs a fundamental transition (as indeed do agriculture, capture fisheries, and forestry) from management that is based solely on maximizing the exploitable biomass of target species (and on “mining” natural resources towards that end) to integrated management of natural resources and ecosystems. This applies at the farm level and also to entire watersheds, the coastal zone, and open waters. The following indicators are suggested as a framework for assessing progress towards such a transition.

3. BIOLOGICAL INDICATORS

3.1. Farmed Fish

Most farmed fish are far less domesticated than terrestrial livestock and there is enormous scope for their domestication, with genetic enhancement and improved husbandry. Genetic enhancement can greatly improve the growth performance, feed conversion ratio (FCR) and disease resistance of farmed fish (Gjedrem, 1998). For comparison, in 1935, it took 16 weeks to raise a broiler chicken to market size with an FCR of 4.4:1, but by 1994 it took only 6.5 weeks at FCR 1.9:1 (Forster, 1999). About 80% of the FCR improvement was attributed to genetics and 20% to better nutrition. Forster (1999) concluded that farmed salmon and other fish can become “more feed cost-efficient” than chickens and other terrestrial livestock, and maintained that an FCR of 1:1 could be approached for salmonids. Following patterns established for plants and livestock, such genetic enhancement contributes to the progressive domestication of fish. This is already occurring, purposefully and coincidentally, on a wide front.

As an example, we compared growth data for farmed and wild Nile tilapia (*Oreochromis niloticus*) (Figure 1). Nile tilapia clearly show different growth patterns in captivity, where on the average they take about half a year to reach a maximum size of 22 cm. Their wild relatives need about 7 years to reach a maximum size of 37 cm. Fast growth, however, correlates with early maturity at about 2 months and 14 cm in captivity, compared to about 20 months and 21 cm in the wild.

There remains the question, to what extent should genetic enhancement research concentrate on developing very high performance fish for use in intensive feedlot systems (which might themselves be unsustainable) or on fish that can perform well in less intensive systems, thereby maximizing use of the natural aquatic productivity on site? Whatever the answer, all fish breeders face some unavoidable fish design constraints.

3.2. Design Constraints

One design constraint affecting finfish is that their scope for growth depends strongly on oxygen uptake through gills, the surface of which, for reasons of

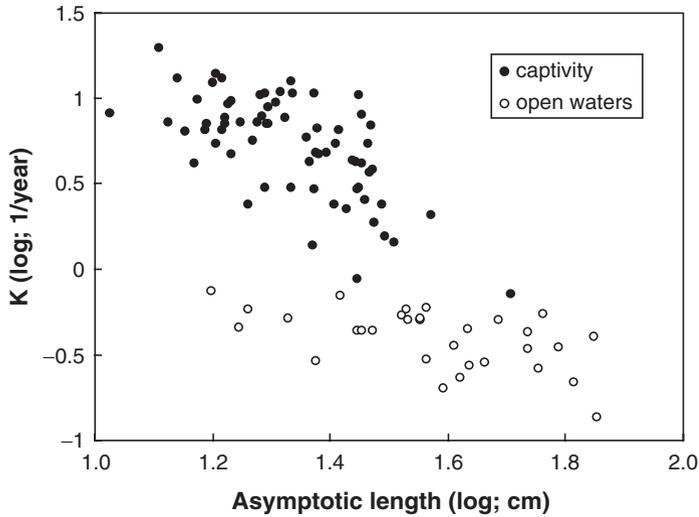


Figure 1. Growth performance of Nile tilapia (*Oreochromis niloticus*) in captivity and in open waters as expressed by two parameters (Asymptotic length and K) of the von Bertalanffy growth function; K is a constant. Data from independent growth studies as compiled in FishBase (Froese and Pauly, 1999)

geometry, cannot grow as fast as their body mass. Thus, as fish grow, their gill area per unit body weight declines, thereby reducing growth and precipitating a number of related processes, including maturation (Pauly, 1994). This mechanism explains the stunting of tilapias crowded in small waterbodies (Noakes and Balon, 1982). Moreover, it explains why domestication, which leads to calmer fish that waste less of their scarce oxygen on aggressive encounters, also leads to faster-growing fish (Bozynski, 1998; see also Figure 1).

3.3. Feeds, Trophic Levels, and Energy

The future availability and costs of fish feeds and their ingredients (especially proteins), fertilizers that enhance aquatic productivity, and energy are major topics for forecasters of the future of aquaculture (e.g., Chamberlain, 1993; Tacon, 1995, 1997). Concerning “fed” aquaculture, a comparison with feedlot livestock is useful. Goodland (1997) regarded current livestock production methods as unsustainable, pointed out that livestock eat about half of the global production of grain, and considered aquaculture as potentially “more productive and at much less environmental cost than livestock if grain inputs only are counted.” However, he found (intensive) aquaculture to be economically uncompetitive “if fossil energy and water costs are included.”

The fossil fuel energy requirements of intensive aquaculture can indeed be high. For example, cage farming of salmon was found to require 50 kcal of fossil

energy/kcal protein output, compared to 22 for raising broiler poultry and 35 for raising pigs, in the USA (Folke and Kautsky, 1992). Analyses of change in agriculture have indicated the importance of energy; for example, Dazhong and Pimentel (1990) showed that from 1957 to 1978, fossil fuel use in Chinese agriculture increased about 100-fold, whereas grain production increased only 3-fold. Simultaneously, most traditional, organic farming systems disappeared.

Goodland (1997) suggested that humans should eat more sustainably (lower in the food chain) and be differentially taxed on consumption of food items produced by inefficient conversion processes: for example, grains—no tax; poultry, eggs, dairy—moderate tax; pork, beef—high tax. He also suggested that “ocean fish” be taxed the lowest among the animals consumed (Goodland, 1997). Note, however, that most of the ocean fish consumed by humans have trophic levels ranging between 3.0 and 4.5 (Pauly et al., 1998)—up to 1.5 levels above that of lions. Moreover, the energy costs of catching these fish are high, especially for large commercial fishing vessels.

Kinne (1986) has also drawn attention to the necessity to “develop new, long-term concepts for combating hunger and for harmonizing large-scale food production with ecological dynamics and principles . . . the solution is recycling and large-scale food production from *low-trophic-level* (present authors’ emphasis) organisms.”

Aquaculture statistics on levels of production over time of species in different trophic levels can be compared to determine whether aquaculture production of low-trophic-level species is increasing relative to that of higher-trophic-level species. We looked at aquaculture statistics to see if there are any discernible trends in this direction.

3.4. Trends in Aquaculture

Unfortunately, the time series for aquaculture production statistics available from FAO (1998) is rather short (1984–1997). Before 1984, values for aquaculture production were contained in the FAO fisheries *catch* statistics.

We used the following approach to extract pre-1984 values for aquaculture production from the FAO fisheries catch statistics.

1. We linked the FAO “Catch” and “Aquaculture” databases so that species, country, and FAO area were identical.
2. For every record, we calculated the average ratio of aquaculture production in the reported total production in the Catch database for the years 1984–1987.
3. If no catch and no aquaculture production were reported by a country in these years, we assumed that no aquaculture had been conducted with the species in question in the past.
4. We used the obtained ratios to calculate aquaculture production for the years 1950–1983. This approach worked well for most records—over 1600 cases. However, in 286 cases, there were no pre-1984 records in the Catch

table, although substantial and continuous production was reported after 1984, suggesting that production data for these species had not been reported to FAO before 1984. This caused an increase in total aquaculture production from 1983 to 1984. Therefore, we used the following approach to estimate previous aquaculture production for these cases.

5. We looked at cases where no production was reported in 1981, 1982, and 1983, but some production was reported in 1984.
6. We ignored cases where the production in 1984 was 10 metric tons (t) or less, or where the aquaculture part of the production + catch (see above) was less than 10% of the total.
7. We calculated the average year-to-year production difference between the years 1984 and 1987 as ratio of the later year (ignoring cases where this value was negative or zero).
8. We used the average of the ratio derived in (7) to project the production backwards for the pre-1984 years as a continuous exponential decline in this ratio from year to year, to approach gradually the “no production reported” status.
9. In cases where the ratio in (7) had been negative or zero, we replaced it with the arbitrary ratio of 0.05, so as to avoid projecting steady or increasing production when actually none had been reported.
10. When the back-calculated production value reached a value less than 10 t, we set it to zero.
11. For introduced species, where the year of their introduction to the respective country was known from the FishBase Introductions Table, (www.fishbase.org; Froese and Pauly, 1999), we set projected values before that year to zero.

Our dataset (Figure 2) has, undoubtedly, some entries that do not match the real history of aquaculture development in some countries. Further country-specific studies, by experts, would be needed to check this.

We looked at the trends in trophic levels of farmed fish using the trophic levels of their wild populations as reported in FishBase 99 (Froese and Pauly, 1999). Note, however, that fish trophic levels on farms can differ from those in the wild. They can be lower when carnivores such as salmonids are fed pellets rich in plant material like soya protein or higher when herbivores such as grass carp (*Ctenopharyngodon idella*) are fed pellets containing fish or animal protein. We did not attempt to check actual species-specific components.

Based on the assumption that many fish on farms feed as they do in the wild, Figure 3 (upper graph) suggests little overall change, or perhaps a slight decrease, in the mean trophic level of farmed fish in Africa, Asia, the former USSR, and, on average, globally. This result derives mainly from herbivorous carp, tilapia, shrimp, and bivalve mollusk farming in Asian, especially Chinese, aquaculture. The irregular nature of the curve for Africa likely reflects year-to-year uncertainties in the status of aquaculture there, with frequent externally funded, project-dependent starts and stops and the difficulties of an unpredictable

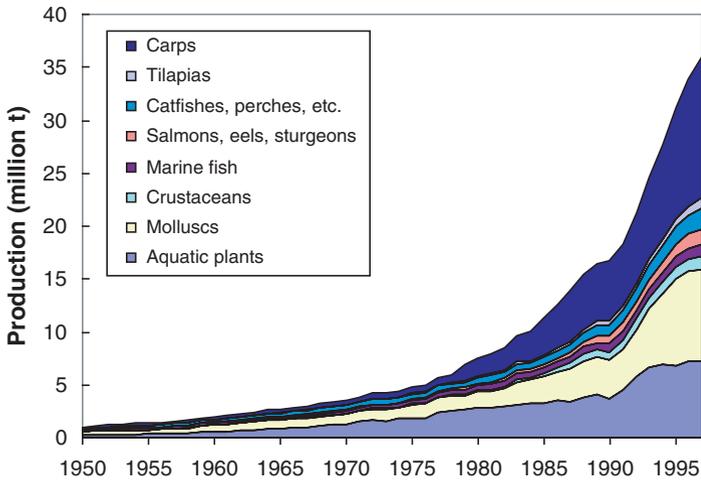


Figure 2. Contribution of major groups to aquaculture production, based on FAO (1998) statistics. For methods of estimating pre-1984 values, see text

climate, especially rainfall. Figure 3, lower graph indicates that the Americas and Europe are farming fish (e.g., catfishes, salmon) at progressively higher trophic levels. These trends are particularly evident since 1984, when aquaculture statistics became more accessible.

3.5. Indicators

From the evidence presented above, it is clear that further domestication and genetic enhancement of farmed fish are needed to raise production. Moreover, understanding the feed and energy requirements of farmed fish is paramount for assessing the environmental implications of these interventions. We therefore suggest the following biological indicators for the sustainability of aquaculture:

1. potential for domestication, with genetic enhancement;
2. trophic level;
3. feed and energy conversion efficiency.

4. ECOLOGICAL INDICATORS

4.1. Footprint

The concept of the ecological footprint—the ecosystem area that is functionally required to support human activities—has been applied extensively in analyses of aquatic food production (e.g., Folke et al., 1998). We note the current criticisms of this method (e.g., see discussions in van der Bergh and Verbruggen, 1999a, b; Ferguson, 1999; Wackernagel, 1999). We conclude that these

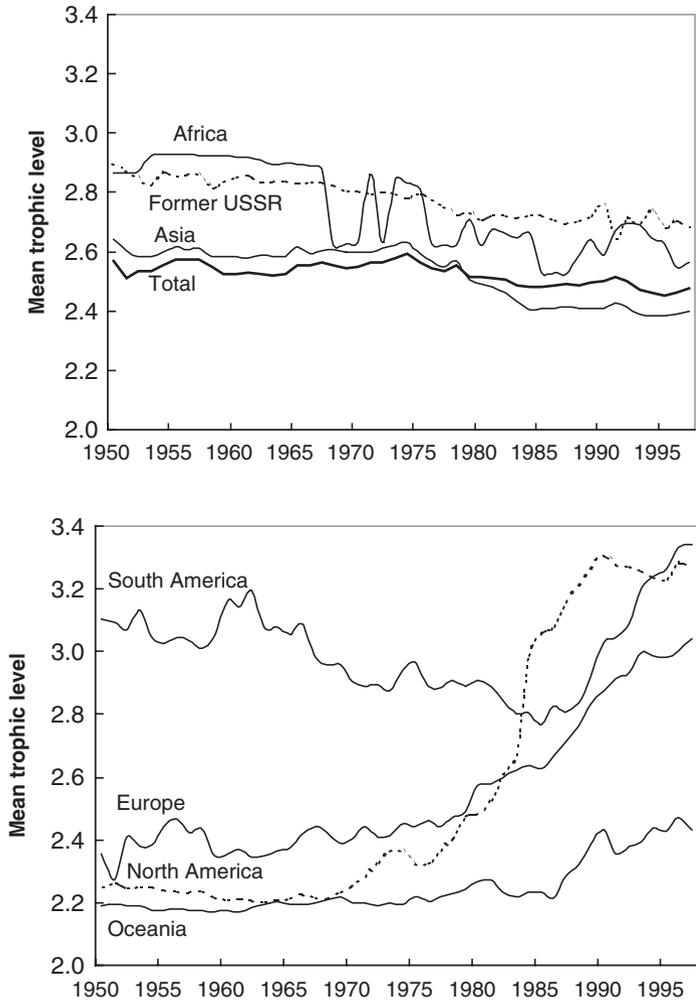


Figure 3. Mean trophic levels (from Froese and Pauly, 1999) of aquaculture production (1950–1997), including mariculture, by region. For methods used, see text

criticisms do not lessen the utility of the method that remains, to quote Wackernagel (1999), “one of the few ecological measures that compares human demand to ecological supply.”

For total food and energy, Wackernagel et al. (1999) found that only 12 out of 52 countries had ecological footprints smaller than the bioproductive areas required for their human populations. This was based on an estimated average requirement of 2.0 ha of land/sea space per global citizen plus an allowance of another 0.3 ha (12%) per caput for sustaining biodiversity. In total, the 52

countries studied were found to use 35% more “biocapacity” than exists within their own land/water space. These authors also suggested that average bioproductive space worldwide will decline to 1.2 ha per caput in just over 30 years. They assumed no further ecological degradation (which is unlikely) and a world population of 10 billion. Their analyses did not mention aquaculture *per se* but for Italy’s annual consumption of “marine fish” at 30 kg per caput they estimated a footprint of about 1.05 ha of sea, compared to only 0.32 ha per caput available to that nation. Pauly and Christensen (1995), and others cited by Wackernagel et al. (1999), have pointed out that of the 6 ha of sea space per caput on the planet only about 0.5 ha are bioproductive and that these generate only about 12 kg per caput per year of actual fish on the table.

Aquaculture has, inevitably, an ecological footprint and draws upon the world’s ecosystem services and natural capital, the total value of which has been estimated to average US \$33 trillion annually, mostly outside of the market and balance sheets (Costanza et al., 1997). What spare capacity is there for human food production in the world’s bioproductive water space, if any? Pauly and Christensen (1995) found that about one third of the primary production over marine shelves—the productive areas down to 200 m around continents—is required to maintain the marine fish catches extracted from these shelves, i.e., about 90% of global fish catches. Channeling more of this production into aquaculture might be a wise investment because some farms might generate more product for less footprint. This needs to be further investigated, through modeling and case studies.

Concerning land-based food and feed production, Wackernagel et al. (1999) concluded that there is currently less than 0.25 ha of highly productive arable land and about 0.6 ha of grazing pasture per caput. No doubt more of the produce and by-products of agriculture from these lands could be used to feed farmed fish. Ultimately, however, the ecological footprint of feeding humans will be minimized if humans eat plants and maximized if we eat carnivorous animals, including carnivorous fish.

4.2. Emissions

Aquaculture systems, except closed recirculating systems, have emissions (effluents, diffusion and settlement around cages, drainage products, etc.). The nutrients (principally nitrogen and phosphorus) and suspended solids in such emissions, together with associated microorganisms, create oxygen demands and sediment accumulation in the surrounding environment. These nutrients and suspended solids are derived from excreta and the proportions of feeds and fertilizers that are not either incorporated into the fish or retained by the system. Moreover, the residues of anthropogenic chemicals used in the production process (e.g., antibiotics, disinfectants, heavy metals in feeds, etc.) are also present in emissions. The environmental impacts can be serious; for example, see papers in Pullin et al. (1993), Rosenthal et al. (1993), Ackefors and Enell

(1994) and Páez-Osuna et al. (1998). The safety for human consumption of aquaculture produce from such systems must, of course, be assured. Forecasting the composition and minimizing the impacts of emissions from aquaculture has become a major research field (see, e.g., Kaushik, 1998; Young Cho and Bureau, 1998).

Clearly it is advantageous, both for farmers and for the environment, that feed conversion efficiency (see Biological Indicators, above) and the efficiency of fertilizers used to produce natural foods for farmed fish are maximized and that emissions from aquaculture are as low as possible in oxygen demand, nutrient content, and suspended solids and residues from anthropogenic chemicals. The same applies to agriculture (see, e.g., Pan and Hodge, 1993; Oláh and Pékar, 1995). Note in this context that aquaculture can sometimes act as a waste-processing and clean-up system, for example, in wastewater-fed aquaculture (see below, Intersectoral Indicators).

4.3. Escapees and Feral Populations

Farmed fish (whether native or alien species and whether genetically distinct from wild types or not) can escape and establish feral populations. Escapees and feral populations of domestic animals (e.g., cats, camels, cattle, dogs, goats, pigs) have caused adverse environmental impacts. Feral fish (e.g., some tilapias [Pullin et al., 1997]) have done likewise and are usually impossible to eradicate. Hence, the development of aquaculture must proceed in parallel with effective environmental safeguards, including biosafety procedures, for *all* farmed fish—and especially for alien species and “alien genotypes.” We looked at the proportions of native and alien finfish species used in aquaculture from 1950 through 1997 (Figure 4).

Most aquaculture production that is reported by countries to FAO derives from species that are native to these countries. The proportion of farmed fish production from native species increased from about 75% in the 1950s to about 85% in the 1990s. However, this result is again highly biased by the predominance in aquaculture production statistics of Chinese carps farmed in China. The percentages for the actual numbers of native fish species that contributed to aquaculture production decreased from about 60% in the 1950s to about 55% in the 1990s. Although over 80% of aquaculture production still comes from native species, the number of alien fish species used in aquaculture is now high (over 40%) and is tending to increase.

4.4. Indicators

From these ecological considerations, we conclude that if the farming and ranching of fish are to expand and be sustainable, they must contribute to *reducing* the ecological footprints of food production. The effects of emissions and escapes from fish farms will have to be kept within acceptable limits.

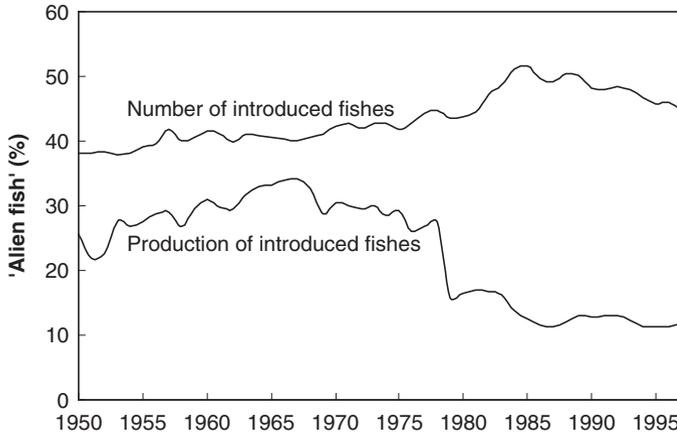


Figure 4. Aquaculture production (%) derived from introduced (i.e., alien) species, 1950–1997, and numbers of species contributing to that production. Data were derived from back-calculations of FAO statistics and from FishBase 99 (Froese and Pauly, 1999)

We therefore suggest the following ecological indicators for assessing the environmental relations of aquatic farms:

1. ecological footprint of the aquaculture enterprise as a whole, and per metric ton of product;
2. composition and environmental impacts of aquaculture emissions;
3. impacts of escapees and feral populations.

5. INTERSECTORAL INDICATORS

5.1. Sectoral Boundaries

Land can be used for growing crops, pasturing livestock, forestry, etc. Waters also have many options for use; e.g., irrigation, waste processing, recreation, navigation, aquaculture and fisheries, etc. These uses are often competitive rather than cooperative. Moreover, institutional structures and governance mechanisms have established and tend to maintain boundaries among sectors rather than fostering intersectoral partnerships. This can reduce resource-use efficiency and prevent synergism among sectors. The limited reuse of organic wastes and wastewater worldwide, despite a wealth of knowledge and skills that would facilitate greater recycling (e.g., Strauss and Blumenthal, 1990; Bartone, 1991; Edwards, 1992; Prein, 1996; Yan et al., 1998), is an example.

5.2. Water

The water resources sector has greatly underutilized the *aquatic* productivity of waters that are managed for domestic and industrial supply, irrigation,

hydropower, etc. Even the more farsighted advocates of an ecological approach to water resources management (e.g., see Zalewski et al., 1997) have under-emphasized the potential for producing food *in water itself*, before and/or after its use for other purposes. For water resources managers, the resource of interest has been usually only the water. They have tended to see aquatic biota only as agents that influence its supply and quality. In irrigation science and management, the very term “aquatic productivity” has usually meant the harvests of *terrestrial* plants grown through the use of irrigation waters. These attitudes are now changing. For example, the “Global Water Partnership”, hosted by the Stockholm International Water Institute, is emphasizing *multiple* use/reuse of water (for information, see <http://www.gwp.sida.se>).

For inland aquaculture, the growing scarcity of freshwater (e.g., Gleick, 1993; Abramovitz, 1996; McAllister et al., 1997) poses both constraints and opportunities. The constraints apply particularly to aquaculture for which freshwater is used exclusively, without recovery or multipurpose use or reuse. The same applies to crops and livestock. According to Pimentel (cited by Pearce, 1997), producing 1 kg of beef requires 100,000 l of water, compared to 3,500 l for 1 kg of chicken. Obviously, there are huge variations in freshwater requirements among aquaculture systems and species. These would have to be thoroughly compared with those for other food production systems in order to make policy decisions. Boyd (2000) compared the water requirements for soybean, rice, and pond-raised channel catfish (*Ictalurus punctatus*) in the USA and estimated production values (US \$ per m³) of water used as follows: rice, 0.12; soybean, 0.13; catfish, with annual pond draining, 0.31; and without annual pond draining, 0.78. Moreover, some of the freshwaters used for aquaculture can probably be used or reused for other enterprises prior to, simultaneously with, or after their use in aquaculture.

We compared, for 1997, the intensity of freshwater aquaculture (FAO, 1998) with human population density (Figure 5). This plot suggests a log-linear relationship between the intensity of freshwater aquaculture and human population density; i.e., more people results in more demand and higher productivity per unit area for local or national supplies of freshwater aquaculture produce. Inland aquaculture is heavily dependent upon the availability and cost of freshwater. Figure 6 shows inland aquaculture production by region, (excluding Asia), based on the methods that are described above for back-calculating production (from FAO statistics) to 1950.

5.3. Integrated Aquaculture

Aquaculture frequently competes with other sectors rather than seeking partnerships. Tacon (1998) stated, “. . . if finfish and crustacean aquaculture is to maintain its current high growth rate then it will have to compete with other users (i.e., human and animal livestock) for . . . nutrient or feed resources.” The same author concluded, however, that long-term expansion of aquaculture will

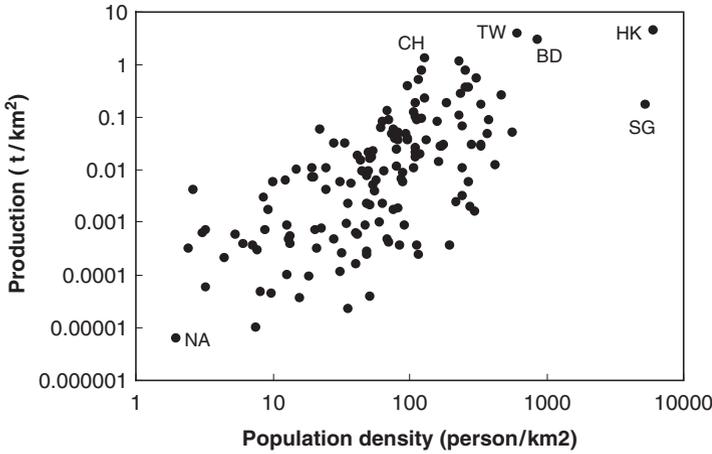


Figure 5. Freshwater aquaculture production in 1997 per square kilometer for various countries and territories, plotted against population density. BD = Bangladesh, CH = People's Republic of China, HK = Hong Kong, NA = Namibia, SG = Singapore, TW = Taiwan, Province of China (data from FAO, 1998)

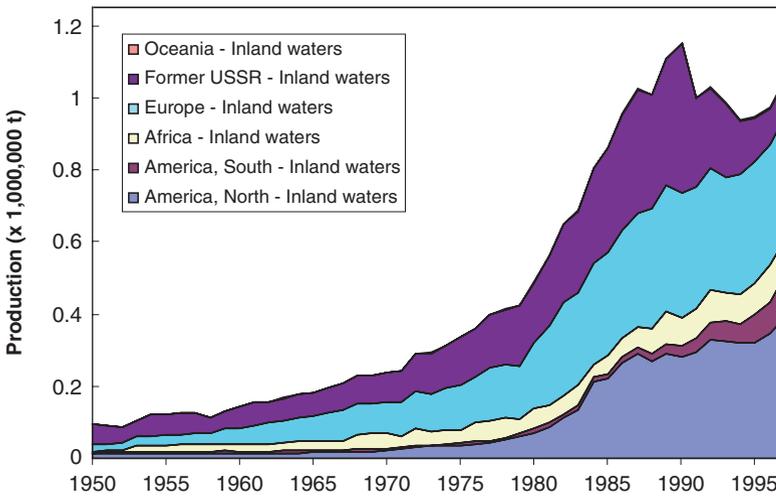


Figure 6. Inland aquaculture production by FAO area, aquatic plants excluded; estimated from FAO (1998). For methods of estimation of pre-1984 values, see text

depend upon improved efficiency of resource use and on systems that use “primary renewable resources.” This implies intersectoral integration.

Edwards (1998) published “narrow” and “broad” definitions of “integrated aquaculture,” the former meaning synergistic linkages among subsystems on mixed enterprise farms and the latter covering integration with agriculture,

agroforestry, fisheries, industry, power supply, sanitation, and water supply. In addition to those tabulated by Edwards (1998), sectors such as forestry, nature conservation, sport, and tourism can be integrated with aquaculture. For example, the historic sewage-fed fishponds near Munich are an important bird sanctuary (Prein, 1996). Folke and Kautsky (1992) made the case for aquaculture as a subsystem of overall ecosystems and pointed out the advantages of integrating agriculture, vegetable production, mangrove forestry, polyculture ponds, and small-scale fisheries in the coastal zone, rather than maintaining them as “industrial monocultures”, whether aquatic or terrestrial.

The problem is how to put into practice the environmentally desirable concepts called for by these and many other authors while increased productivity is pursued largely through monosectoral intensification (and often monocultures) and integrated systems are in decline; (e.g., in China [Dazhong and Pimentel, 1990; Boyd, 1999]). Edwards (1998) has “small-scale farms” in mind for integrated aquaculture but, despite their productivity and efficiency, their survival is threatened by current policies and trends. Agriculture faces similar problems of resource limitations and sectoral isolation. Lightfoot et al. (1993) have illustrated the role that integrated aquaculture can play in improving this situation.

We suggest that the “narrow” and “broad” categories of integrated systems, as defined by Edwards (1998), are really the same things at different scales. The problems of achieving partnerships and integration among enterprises on farms and among sectors at watershed, coastal zone, waterbody, and even national levels, are similar. For example, Pauly and Lightfoot (1992) adapted concepts and tools from farming systems research for analyzing resource systems in the coastal zone. Similarly, some established ecological indicators could be adapted for analyzing intersectoral relationships in large ecosystems.

We looked at four such indicators—diversity, cycling, stability, and capacity (Dalsgaard et al., 1995). These indicators, well-proven in ecological research, were applied by Dalsgaard et al. (1995) for assessment of the ecological sustainability of integrated versus non-integrated farms. We propose that these indicators be further investigated for assessing intersectoral integration in coastal zones, islands, river basins, entire countries, and seas. In Table 1, we compare the use of these indicators at the farm level (Dalsgaard et al., 1995) with our suggestions for their application at intersectoral level.

5.4. Indicators

Aquaculture must become more integrated with other sectors that use natural resources. We suggest the following intersectoral indicators for assessing the intersectoral integration of aquaculture:

1. sharing water with other sectors;
2. diversity of produce, services and livelihood opportunities;
3. cycling of by-products among sectors;

Table 1. Suggested indicators for assessing the degree of integration of aquaculture with other sectors. Entries in brackets are those adopted by Dalsgaard et al. (1995) for using these indicators at the farm level

| Indicators (system attributes) | Goals (desirable properties) | Methods of assessment (measures/selected method of quantification) |
|--------------------------------|--|---|
| Diversity | High diversity of produce and of livelihood opportunities (high diversity of farm enterprises, functional diversity) | Quantify the diversity of produce on farms and in markets, and of livelihood opportunities (species diversity/Shannon index) |
| Cycling | Extensive recycling of by-products; positive interaction and feedback loops within system (as above) | Develop cycling indices and flow diversity indices (internal ascendancy) |
| Stability | High reliance on sharing resources; mutual benefits of integration to cope with changes in climate, markets, etc. (high reliance on internal dynamics and ability to recover from perturbations) | Quantify the degree to which natural resources and ecosystem services are conserved (buffer capacity; system overhead; resilience; development—capacity; ascendancy) |
| Capacity | High quantity and quality of produce, with a healthy environment (high resource quality) | Quantify production levels and quality, with corresponding water, soil, and air quality (soil depth, organic content, pH; water color, pH, biomass/throughput; average standing biomass/sum of all flows) |

4. stability to cope with change;

5. capacity—quality of produce, services, and the environment.

And for all of these, the higher the level that a given aquaculture enterprise can achieve the more acceptable and sustainable it is likely to be.

6. PROSPECTS FOR USE

In Table 2, we summarize our proposed indicators and give broad indications of their desired levels (high or low) for the sustainability of aquaculture. There are, of course, interactions within and between categories. Are these indicators likely to be of any practical use? The complexity of ecosystem-based management and sustainable food production systems (e.g., see Slocombe, 1993; Parris, 1995; Bertollo, 1998) means that some of the codes of conduct and tools that have been developed for the pursuit of these goals are difficult to apply. For example, codes of practice on fish introductions and transfers (Turner, 1988) and a schema that was devised for assessing environmental impacts of aquaculture (Pullin, 1993) have seen little use. The FAO Code of Conduct for Responsible Fisheries (FAO, 1995) includes criteria, indicators, and obligations for responsible aquaculture development, and it has been expressed as a questionnaire (Sproul, 1997). Barg et al. (1997) suggested that this voluntary code be

Table 2. Summary of biological, ecological, and intersectoral indicators with broad levels (F = few, H = high, L = low, S = small) that are appropriate for sustainability in aquaculture

| Indicators | Desirable levels |
|---------------|--|
| Biological | Potential for Domestication (H), with Genetic Enhancement (H); Trophic Level (L, 2.5 to 3.0; see Froese and Pauly, 1999); Feed and Energy Conversion Efficiency (H) |
| Ecological | Ecological Footprint (S); Emissions (L in contents harmful to the environment and to humans); Escapees (F) and Feral Populations (S and/or harmless to other biota and ecosystems) |
| Intersectoral | Water Sharing (H); Diversity (H); Cycling (H); Stability (H); Capacity (H) |

viewed as a “framework” for dialogue. It contains the key recommendation that, “States should produce and regularly update aquaculture development strategies and plans, as required, to ensure that aquaculture development is ecologically sustainable and to allow the rationale use of resources shared by aquaculture and other activities” (FAO, 1995).

We believe that the main actors in aquaculture—policymakers, regulators, the private sector, communities, development donors, and individuals involved as producers and consumers of farmed fish—will have to strive more for its sustainability. Its net contributions to world fish supply and their ecological consequences (Naylor *et al.*, 2000) will also have to be examined more thoroughly. Otherwise aquaculture will decline, as many capture fisheries are doing. The general public is beginning to ask questions about the sustainability of fish supply and to find some guidance for what they can do to improve it. For example, Lee (2000), for the National Audubon Society, has a color-coded “Audubon Fish Scale” for what are, in effect, the implications of choosing to eat a particular species farmed or fished by a particular method.

The Second International Symposium on Sustainable Aquaculture, held in Oslo in 1997, issued a revised set of what are termed the “Holmenkollen Guidelines for Sustainable Aquaculture” (NATS, 1998). This document is a consensus statement from that symposium and has, as an appendix, aquaculture-related sections of the FAO Code of Conduct for Responsible Fisheries (FAO, 1995). The Holmenkollen Guidelines set out principles and practices which are entirely compatible with the indicators that we suggest here, although they give less emphasis to intersectoral issues and do not mention explicitly the concept of ecological footprints.

For some of our proposed indicators, quantitative information is already available. For example, information on the trophic levels of fish available in FishBase (Froese and Pauly, 1999) and information on feed conversion is available through the aquaculture trade and scientific journals. Therefore, it should be relatively easy for a proposed development or research initiative to be checked against these indicators for its implications with respect to sustainability.

For the remainder, (domestication with genetic enhancement, footprints, escapes, emissions) information is less accessible and needs to be supplemented through research and collated for cross-comparisons, preferably via the internet. In the case of water sharing and our suggested intersectoral “analogues” of ecosystem parameters, quantification has either barely started or is not yet readily accessible. Therefore, the use of these indicators will require a marked improvement in the availability of quantitative information—locally, nationally, and internationally.

Ultimately, the use of any or all of these indicators will depend on the *will* of potential users to actually use them. Those responsible for aquaculture development within sovereign States, as well as other actors who are involved directly or indirectly with aquaculture development, will need to become more proactive in the quest for sustainability. History suggests, however, that serious environmental degradation must be experienced before countermeasures are sought. During such degradation and (where possible) recoveries, the “baselines” for what is regarded as acceptable will shift (Pauly, 1995) as will the modes of governance that are chosen by or imposed on resource users (Kooiman et al., 1999).

Kiley-Worthington (1998) cited evidence that “Current developments in high-input agriculture, which were predicted to be able to feed the exponentially growing world population...are not solving the world’s food problems; rather, in some cases, they have been responsible for creating them...” A similar path for aquaculture development would further damage the environment and lessen food security. Aquaculture must rather seek to avoid or to minimize environmental degradation. It cannot rely indefinitely on “mining” resources from elsewhere. The “elsewheres” will run out—like switching from one overfished species to another in capture fisheries (Pauly et al., 1998). We hope that use of broad biological, ecological, and intersectoral indicators will contribute to progress towards the sustainability of aquaculture.

REFERENCES

- Abramovitz, J.N. 1996. *Imperiled Waters, Impoverished Future. The Decline of Freshwater Ecosystems*. Worldwatch Paper Number 128. Worldwatch Institute, Washington D.C., USA. 80 pp.
- Ackefors, H., and M. Enell. 1994. The release of nutrients and organic matter from aquaculture systems in Nordic countries. *Journal of Applied Ichthyology* 10: 225–241.
- Barg, U.C. 1992. *Guidelines for the Promotion of Environmental Management of Coastal Aquaculture Development*. FAO Fisheries Technical Paper 328. United Nations Food and Agricultural Organization, Rome, Italy. 122 pp.
- Barg, U.C., D.M. Bartley, A.G.J. Tacon, and R.L. Welcomme. 1997. Aquaculture and its environment: a case for collaboration. In: D.A. Hancock, A. Grant, D.C. Smith, and J.P. Beumer (eds.), *Developing and Sustaining World Fisheries: the State of Science and Management: 2nd World Fisheries Congress Proceedings*. CSIRO Publishing, Collingwood, Victoria, Australia. Pp. 462–470.
- Bartone, C.R. 1991. International perspectives on water resources management and wastewater reuse—appropriate technologies. *Water Science and Technology* 23: 2039–2047.

- Becker, B. 1997. *Sustainability Assessment: a Review of Values, Concepts and Methodological Approaches*. Issues in Agriculture, Number 10. Consultative Group on International Agricultural Research, Washington D.C., USA. 63 pp.
- Bertollo, P. 1998. Assessing ecosystem health in governed landscapes: a framework for developing core indicators. *Ecosystem Health* 4: 32–51.
- Born, A.F., M.C.J. Verdegem, and E.A. Huisman. 1994. Macro-economic factors influencing world aquaculture production. *Aquaculture and Fisheries Management* 25: 519–536.
- Boyd, C.E. 1999. Aquaculture sustainability and environmental issues. *World Aquaculture* 30: 10–13, 71–72.
- Boyd, C.E. 2000. Water use in aquaculture. *Global Aquaculture Advocate* 3: 12–13.
- Bozynski, C.C. 1998. *Growth, Reproduction and Behavior of Control and Selected Strains of Nile Tilapia (Oreochromis niloticus)*. M.S. Thesis, University of British Columbia, Vancouver, British Columbia, Canada. 109 pp.
- Chamberlain, G.W. 1993. Aquaculture trends and feed projections. *World Aquaculture* 24: 19–29.
- Costanza, R.R. et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387: 253–260.
- Dalsgaard, J.P.T., C. Lightfoot, and V. Christensen. 1995. Towards quantification of ecological sustainability in farming systems analysis. *Ecological Engineering* 4: 181–189.
- Dazhong, W., and D. Pimentel. 1990. Energy flow in agroecosystems of Northeast China. In: S.R. Gliessman (ed.), *Agroecology, Researching the Ecological Basis for Sustainable Agriculture*. Springer Verlag, New York City, New York, USA. Pp. 322–336.
- Edwards, P. 1992. *Reuse of Human Wastes in Aquaculture: a Technical Review*. The World Bank, Washington D.C., USA. 350 pp.
- Edwards, P. 1998. A systems approach for the promotion of integrated aquaculture. *Aquaculture Economics and Management* 2: 1–12.
- FAO (Food and Agriculture Organization of the United Nations). 1995. *Code of Conduct for Responsible Fisheries*. FAO, Rome, Italy. 41 pp.
- FAO. 1997a. *Review of the State of World Aquaculture*. FAO Fisheries Circular Number 886, Revision 1. FAO, Rome, Italy. 163 pp.
- FAO. 1997b. *Aquaculture Development*. FAO Technical Guidelines for Responsible Fisheries, Number 5. FAO, Rome, Italy. 40 pp.
- FAO. 1998. *Fishstat Plus*. FAO, Rome, Italy. Electronic Publication. Website: <http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp>
- Ferguson, A.R.B. 1999. The essence of ecological footprints. *Ecological Economics* 31: 318–319.
- Folke, C., and N. Kautsky. 1992. Aquaculture with its environment: prospects for sustainability. *Ocean and Coastal Management* 17: 5–24.
- Folke, C., N. Kautsky, H. Berg, A. Jansson, and M. Troell. 1998. The ecological footprint concept for sustainable seafood production: a review. *Ecological Applications* 8, Supplement 1998: S63–S71.
- Forster, J. 1999. Aquaculture chickens, salmon—a case study. *World Aquaculture* 39: 33–40, 69–70.
- Froese, R., and D. Pauly (eds.). 1999. *FishBase 99: Concepts, Design and Data Sources*. International Center for Living Aquatic Resources Management (ICLARM), Manila, Philippines, 324 pp. and 2 CD-ROMs. Electronic publication. Website: <http://www.fishbase.org>
- Gjedrem, T. 1998. Selective breeding in aquaculture. *Infofish International* 3: 44–48.
- Gleick, P.H. (ed.). 1993. *Water in Crisis: a Guide to the World's Freshwater Resources*. Oxford University Press, Oxford, England. 473 pp.
- Goodland, R. 1997. Environmental sustainability in agriculture: diet matters. *Ecological Economics* 23: 189–200.
- Kaushik, S.J. 1998. Nutritional bioenergetics and estimation of waste production in non-salmonids. *Aquatic Living Resources* 11: 211–217.

- Kiley-Worthington, M. 1998. Integrating conservation and agriculture production: a case study in the United Kingdom. *Ecosystem Health* 4: 61–72.
- Kinne, O. 1986. Realism in aquaculture—the view of an ecologist. In: M. Bilio, H. Rosenthal, and C.J. Sinderman (eds.), *Realism in Aquaculture: Achievements, Constraints, Perspectives*. European Aquaculture Society, Bredene, Belgium. Pp. 11–22.
- Kooiman, J., M. van Vliet, and S. Jentoft (eds.). 1999. *Creative Governance: Opportunities for Fisheries in Europe*. Ashgate Publishers, Aldershot, England. 287 pp.
- Lee, M. (ed.). 2000. *Seafood Lover's Almanac*. National Audobon Society, Islip, New York, USA. 120 pp.
- Lightfoot, C., M.A.P. Bimbao, J.P.T. Dalsgaard, and R.S.V. Pullin. 1993. Aquaculture and sustainability through integrated resources management. *Outlook on Agriculture* 22: 143–150.
- McAllister, D.E., A.L. Hamilton, and B. Harvey. 1997. Global freshwater biodiversity: striving for the integrity of freshwater ecosystems. *Seawind* 11: 1–139.
- NATS (Norwegian Academy of Technological Sciences). 1998. *Holmenkollen Guidelines for Sustainable Aquaculture, 1998*. NATS, Oslo, Norway. 21 pp.
- Naylor, R.L. et al. 2000. Effect of aquaculture on world fish supplies. *Nature* 405: 1017–1024.
- New, M.B. 1998a. Responsible aquaculture and the new millenium. *EC Cooperation Bulletin* 11: 16–70.
- New, M.B. 1998b. Global aquaculture: current trends and challenges for the 21st Century. *Anals do Aquicultura Brasil (Proceedings of Aquicultura Brasil '98, 2–6 November 1998, Recife, Brasil.)* 1: 9–57.
- Noakes, D.L.G., and E.K. Balon. 1982. Life histories of tilapias: an evolutionary perspective. In: R.S.V. Pullin, and R.H. Lowe-McConnell (eds.), *The Biology and Culture of Tilapias*. ICLARM Conference Proceedings 7: 61–82.
- Oláh, J., and F. Pékar. 1995. Transfer of energy and nitrogen in fish farming integrated ecosystems. In: J.-J. Symoens, and J.-C. Micha (eds.), *The Management of Integrated Freshwater Agropiscicultural Ecosystems in Tropical Areas. Proceedings of an International Seminar Brussels, 16–19 May, 1994*. Technical Centre for Agricultural and Rural Co-operation (CTA), Wageningen, Netherlands, and Belgian Royal Academy of Overseas Sciences (ARSOM), Brussels, Belgium. Pp. 17–201.
- Páez-Osuna, F., S.R. Guerrero-Galván, and A.C. Ruiz-Fernandez. 1998. The environmental impact of shrimp aquaculture and the coastal pollution of Mexico. *Marine Pollution Bulletin* 36: 65–75.
- Pan, J.H., and I.D. Hodge. 1993. Environmental standards versus structural changes as sustainability alternatives: an empirical evaluation of nitrate pollution control. *Environment and Planning A* 25: 1759–1772.
- Parris, K. 1995. OECD *Agri-environmental Indicators: Preliminary Work*. Paper presented at the Resource Policy Consortium Symposium, “Developing Indicators for Environmental Sustainability: the Nuts and Bolts,” 12–13 June, 1995, Washington D.C. Organization for Economic Cooperation and Development, Paris, France. 20 pp.
- Pauly, D. 1994. On the sex of fish and the gender of scientists. *Essays in Fisheries Science, Series No.14*. Chapman and Hall Fish and Fisheries, London, England. Pp. 61–73.
- Pauly, D. 1995. Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology and Evolution* 10: 430.
- Pauly, D., and C. Lightfoot. 1992. A new approach for analyzing and comparing coastal resource systems. *Naga, the ICLARM Quarterly* 15: 7–10.
- Pauly, D., and V. Christensen. 1995. Primary production required to sustain global fisheries. *Nature* 374: 255–257.
- Pauly, D., V. Christensen, J. Dalsgaard, R. Froese, and F. Torres, Jr. 1998. Fishing down marine food webs. *Science* 279: 860–869.
- Pearce, F. 1997. Thirsty meals that suck the world dry. *New Scientist*, February 1, 1997: 7.
- Pillay, T.V.R. 1997. Aquaculture development and the concept of sustainability. In: K.P.P. Nambiar, and T. Singh (eds.), *Sustainable Aquaculture*. Infomfish, Kuala Lumpur, Malaysia. Pp. 1–6.

- Prein, M. 1996. Wastewater-fed aquaculture in Germany: a summary. *Environmental Research Forum* 5-6: 155-160.
- Pullin, R.S.V. 1993. Discussion and recommendations on aquaculture and the environment in developing countries. In: R.S.V. Pullin, H. Rosenthal, and J.L. Maclean (eds.), *Environment and Aquaculture in Developing Countries*. ICLARM Conference Proceedings 3: 312-338.
- Pullin, R.S.V., H. Rosenthal, and J.L. Maclean (eds.). 1993. *Environment and Aquaculture in Developing Countries*. ICLARM Conference Proceedings 31: 1-359.
- Pullin, R.S.V., M.L. Palomares, C.M.V. Casal, M.M. Dey, and D. Pauly. 1997. Environmental impacts of tilapias. In: K. Fitzsimmons (ed.), *Tilapia Aquaculture. Proceedings of the Fourth International Symposium on Tilapia in Aquaculture, Volume 2*. Northeast Regional Agricultural Engineering Service, Ithaca, New York, USA. Pp. 554-570.
- Rosenthal, H., V. Hilge, and A. Kamstra (eds.). 1993. *Workshop on Fish Farm Effluents and Their Control in EC Countries*. Institute for Marine Science, Christian-Albrechts University of Kiel, Kiel, Federal Republic of Germany. 205 pp.
- Slocombe, D.S. 1993. Implementing ecosystem-based management. *BioScience* 43: 612-622.
- Sproul, J.T. 1997. Sustainable aquaculture certification: a questionnaire based on the FAO Code of Conduct for Responsible Fisheries. In: K.P.P. Nambiar, and T. Singh (eds.), *Sustainable Aquaculture*. Infofish, Kuala Lumpur, Malaysia. Pp. 154-158.
- Strauss, M., and U.J. Blumental. 1990. *Human Waste Use in Agriculture and Aquaculture. Utilization, Practices and Health Perspectives, Executive Summary*. International Reference Center for Waste Disposal Report 09/90, Duebendorf, Switzerland. 52 pp.
- TAC/CGIAR (Technical Advisory Committee, Consultative Group on International Agriculture Research). 1989. *Sustainable Agricultural Production: Implications for International Agricultural Research*. FAO Research and Technology Paper Number 4. Food and Agriculture Organization of the United Nations, Rome, Italy. 131 pp.
- Tacon, A.G.J. 1995. Aquaculture feeds and feeding in the next millenium: major challenges and issues. *FAO Aquaculture Newsletter* 10: 2-8.
- Tacon, A.G.J. 1997. Feeding tomorrow's fish: the Asian perspective. In: K.P.P. Nambiar, and T. Singh (eds.), *Sustainable Aquaculture*. Infofish, Kuala Lumpur, Malaysia. Pp. 20-42.
- Tacon, A.G.J. 1998. Aquaculture. Issue: dependence on agricultural and fishery resources. *Infofish International* 2/1998:19-25.
- Turner, G.E. 1988. *Codes of Practice and Manual of Procedures for Consideration of Introductions and Transfers of Marine and Freshwater Organisms*. FAO, EIFAC/CECPI, Occasional Paper 23. United Nations Food and Agriculture Organization, Rome, Italy. 44 pp.
- van der Bergh, J.C.J.M., and H. Verbruggen. 1999a. Spatial sustainability, trade and indicators: an evaluation of the "ecological footprint." *Ecological Economics* 29: 61-72.
- van der Bergh, J.C.J.M., and H. Verbruggen. 1999b. An evaluation of the 'ecological footprint': reply to Wackernagel and Ferguson. *Ecological Economics* 31: 319-321.
- Wackernagel, M. 1999. An evaluation of the ecological footprint. *Ecological Economics* 31: 31-318.
- Wackernagel, M., L. Onisto, P. Bello, A.C. Linares, I.S.L. Falfán, J.M. Garcia, A.I.S. Guerrero, and M.G.S. Guerrero. 1999. National natural capital accounting with the ecological footprint concept. *Ecological Economics* 29: 375-390.
- Yan, J.S., R.S. Wang, and M.Z. Wang. 1998. The fundamental principles and ecotechniques of wastewater aquaculture. *Ecological Engineering* 10: 191-208.
- Young Cho, C., and D.P. Bureau. 1998. Development of bioenergetic models and the Fish-PrFEQ software to estimate production, feeding ration, and waste output in aquaculture. *Aquatic Living Resources* 11: 199-210.
- Zalewski, M.G., A. Janauer, and G. Jolánski. 1997. *Ecohydrology. A New Paradigm for the Sustainable Use of Aquatic Resources*. International Hydrological Programme IHP-V Technical Documents in Hydrology Number 7. United Nations Educational, Scientific and Cultural Organization, Paris, France. 58 pp.