

## Review Article

# **Sustainable Land-based Aquaculture: Rational Utilization of Water, Land and Feed Resources**

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## **Introduction**

Much has been said on the need to practice aquaculture in a sustainable manner, preferably without jeopardizing the environment (Naylor, et al. 2000 and FAO 1997). As a result, best management practices for the aquaculture industry, considering environmental, economic and social sustainability, have been established (e.g. [www.gaalliance.org/bap.html](http://www.gaalliance.org/bap.html)). Standards of some organizations for organic farming restrict stocking density and maximum pond biomass per unit surface area. For example, to produce organic shrimps, less than 15 postlarvae (PL) per square meter should be stocked with shrimp biomass always remaining below 800kg/ha (e.g. Naturland standards 2004; [www.naturland.de/englisch/n2/NL-Stand-Aquaculture\\_01-2005.pdf](http://www.naturland.de/englisch/n2/NL-Stand-Aquaculture_01-2005.pdf)). These rules were mainly put forward to protect shrimp health and welfare, and to avoid the development of diseases. Naylor et al. (2000) stated that “intensification implies increasing the density of individuals, which requires greater

use and management of inputs and greater generation of waste products”. Such rules or statements suggest that intensification will always lead to the production of more wastes or to a reduction of animal welfare, which should be avoided.

This places aquaculture developers into a dilemma, as there is also a need for the aquaculture industry to keep up with a growing demand for fish, due both to population growth and to the need to better feed the population with healthy food (Wijkstorm, 2003). Global capture fisheries reached its limits with 75% of the major fisheries being over-fished or fished at their biological limits (CEOS, 2005). Thus, the aquaculture industry carries the responsibility of increased fish supply. A five-fold increase in global aquaculture production is needed within the next five decades to maintain current aquatic food consumption levels (FAO, 2004).

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To achieve this, using conventional extensive aquaculture ponds, a five folds increase of water consumed and land occupied will be needed. Soil and water resources are scarce, and in many situations expanding pond area is no longer a viable option.

In this review, the hypothesis is put forward that intensification of pond aquaculture is possible, without discharging more wastes, and in accordance with established codes of conduct and best management practice standards. This can be done by applying low cost technologies, technologies that can be adopted by developing countries. Intensification of pond aquaculture is necessary to provide aquatic food consumption for future generations, without putting larger claims on our dwindling land and water resources and is thus a central feature of sustainable aquaculture.

### **Increasing aquaculture production: needs and constraints:**

Presently, the total annual capture fisheries production, including marine and inland waters, is about 90 million metric tones. Total capture fisheries production has not grown since the mid 80's and is not expected to do so in the future. About 30% of global capture fisheries production is not used as human food, but to produce fish meal and fish oil used in animal feeds.

The stagnating capture fisheries production is confronted with a growing demand for fish due to population growth and to an increase in the per capita fish consumption (Wijkstrom, 2003). In 2003, the per capita fish supply was 16.3 kg/caput, including China, and 13.3kg/caput excluding China (FAO, 2004). The FAO would like to see a 53-200% increase in per capita consumption, to 25kg in 2025 (New, 1991) and to 30-40kg in 2050 (Wijkstrom, 2003). The growing gap between global fish demand and supply through capture fisheries is expected to be closed through aquaculture. Past and predicted aquaculture productions are given in Table (1).

**Table 1:** Global aquaculture production of finfishes, crustaceans and molluscs (FAOSTAT statistic database, [www.fao.org](http://www.fao.org). New 1991; Wijkstrom 2003).

Year	1953	1963	1973	1983	1993	2003
Million MT	0.96	1.76	3.07	6.21	17.77	41.90
<b>Expected (or required) production</b>						
Year	2010	2025 <sup>(1)</sup>	2025 <sup>(2)</sup>	2050		
Million MT	61	120	150	210		
Source	Wijkstrom 2003	New 1991	New 1991	Wijkstrom 2003		

1. Assuming per capita consumption identical to present one (i.e. no increase).
2. Assuming recommended FAO's 25 kg per capita.

Aquaculture production increased more than 40 times during the last 50 years and is expected to rise another 5 times in the coming 50 years. Such rise of aquaculture production has to be planned, considering the goal is to minimize environmental impact while optimizing resource utilization.

### **Sustainable aquaculture: rational use of natural resources:**

Land based aquaculture operations use land and water, mostly fresh, but also brackish or marine water. On a global scale, fresh water resources are becoming scarce and expensive. About 41% of the world's population today lives in water-stressed river basins. In 2050, 70% of the world population will face water shortage (CEOS, 2005).

Water losses in pond-based aquaculture are mainly caused by evaporation and seepage. Drainage water can be transferred to a potentially new user, and therefore was not considered as a net loss (Although, drainage water is not re-used in many cases, due to low quality and marginal accessibility). Daily evaporation is usually in the range of 2-10mm, i.e. 20-100m<sup>3</sup>/ha, depending on seasonal temperature and humidity (Yoo and Boyd, 1994; Boyd and

Gross, 2000). Seepage from properly built ponds (i.e. not built on highly permeable soil) will be less than five mm per day (Yoo and Boyd, 1994). Combined evaporation and seepage losses can be considered to be around 10mm per day, or about 3500mm per year. In consequence, a 1-ha pond will use 35,000m<sup>3</sup> of water per year to replace evaporation and seepage losses.

Aquaculture lands must be more or less flat, easily drained and close to reliable water sources like rivers, lakes or artesian wells. Such lands are also in high demand for other purposes: urbanization, agriculture, wetland (including mangrove) conservation, recreation and tourism. Marine aquaculture farms do not use large quantities of fresh water, but are developed in the coastal zone where land is scarce: 60% of the world population lives within 60km of the sea coast and more than two thirds of cities with over 2.5 million habitants are situated in the coastal zone (e.g. [www.unesco.org/mab/apasco/project.htm](http://www.unesco.org/mab/apasco/project.htm)). Coastal zones are ecologically sensitive, containing mangroves, coral reefs, and other unique ecosystems. The need to protect these environments leads to public and legal objections to any further enlargement of pond areas in coastal regions. For instance in India, where population density in the coastal zone is high, the Indian Supreme Court decided in 1996 not to allow construction of ponds within 500m from the high tide line ([www.fao.org/figis/servlet/static?dom=legalframework&xml=nalo\\_india.xml](http://www.fao.org/figis/servlet/static?dom=legalframework&xml=nalo_india.xml)). Other countries also limit construction of

coastal ponds by demanding compliance with stringent environmental conditions. Getting permission to develop new aquaculture sites is becoming a difficult, time-consuming process all over the world.

### Intensity of production and use of resources:

An overview of aquaculture systems, ranked by culture intensity from essentially enhanced-fishing impoundments to super-intensive recirculating systems, is given in Table (2). The most extensive aquaculture systems are based on the stocking of fish in water impoundments and feeding the ponds with additional feeds such as grains, house and farm-yard residues. Annual yields are usually below 1000kg/ha, though occasionally, yields of up to 2000kg/ha are obtained. When better, more complete diets are used, yields of 2000–4000 kg/ha/yr are obtained. On a global scale, most ponds produce appreciably less than 4000kg/ha/yr. For instance, the average productivity of fish farms in India (1999-2000) was 2226kg/ha/yr (Indian ministry of Agriculture).

Water use in aquaculture per kg fish produced decreases with the increase in production intensity. In an average extensive pond, with a yearly evaporation and seepage loss of 35,000m<sup>3</sup>/ha and an annual production of 2000kg/ha, 17.5 m<sup>3</sup> water is used to produce 1kg of fish. Only 50% of this is needed when the production level doubles to 4000kg/ha/yr.

**Table 2:** Schematic presentation of pond intensity levels, approximate annual fish yields and limiting factors.

Pond type	Intervention	Approximate yields (kg ha <sup>-1</sup> yr <sup>-1</sup> )	Limiting factors
Minimal feed	Minimal feeding with grains, farm and home residues	<2000	Limits of primary production, food chain efficiency
Fed ponds	Feeding by complete diet pellets	2000-4000	Early morning oxygen
Night time aeration	Night time or emergency aerators, ~1-5 hp ha <sup>-1</sup>	4000-10,000	Sludge accumulation, anaerobic pond bottom
Intensive mixed aerated ponds	24 hr aeration >20 hp ha <sup>-1</sup> –150 hp ha <sup>-1</sup> , (pure oxygen) Completely mixed	20,000-100,000	Water quality control

Aquaculture production should increase five-fold in the next five decades. If such a production increase would be realized maintaining an average pond production of 2000kg/ha/yr, an additional 330 m<sup>3</sup> fresh water/caput will be consumed, assuming an average annual per capita fish consumption of 35kg. This is more than three times the present residential per capita water consumption in developed countries and is similar to the total renewable per capita water resources in many Middle Eastern and North African countries (Rosegrant, et al. 2002). The real increase in water consumption will be much higher, as population growth still needs to be considered. In consequence, increasing fish production in extensive ponds cannot be sustainable, considering global water availability. Large-scale expansion of extensive pond aquaculture is also not possible due to land constraints. Assuming an annual production of 2000kg/ha, 5m<sup>2</sup> are needed to produce 1kg/fish. To raise per capita fish supply by ±20kg/capita this means an additional 100m<sup>2</sup> per capita is needed, area which is simply not available. In consequence, increased aquaculture production will have to come primarily from increased intensity rather than from added area and more water consumption. The challenge is to raise productivity while maintaining environmental sustainability.

To minimize waste discharge, while putting a minimal claim on land and water resources, highly intensive pond systems were developed in various countries, such as the USA, the Netherlands, Germany and Israel. The total production from these systems is still less than 1% of global pond production. Highly intensive ponds rely heavily on continuous mixing and aeration. The production in highly intensive ponds is within the range of 10-200kg/fish/m<sup>2</sup>/yr, i.e. 50 to 1000 times higher per unit of water or land compared to extensive systems. However, these systems are expensive to operate and need reliable infrastructure, including emergency backup systems and supplies. Such systems are not likely to be used to produce low-cost fish, especially not in the developing countries, where more than 90% of aquaculture fish production

and consumption takes place (FAO, 2004). An approach that is becoming very popular in recent years is the use bio floc technology (BFT). Water exchange in such ponds is limited or even null, leading to the accumulation of organic residues and to the development of a dense heterotrophic microbial population (Avnimelech, 2003 and McIntosh, 2001). As in all intensive aquaculture systems, inorganic nitrogen, including toxic ammonia and nitrite, accumulate in the water. This problem is prevented in ASP systems through the addition of carbonaceous substrates leading to assimilation and incorporation of the soluble inorganic nitrogen into microbial protein (Chamberlain, et al. 2001 and Tacon, et al. 2002). The microbial protein, aggregated in microbial flocs serves as a rich source of amino acids and growth factors for fish and shrimp, leading to significant recycling of protein and higher utilization of feed (Avnimelech, et al. 1994; Chamberlain, et al. 2001 and Tacon, et al. 2002).

Although with BFT systems depend on a massive input of energy for aeration and mixing, there are means to significantly raise pond productivity using similar principles, yet with low and medium cost technologies. The development, demonstration and dissemination of such technologies should be of high priority if the goal is to continue feeding a growing world population relying on truly sustainable aquaculture.

## **Optimizing productivity in stagnant ponds:**

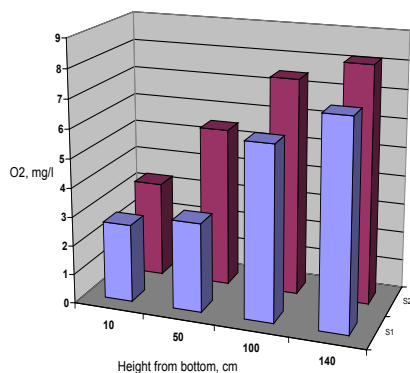
### **Oxygen-depleted sediments versus an oxygen-rich water column**

Highly intensive ponds are continuously and thoroughly mixed and aerated, keeping particulate matter suspended in an oxygen-rich water column. The dominance of aerobic conditions is a pre-requisite to the operation such active suspension ponds. To make better use of existing extensive ponds (Further referred to as stagnant ponds), similar conditions favoring microbial development and nutrient cycling should be created.

Nevertheless, the situation in stagnant ponds is different from bio floc technology ponds. In stagnant ponds, organic residues including uneaten feed, fecal pellets and dead algae settle to the pond bottom, creating a site of high biological oxygen demand. The oxygen supply to the pond bottom is limited, even in periods of natural mixing and surface re-aeration due to strong winds. In consequence, pond bottoms are oxygen-limited environments and often anaerobic (Avnimelech and Ritvo, 2003 and Meijer and Avnimelech, 1999). The water directly above the bottom is low in oxygen, also during day-time when the surface water is well oxygenated. Low oxygen availability affects benthic communities diversity and structure (Gray, et al. 2002 and Buzzelli, et al. 2002), including shrimp populations. Dissolved oxygen concentrations measured from 10-140cm above the pond bottom in two different shrimp ponds, are shown in Fig. (1). At 11.00a.m., 7-8mg/L of oxygen was present close to the surface, as compared with 2-3mg/O<sub>2</sub>/L at 10cm above the bottom. The oxygen concentration gradually increased from the pond bottom toward the surface.

### Carbohydrate addition:

Pond bottoms become more oxygen depleted when high quantities of organic matter are added to the pond. Thus, there is reason to expect that addition of carbonaceous substrates to enhance microbial activity will worsen the oxygen deficit and will not be effective in stagnant ponds.



**Fig. 1:** Oxygen Profile In A Commercial Shrimp Pond, 11am (Avnimelech and Serna, unpublished).

Studies by Hari, et al. demonstrated that the latter is not necessarily true. Microbial development and protein recycling was enhanced when supplementing a 25% protein feed with tapioca as carbohydrate source at a rate of 20g tapioca for every 1g of expected NH<sub>4</sub> excretion, assuming that 50% of the dietary nitrogen is excreted. The effect of carbohydrate addition to stagnant ponds was similar to the results obtained in bio floc technology ponds (Table 3). A careful preparation of the pond bottom, removing accumulated organic matter prior to stocking through drying and scraping was practiced prior to stocking. A dense aerobic microbial community harvested by the shrimp developed on the oxidized pond bottom and enhanced production.

Though this work has to be repeated and expanded, it can be considered as a breakthrough and an indication of the feasibility of enhancing microbial processes to raise yields while lowering dietary protein levels and hence feeding costs. It has to be noted that shrimp yields were raised by 50%, protein utilization doubled and net profit increased by a factor of five (Table 3).

**Table 3:** Summary of shrimp production in stagnant earthen ponds (Hari et al. 2004), as affected by feed C/N ratio. Control ponds, P40 got feed pellets with 40% protein. Treated ponds, P25+CH, got 25% protein pellets+tapioca flour, at levels adjusted to induce full recycling of N excreted by shrimp.

	P25 + CH	P 40
FCR	1.6	2.2
N Retention, % (a)	45	20
Net yield, g/m <sup>2</sup>	64	45
Gross Return (Rs/ha)	193,275	125,406
Production costs (Rs/ha)	83,202	103,420
Net Profit (Rs/ha)	110,073	21,986

Nitrogen accumulation in shrimp as a percentage of nitrogen added with feed.

## Vertical substrate addition

Another means to enhance microbial activity under aerobic conditions is to stimulate organic carbon accumulation on substrates in the water column, rather than on the pond bottom. Microbial communities containing algae, blue-green algae, bacteria, protists, zooplankton, and fungi embedded in an extracellular polysaccharide matrix develop on submerged surfaces. Within these communities, autotrophic or heterotrophic biomass dominates, depending on light, dissolved oxygen, and nutrient availability. The assemblage of attached organisms on submerged surfaces, including associated non-attached fauna is referred to as periphyton (Van Dam, et al. 2002). Placing either natural or synthetic submerged substrates (e.g. bamboo poles, plastic sheets etc.) in ponds leads to the adsorption of suspended organic matter on the vertical surfaces, at least partially replacing sedimentation and accumulation of organic matter at the pond bottom. Compared to organic matter at the bottom, the organic matter attached to substrates is exposed to oxygen rich water (e.g. Fig. 1) and is aerobically decomposed, thus contributing to a beneficial microbial food web. The microbial community developing on substrates can be manipulated using C/N control in a way equivalent to the bio-floc technology system. Extensive work was conducted and published during the last decade on periphyton's role and ecology in aquaculture ponds (Azim, et al. 2005).

Providing substrate at a density of 1m<sup>2</sup>/m of pond area increased the production of rohu (*Labeo rohita*) by 80% in fertilized ponds (Azim, et al. 2001a). Wahab et al. (1999) obtained a similar production increase with kalbaush (*L. calbasu*) using a substrate density of 0.5m<sup>2</sup>/m pond area. Not all fish species are able to utilize periphyton. For instance, gonia (*L. goniuis*) in ponds with a substrate density of 1m<sup>2</sup>/m of pond area did not yield a higher production compared to substrate free ponds (Azim, et al. 2001a). Proper selection of species for use in periphyton based aquaculture is important.

Substrate density influences production but the effect varies between species. With mahseer (Tor khudree) a substrate density of 98, 5-7 diameter, poles 25/m tank increased production 41% compared to pole-free tanks. Doubling the pole density to 196 poles 25/m led to a production increase of 51% (Keshavanath, et al. 2004). With tilapia (*Oreochromis mossambicus* × *O. niloticus*) using similar densities of poles, the production increased 112% at the low substrate density and 116% at the high substrate density (Keshavanath, et al. 2004). In addition, the fish production increase due to feeding a quality pellet-feed with species like masher and tilapia was less than when providing substrate for periphyton development (Keshavanath, et al. 2002, 2004). In consequence, providing substrate for periphyton developments in stagnant ponds contributed more to fish production than adding formulated feed.

The relation between periphyton and water quality was explored by Azim et al. (2003) using factorial analysis. Biofilm dislodgment increased with biofilm biomass. Attached algal development also positively influenced oxygen availability and decomposition in biofilms. In turn, nutrients released through decomposition stimulate autotrophic production by suspended and attached organisms. There is always competition between periphyton and phytoplankton for nutrients, but provided there is no nutrient limitation, the combined primary production by suspended and attached algae in periphyton-based systems is higher than in substrate-free ponds.

### Fish driven production enhancement:

Besides the provision of substrate and feed to increase production, synergism was observed with specific species combinations stocked in polyculture ponds (Hepher, et al. 1989). In non-fed fertilized periphyton-based ponds, various mixed stocking ratios of rohu (*L. rohita*) and catla (*Catla catla*) yielded 50-210% higher production than either species stocked in monoculture (Azim, et al. 2001b). By stocking

a bottom feeder, e.g. calbaush, as a third species, the production was further enhanced, resulting in an annual production of 6,900 kg/ha/yr (Azim, et al. 2002).

Stocking of fish species that browse in the sediment for food may help to oxidize the pond bottom. This method is used traditionally by farmers worldwide. A recent experiment by Ritvo et al. (2004) demonstrated that stocking carps leads to an appreciable mixing of the sediment. Sulfide concentration, an indicator for anaerobic metabolism and a highly toxic species, was diminished to practically zero when carps were present at a density of about 1 fish/m (Fig. 2). The mixing of the sediment by fish resuspends organic particles into the aerobic water column and thus raises the fraction of aerobically metabolized organic matter. The combination of fish driven resuspension with submerged substrates may be even more efficient, due to the possibility that the resuspended organic particles will be trapped by the biofilms growing on submerged surfaces.

#### Aeration:

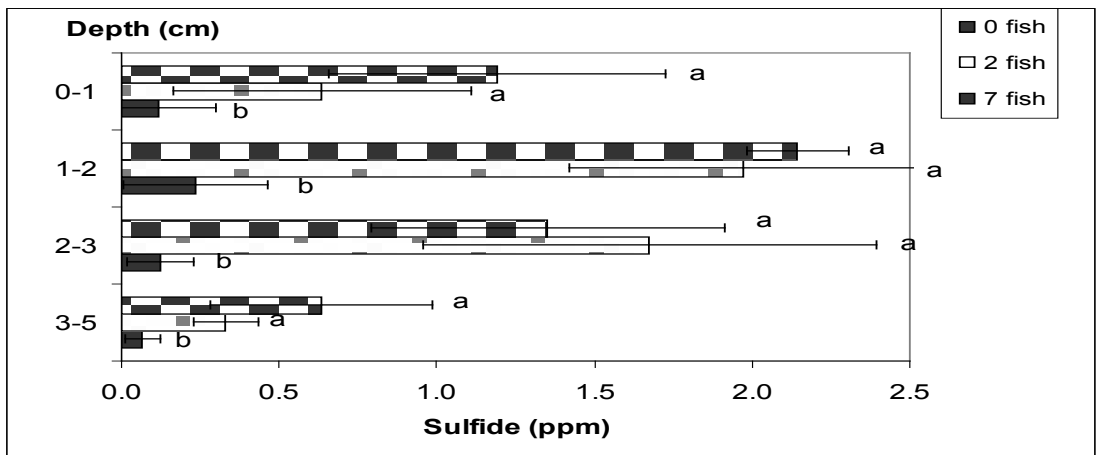
It has to be noted that an additional intensification can be achieved by the deployment of aerators, wherever possible. It was found, empirically, that even with a limited paddle wheel capacity

of 2.5hp/ha, the oxygen stratification in the water column disappeared (Avnimelech, unpublished). In cases where there is an affordable, reliable and continuous energy supply, artificial aeration can be used to further raise the pond production capacity.

#### Raising feeding efficiency:

Modern aquaculture is based on the production of fish fed with artificial feeds. In most cases the feed contains a significant percentage of fish meal and fish oil to supply essential amino and fatty acids. Today, close to 30 million MT of fish caught annually through capture fisheries are used for fish meal and fish oil production (Barlow and Pike, 2001). This leads to an annual supply of 6 to 7 million MT of fishmeal and 1.1 to 1.4 million MT of fish oil. Of these amounts, 34 and 56%, respectively, were used in aquaculture feeds in 2002, and this percentage is expected to increase to 48 and 79%, respectively, by 2010 (Pike and Barlow, 2003).

Fishmeal is still the primary source of dietary protein in fish feeds (Olvera-Novoa, et al. 2002), mainly for carnivorous species with inclusion levels of 30-45%. About 5kg of wild fish are needed to produce 1 kg carnivorous fish, and an average of 1.9kg wild fish is needed to produce 1kg fish in ponds (Naylor, et al. 2000). Over-



**Fig. 2:** Concentrations of total sulfide in pond bottom soil in enclosures (6 m<sup>2</sup>) 45 days subsequent to stocking by carp. Treatments with different letter are statistically differ at P-value<0.05. Comparisons are within each soil depth slice. Error bars represent standard deviations.

fishing in the ocean to obtain enough fishmeal and fish oil may endanger the global marine environment (Pauly, et al. 2002). On a long-term basis, relying on fishmeal and fish oil for aquaculture feed is not sustainable. One option to reduce the dependence of the aquaculture industry on fishmeal and fish oil is to maximize utilization of the natural food chain in the pond while maximizing feed utilization. A similar approach can also be applied to nutrients supplied through inorganic and organic fertilizers.

In bio flocculation technology, minimizing water exchange (Zero or very limited exchange), in combination with continuous aerating and mixing, leads to the development of a dense microbial population, metabolizing organic residues. Ammonium, nitrite, and nitrate concentrations in such systems are controlled through the addition of carbonaceous substrates (C/N control) to enhance microbial production (Avnimelech, 1999). Microbial proved to be an effective source of proteins, vitamins, and essential fatty acids for shrimp and several fish species (Decamp, et al. 2003, Tacon, et al. 2002). It was shown that proteins can be recycled through the activity of aerobic microorganisms and that protein utilization is doubled in BFT ponds (Avnimelech, et al. 1994 and McIntosh, 2000). Studies by Hari et al. demonstrated the same principles can be applied in stagnant ponds. The challenge is to further fine-tune this technology.

## **Conclusions**

Fish, shellfish and crustaceans, collectively referred to as 'fish' in the text above, are essential sources of protein and healthy nutrition in large parts of the world. Capture fisheries cannot expand further (FAO, 2004). To increase the contribution of aquatic foods to human nutrition for a growing world population, aquaculture production should increase five-fold during the next five decades. Increasing aquaculture production by expanding the present pond area and raising water consumption is simply

not possible. The necessary additional water use per capita would surpass more than three times today's residential water consumption in developed countries as well as the total per capita renewable water resources in many parts of the world. There is also not enough land available to further expand pond area. In consequence, the only sustainable way to increase aquaculture production is to intensify aquaculture, which today is mainly produced in extensive or fed ponds.

Stimulating microbial development in BFT ponds improved nutrient efficiency, and reduced the need for dietary fishmeal and fish oil, which in the long-term cannot be produced in sufficient quantities in a sustainable way. In addition, less nutrients were discharged while water use was minimized. Microbial activity is controlled through C/N ratio manipulation, and the addition of carbonaceous substrates, leading to the doubling of protein utilization and supply of essential lipids and vitamins. The same principles can be applied to stagnant ponds by combining C/N ratio control, with enhancement of periphyton development on submerged substrates and a reduction of organic matter accumulation in sediments through the stocking of bottom feeders. Previous studies showed that each of these techniques enhanced production in stagnant ponds, and further production increases might be obtained through synergism between the various techniques. Exploring such synergisms might lead to achieving a new blue revolution in aquatic systems, similar to the green revolution in terrestrial systems 40-50 year ago. The evidence brought in this paper demonstrates the importance and feasibility of raising ponds productivity and calls for a global effort to optimize, integrate and disseminate the appropriate technologies.

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