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Sustainable Aquaculture in the Twenty-First Century

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ABSTRACT: There have been many efforts to create a conceptual framework for understanding and defining sustainable aquaculture. A recent consensus or stakeholder view (Caffey et al., 1998) approached sustainability from three perspectives: environmental, economic and sociological. Often, stakeholder views are snapshot or present oriented. The multiple variables affecting sustainability and viability are considered from a here-and-now perspective rather than considering the effects that significant change in one or several variables might cause. Aquatic nitrogen loads generated from the sewage effluent of a growing, global human population (15 billion vs. 6 billion people) may prevent the legal discharge of any aquacultural effluents. Much of the intensive aquaculture industry has a highly centralized structure with respect to production and distribution. This centralized development has flourished around energy rich -- at times extravagant -- cultures and economies. How will increased costs or shortages of electricity, gasoline, and diesel fuel affect the sustainability or survival of the current production system? Does a large, centralized industry provide more jobs and profit or a better quality of life (per capita) than widely dispersed, small scale operations producing at local or county levels?

Nutrient recycling (converting nitrogen back to protein) through different polyculture systems could be more practical and efficient than controlling or treating the effluents associated with traditional, intensive monoculture practices. Phytoplankton and zooplankton occupy sizable respiratory (oxygen consumption) niches in the production pond environment -- and have no market value. Careful selection of suitable filter feeding fish and mollusks for polyculture could open up these niches for production of species with greater economic value. It might be more desirable to culture channel catfish with paddlefish and some species of freshwater mussel than to face bankruptcy because it has become illegal to discharge effluents from production ponds used for intensive monoculture. Ultimately, sustainability may be the aquaculture industry's ability to adapt on a planet with an ever increasing human population which continues to consume its limited supply of non-renewable resources at an alarming rate.

KEY WORDS: sustainable aquaculture, nutrient recycling, polyculture systems, plankton harvest.

I. INTRODUCTION

Considerable discussion and debate have arisen about sustainability. The temptation to oversimplify sustainability and present it as a single issue can be, at times, overwhelming. Some have contended that the term "sustainability" is worthless, has no practical value and should be rejected altogether. However, sustainability is a complex idea and an abstract concept that provides a framework for interdisciplinary dialogue, interaction and research. Usually, solutions require multiple inputs and diverse perspectives. Whether the word sustainability has become overused or not, it has catalyzed a forum for oversight of the growth and development of aquaculture on a global scale. The future is created by our actions or inactions in the present.

On a geologic or galactic time scale, life on this planet is not truly sustainable because it is dependent on solar energy. Stars burn out and entropy prevails. The word sustainability carries many connotations, which vary as widely as the opinions of the individuals who comment or are questioned. Boyd (1999) commented that "environmental management" is the critical issue and that aquaculture is not truly sustainable because production relies on external feed, chemical and energy inputs (Boyd and Tucker, 1995). Caffey et al. (1998) conducted a "stakeholder" survey in an attempt to develop a consensus assessment of sustainable aquaculture in the southeastern United States. Respondents were polled to determine measurable indicators of sustainability in three different areas: sociological, economic and environmental. Environmental concerns dealt with the quantity of land, water and energy used; water quality; and effluents. Economic issues focused on profitability, market demand and improved feeding efficiency. Sociological interests centered on employment, local concerns such as residency/ownership and aesthetics, and regional sources of inputs (feed, labor, money). The United States Farm Bill of 1990 defined the key components of sustainability as: maintaining profitability, using non-renewable resources efficiently, supplying food and fiber needs, enhancing renewable resources and improving the quality of life in rural areas. Sustainability should incorporate as many different aspects as are manageable.

II. OPINIONS, VARIABLES AND CHANGE

Often individual opinions and consensus views are snapshot or present oriented, and ephemeral. There are multiple and interdependent variables affecting sustainability. The "here-and-now" perspective ignores the effects that significant change in one or more of these variables might cause over time scales of decades and centuries. The global population has almost doubled since 1960, growing from 3 to 5.9 billion people by 1999. Sewage effluent from our growing human community will certainly affect how much effluent may be discharged by the aquaculture industry. Intensive, highly centralized and energy dependent aquaculture industries could be jeopardized by shortages or increased costs of electricity, diesel fuel and gasoline. A centralized industry structure might not provide more jobs, profit or a better quality of life (per capita) than widely dispersed, small-scale operations which produce at the local or county level. Furthermore, biological limits to pond carrying capacity suggest that increased profits are not likely to come from higher stocking densities.

By 2050, the number of humans on this planet is expected to reach 9.3 billion (Table 1), more than three times greater than the population of 1960. The resultant increase in aquatic nitrogen loads from human sewage effluents may prevent the discharge of any aquacultural effluents. One of the more recent and popularized crises in the United States is the "*Pfiesteria* hysteria." A few opportunistic journalists and microbiologists seized the occasion to blame the swine production industry for toxic dinoflagellate blooms *(P. piscicida)* that developed in estuaries along the east coast of the United States. They claimed that the nutrients released from the overflow of swine sewage lagoons stimulated the development of this alga. It seems more likely that the nutrient loads associated with the discharge of sewage effluents from several large, urban population centers (e.g. Baltimore, MD; the District of Columbia; Richmond, VA; and Norfolk, VA) would have had much greater impact on the affected estuaries than swine wastes. While swine farms may generate more nitrogenous waste per kg of animal produced, humans produce 17 times more waste volume (water used) than swine (EPA, 1980; ASAE, 1993; Table 2). As our population and the concomitant sewage effluents grow, the occurrence of toxic algal

TABLE 1
Estimated Global Population Growth and the Average Annual Percent Increase: 1950-2050.[a]

Year	Annual Increase (%)	Humans (billions)
1950		2.6
1975	1.88	4.1
2000	1.58	6.1
2025	1.05	7.9
2050	0.65	9.3

[a]*Adapted from the U.S. Bureau of the Census. (1998)*

TABLE 2
Total Nitrogen and Volume of Waste Effluent Generated by an Equal Swine and Human Biomass (79.5 kg Animal).

Source	Total N (g/day)	Volume (L/day)
Human[a]	11	173
Swine[b]	41	11

Adapted from:
[a]*EPA (1980)*
[b]*ASAE (1993)*

blooms may become more prevalent worldwide. If it comes to a decision whether to close a fish farm versus a sewage treatment plant for a large city, the fish farm will lose.

Channel catfish farming in the U.S. is a highly centralized industry (Figure 1). Most of the acreage (> 40,000 ha) and production (approx. 70%) are located in northwest Mississippi. To sell their harvest, Mississippi farmers process catfish in-state and ship their products throughout the country. Ponds are stocked heavily and, as such, must be aerated throughout much of the production season. It is unlikely that these intensive practices could be continued if the cost of electricity (for aeration) was to increase sharply. Similarly, increased prices or shortages of diesel fuel and gasoline, like those experienced during the "oil embargo" of the 1970's, would make distribution of catfish to nation-wide markets costly or impossible. While it might be possible to harvest ponds with plow horses, cross-country transport (Mississippi to California) of fresh or frozen catfish fillets using a mule team and a wagon is not realistic. Other aquaculture industries, such as shrimp and salmon farming, are dependent on global delivery systems to export and market their products.

Diesel trucks and extensive interstate highway systems that link remote agricultural areas and major population centers are not as common in developing nations as they are in highly industrialized countries. As fossil fuels become progressively more expensive and scarce,

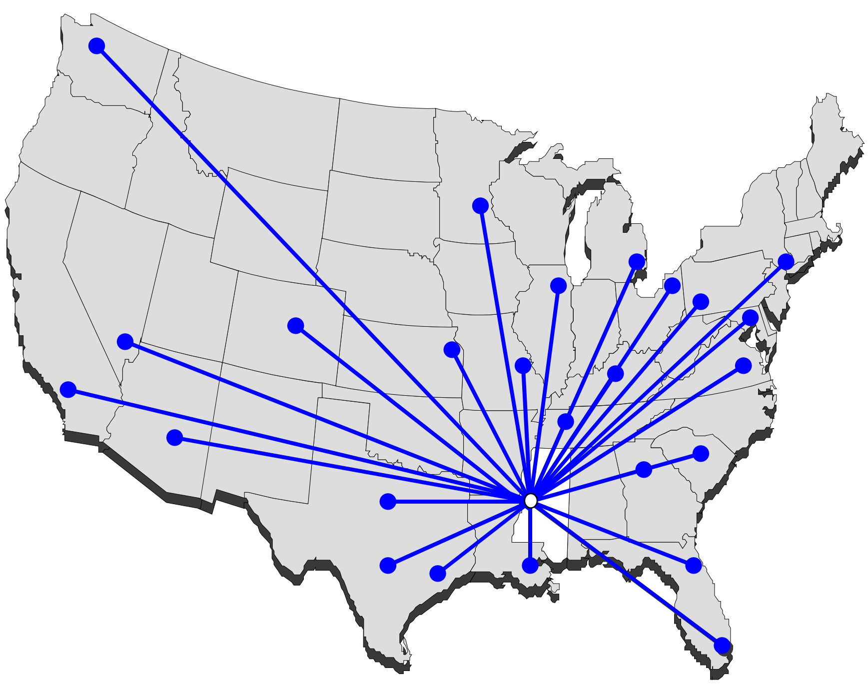

FIGURE 1. Centralized production, distribution, and market structure of the U.S. channel catfish industry, which is located primarily in Mississippi.

construction of large-scale, national road networks may be impractical for underdeveloped countries. Although some have scoffed at economic planning based on a small-scale industry structure, this may be the best option for the widespread growth of aquaculture on a global scale. An industry could be composed of multiple owner-operators with limited to moderate acreage, at short distances from their markets. Transport to the market would be less dependent on the availability of fossil fuels. Several farms could be located at the perimeters of markets which are widely dispersed across large geographic regions, as opposed to a very large industry situated at the center of a single, massive distribution web (Figure 2). The ancient Aztec and Roman civilizations collapsed when the perimeters of their centralized empires became too large to control -- "All roads lead to Rome."

Large, intensive aquaculture businesses and their profits are typically controlled by relatively few individuals. The big farms and their support industries, such as feed and processing plants, often employ many people by the hour and as temporary or seasonal contract labor. From a sociological perspective, it seems plausible that an industry composed of widely dispersed, small-scale and intermediate size farms and businesses owned by multiple, independent operators would promote greater self-sufficiency and provide a higher standard of living overall than would be associated with day laborers and hourly-wage earners.

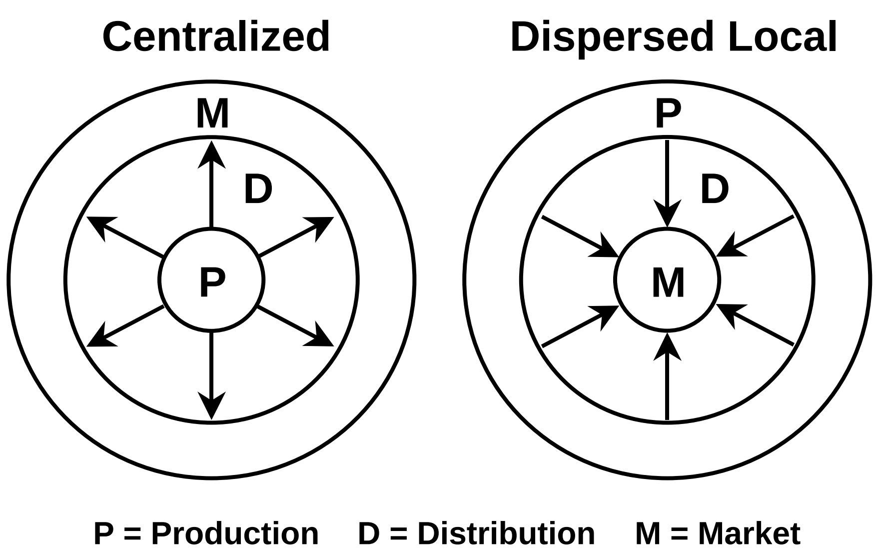

FIGURE 2. A large, centralized industry versus widely dispersed, local or regional industries.

III. PRODUCTION LIMITS

There are biological limits in the production pond or aquatic environment. Stocking densities and harvest yields are finite and determined by pond (environmental) carrying capacity. The availability of dissolved oxygen is the primary factor determining maximum pond biomass. Depending on temperature, salinity and atmospheric pressure, water can only hold a certain concentration of oxygen. As the overall weight or biomass of a farmed species increases in the culture pond, so does oxygen demand. When respiratory demand exceeds the rate of oxygen replacement from surface diffusion and photosynthesis, either aeration is employed or oxygen becomes depleted and the culture species suffocate.

The total biomass in production ponds is composed primarily of phytoplankton, zooplankton, the culture species and other micro-organisms (bacteria, fungi, etc.). Phytoplankton produce most of the oxygen consumed in the production pond through photosynthesis. But phytoplankton consume oxygen as well. The waste products (manure, uneaten feed and excreted ammonia) from the primary culture species release nitrogen and phosphorus (fertilizer) into the pond which stimulate the growth of phytoplankton. The nitrogenous wastes can be toxic to aquatic animals. However, when the phytoplankton population (or bloom) becomes too dense, nighttime oxygen consumption becomes greater than the rate of replacement from surface diffusion and photosynthesis. Production wastes cap harvest biomass by increasing phytoplankton growth beyond critical densities.

Phytoplankton productivity and biomass are measured indirectly as the chlorophyll a concentration (μg/l). Contrary to the popular maxim that "nutrients (e.g., phosphorus and nitrogen) are limiting" for plant (phytoplankton) growth, in heavily stocked or intensive, production ponds, light can be the limiting factor. The concentration of plants becomes so high (400-600 μg/L chlorophyll a) that light can not penetrate to any appreciable depth (Tucker, 1996). This limits photosynthetic oxygen production and primary productivity while respiration increases or continues unattenuated. When phytoplankton populations are sufficiently dense, even aeration will not maintain dissolved oxygen at concentrations acceptable for aquatic life. In addition to oxygen depletions, the off-flavors commonly associated with dense algal blooms will hamper production (i.e., unmarketable product).

IV. POND BIOMASS

From a commercial standpoint, it is easy to view the cash crop as being the only significant species in a production pond. As discussed previously, pond biomass consists of several aquatic life-forms, not the least of which are planktonic. Little empirical data exist about zooplankton productivity in aquaculture ponds (eutrophic waters) and even less practical information is available for predicting standing, zooplankton biomass. However, there is some knowledge about phytoplankton productivity, respiration and standing biomass in intensively farmed ponds (Boyd, 1982; Losordo, 1988; Piedrahita, 1991; Smith, 1991; Tucker, 1996). Boyd and Tucker (1995) reported that for every 1,000 kg of live channel catfish harvested, total phytoplankton productivity is 2,500 kg/ha dry weight or approximately 50,000 kg/ha wet weight. Each season the plankton biomass is lost when these organisms die, break down, and return to their basic components: water, carbon dioxide, nitrogen and phophorus.

On a dry weight basis, phytoplankton and zooplankton could easily account for almost half of the total, daily biomass in a culture pond. At harvest, there would be a standing biomass (dry weight) of approximately 900-1,000 kg/ha of plankton for 1,000 kg/ha (5,000 kg/ha wet weight) of channel catfish. Because of their smaller size and greater surface area to volume ratio, phytoplankton and zooplankton have significantly greater metabolic rates and therefore, much higher respiratory rates. In a commercial production pond, phytoplankton alone can consume greater than five times more oxygen per day than channel catfish (Table 3).

V. PLANKTON HARVEST

The most obvious way to increase the harvest biomass of a culture species is to lower oxygen demand by reducing plankton biomass. Greater oxygen availability would permit higher stocking densities and bigger yields. Plankton could be harvested either mechanically or biologically. Mechanical harvest would involve pumping water through filters and collecting the plankton retained. Because the mesh or screen size determines the size of the particle harvested, filter screen selection and placement would be critical. Screen mesh must be small enough to retain the size of plankton desired but large enough to allow smaller plankton and particles to pass through unobstructed. Larger particles such as zooplankton must be removed before filtering smaller particles like phytoplankton and minute zooplankton. Otherwise, the small mesh screens for phytoplankton would become clogged rapidly by the large zooplankton, and filtering would be disrupted. While mechanical harvest of plankton may be technologically feasible, it is likely that economic obstacles and the current lack of markets for plankton products would make this approach impractical.

TABLE 3
Daily Respiratory Oxygen Demand for Channel Catfish and Phytoplankton in an Intensive Production Pond.

Type	**DO (mg/L • day)**
Catfish[a]	3.5
Phytoplankton[b]	18

Adapted from Tucker (1996)
[a]Standing biomass = 5,000 kg/ha
[b]Chlorophyll a = 300 µg/L

Biological harvest of plankton from aquaculture ponds is not a theoretical concept. Indeed, it is practiced worldwide and is more commonly known as polyculture. In addition to the primary culture species, polyculture ponds incorporate additional species to take advantage of feeding niches present but unused in monoculture ponds. Because phytoplankton and zooplankton offer the largest sources of potential food, filter feeding fish are stocked into polyculture ponds. Mollusks could also be used. Species that eat zooplankton, such as bighead carp, are combined with those that feed on phytoplankton, such as silver carp and tilapia. There are a variety of combinations that could be used in fresh or salt water, two possibilities are listed in Table 4. By removing plankton, filter feeders are indirectly recycling the nitrogen and phosphorus wastes released into the production pond. Nitrogen is converted to protein (muscle) and phosphorus is incorporated into ATP (adenosine triphosphate) and other organic compounds.

VI. MODIFIED POLYCULTURE

The traditional polyculture practice of allowing both zooplankton and phytoplankton feeders to roam freely in the same pond has some drawbacks. This technique can be inefficient and problems like those discussed for mechanical filtration exist. Species that feed on phytoplankton are filtering smaller particles from the water than animals that consume large zooplankton. Both types of filter feeders are grazing simultaneously, or parallel to one another. In addition to removing phytoplankton, herbivorous planktivores remove large zooplankton from the pond non-selectively, because they strain their food from water on the basis of size (i.e., small mesh screens vs. large mesh screens). The net effect is a lowered concentration of zooplankton which reduces the filtration efficiency and potential biomass of zooplankton feeders.

As with mechanical harvest, the most efficient method of plankton harvest would be to place zooplankton feeders in front of phytoplankton feeders and those animals that consume much smaller zooplankton. Each of the different species would have to be compartmentalized

TABLE 4
Examples of Potential Freshwater and Saltwater Polyculture Species and Their Respective Feeding Niches.

Freshwater	Saltwater	Food Niche
Catfish	Shrimp	Prepared feed
Paddlefish	Mullet	Plankton
Mussels/clams	Oysters	Plankton
Crawfish	(Shrimp)[a]	Detritus

[a]Shrimp are detrital feeders as well as the primary culture species.

according to the size of plankton they screen, flowing water past species that filter large particles first and those that feed on the smallest particles last. Pond water could be pumped into the first chamber and then to and from each successive chamber into the next, in a series arrangement of floating or land-based tanks (Figure 3).

In theory, reducing the standing biomass of plankton by half could significantly lower the oxygen demand in a production pond and increase the harvestable cash crop over two-fold. Employing this polyculture or plankton harvest concept, it might be possible to produce 5,000 kg/ha of channel catfish without aeration or high concentrations of waste nitrogen and phosphorus. However, the biomass (filtration rate) of filter feeders must be balanced with total phytoplankton and zooplankton productivity.

VII. CRITICAL CONSIDERATIONS

The aquaculture industry must be able to adapt if it is to survive and grow. The blueprint for modern industrial society may not work well as a template for developing nations. It may be necessary to alter production and market structures, recycle waste effluents, harvest plankton or reduce stocking densities. Transporting fish with a team of Clydesdales is no less practical than hauling beer. Does "Plan B" exist? Is rapid transition feasible?

Time scale is a crucial concern. The global population has been increasing exponentially. Competition for non-renewable resources continues to escalate. Regardless of the culture practice used, there are biological limits to production or environmental capacity. Time measures change, and change is inevitable.

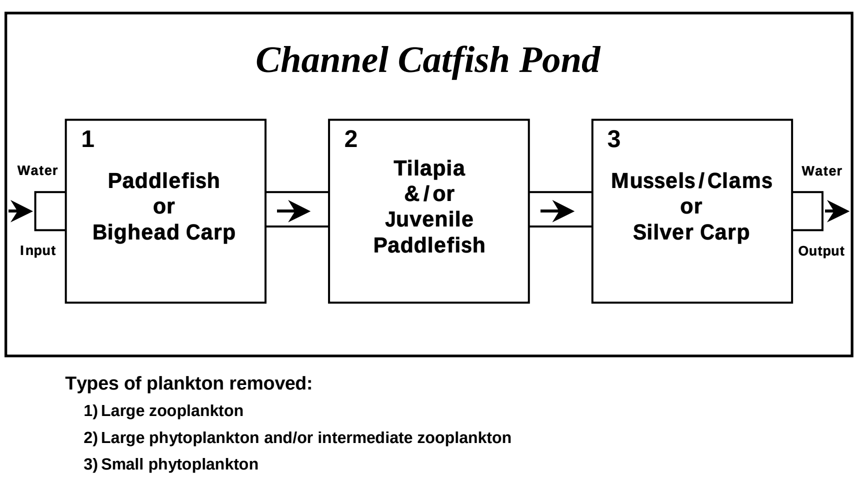

FIGURE 3. Compartmentalized polyculture places filter feeding species in a series arrangement to harvest plankton more efficiently.

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