# PARTITIONED POND AQUACULTURE SYSTEMS

## CRAIG S. TUCKER, DAVID E. BRUNE AND EUGENE L. TORRANS

AQUACULTURISTS HAVE PROPOSED OR DEVELOPED ALTERNATIVE OUTDOOR CULTURE SYSTEMS THAT ATTEMPT TO ADDRESS THE LIMITATIONS AND INEFFICIENCIES OF TRADITIONAL AQUACULTURE PONDS. PARTITIONED PONDS ARE PHYSICALLY DIVIDED INTO AREAS THAT ALLOW BETTER CONTROL OVER CONFINING FISH, PRODUCING OXYGEN, TREATING WASTES OR CULTURING SECONDARY SPECIES.

World aquaculture is dominated by the use of simple earthen ponds. Unlike other common aquaculture systems, ponds provide many of the resources needed to grow aquatic animals in one self-contained unit. The main resource is phytoplankton that use solar energy to drive photosynthesis. Phytoplankton produce new organic matter, generate oxygen as a byproduct of photosynthesis, and assimilate carbon dioxide, ammonia, and other mineral nutrients from the water. Algal photosynthesis provides three essential resources for aquaculture production: 1) potential food for cultured animals, 2) oxygen to support life, and 3) treatment of wastes so that they do not accumulate to toxic levels.

Relying upon sunlight to drive photosynthesis to maintain water quality represents the lowest cost and most sustainable approach to fish or shrimp production, which explains the popularity of ponds as aquatic animal production systems. However, utilization of solar energy comes at a cost and with certain limitations. The capacity of ponds to treat wastes—and, therefore, the upper limit to aquaculture production—is ultimately limited by the finite energy available from sunlight and the relatively low photosynthetic efficiency of algae (only 1 to 2 percent of incident solar energy is converted to chemical energy stored in algal biomass). Aquaculture production per unit area in algal ponds is therefore significantly lower than that achievable in systems using energy subsidies (in the form of feed) from externally supplied fossil fuels.

Another consequence of low photosynthetic efficiency is that relatively large areas are needed for waste treatment relative to the water area (or volume) needed simply to confine the cultured animals (Sidebar). Aquatic animals moving freely within traditional aquaculture ponds are therefore distributed at much lower densities than in more intensively managed culture systems, leading to a number of management inefficiencies.

Aquaculturists have proposed or developed alternative outdoor culture systems that attempt to address the limitations and inefficiencies of traditional aquaculture ponds. In this article, we describe our personal involvement with the development of some of those alternatives. These systems have one design feature in common: the water body is physically divided into areas that allow better control of certain processes, such as confining fish, producing oxygen, treating wastes, or culturing secondary species. Because various ecosystem functions are physically separated, we call these systems "partitioned ponds."

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### SPATIAL REQUIREMENT FOR FISH CONFINEMENT AND WASTE TREATMENT

Channel catfish can be grown in raceways at biomass densities exceeding 135 kg/m$^3$, assuming that water flow is sufficient to provide dissolved oxygen and remove wastes. In a 1-m-deep pond, 135 kg/m$^3$ is equivalent to holding 1,350 kg of catfish in a 10-m$^2$ area. Consider this as an estimate of the 'living space' needed by pond-grown catfish. The amount of ammonia produced by fish can be estimated from feed consumption, ammonia production rate, and fish biomass. If 1,350 kg of fish are fed 2 percent of body weight per day and ammonia excretion is 35 g N/kg of feed consumed,

Ammonia production = (35 g N/kg feed)(27 kg feed/day) = 945 g N/day.

Most ammonia produced by fish is initially assimilated by phytoplankton as a nitrogen source for growth. The nitrogen assimilation rate by phytoplankton can be estimated from the rate of carbon fixation in photosynthesis and the average ratio of carbon to nitrogen in algal tissue (6C:1N by mass). Phytoplankton photosynthetic rates in warm, unmixed, nutrient-rich waters range from less than 1 to more than 6 g C/m$^2$ per days. Using 3 g C/m$^2$ per day as an optimistic carbon fixation rate provides an estimated nitrogen assimilation rate of

(3 g C/m$^2$ per day)(1 g N/6 g C) = 0.5 g N/m$^2$ per day.

Therefore, the pond area required to remove ammonia excreted by 1,350 kg of channel catfish is

(945 g N/day) ÷ (0.5 g N/m$^2$ per day) = 1,890 m$^2$.

The pond area needed as living space for 1,350 kg of channel catfish (10 m$^2$) is about 200 times smaller than the pond area needed to remove ammonia produced the fish (1,890 m$^2$).

# PARTITIONED CATFISH PONDS IN ARKANSAS

*Eugene L. Torrans*

Pioneering catfish farmers used ponds of all sizes—from less than 0.5-ha to a giant 65-ha pond built by R.L. Thompson and W.F. Anderson in 1957—but most ponds ranged from 15 to 30 ha. Ponds were so large that the only way to harvest fish was to draw down the water level until fish became concentrated and were captured with a small seine. These early catfish ponds were difficult to manage but inexpensive to build.

In 1972, two Mississippi State University economists analyzed cost-size relationships for catfish ponds and pronounced 8-ha ponds to be the best compromise among construction and maintenance costs and management ease (Foster and Waldrop 1972). These ponds could be harvested by seining without water drawdown. The 8-ha pond became the standard pond size in Mississippi for the next 30 years.

Although the pond size recommended by Foster and Waldrop was less than half the size of most existing catfish ponds in 1972, an 8-ha pond is—by any current measure—a large, difficult-to-manage aquaculture production system. Inefficiencies in feeding, harvesting, and protecting fish from predators are significant limitations, but the most serious problem with large ponds is the difficulty in maintaining adequate dissolved oxygen concentration.

## Polyculture

Catfish ponds are ideal ecosystems for polyculture. Catfish eat manufactured feed, which enriches the water and stimulates high rates of primary and secondary productivity. This natural production is largely unused by catfish, so adding plankton- or detritus-feeding fish to the pond improves ecological efficiency by making better use of feed nutrients that would otherwise be wasted in catfish monoculture. Fish production based on unutilized natural foods could increase farm income by generating an additional crop at little extra expense.

Arkansas fish farmers were among the first in the United States to appreciate the potential of pond polyculture. Initial foodfish aquaculture development in Arkansas centered on growing bigmouth buffalo *Ictiobus cyprinellus*, a regionally popular food fish. The market demand for buffalofish was not great, however, and Arkansas fish farmers began incorporating channel catfish in polyculture with buffalofish.

During the mid-1970s, interest in polyculture was further stimulated by a wave of Peace Corps aquaculture volunteers returning to the United States from assignments in Africa and Asia. These young aquaculturists had experience spawning and raising tilapias, Chinese carps and Indian major and minor carps, and appreciated the ecological efficiencies and practical benefits of polyculture.

In practice, application of polyculture in commercial catfish ponds was difficult. Although overall fish yields could be doubled or tripled by adding plankton-eating fish to catfish ponds, large-scale marketing of secondary species was problematic. Most candidate polyculture species contain intramuscular bones—a significant marketing impediment in the United States, where the preferred fish product is boneless fillets. From the catfish farmer's perspective, the greatest disadvantage of polyculture was the additional time and labor required to harvest and sort fish by species for marketing.

Until recently, almost all channel catfish were grown in a multiple-batch cropping system, with ponds containing fish that ranged from 20-g fingerlings to 1-kg foodfish (Tucker et al. 2004). Ponds were harvested several times a year to remove foodfish (~0.7 to 0.9 kg) and fingerlings were periodically added to replace harvested foodfish. Ponds remained in production for several years without draining. Most polyculture species require at least 2 years to reach market size, meaning they would have to be sorted by hand and returned to the pond several times a year until market size was achieved. This was clearly impractical on large commercial farms. Farmers who were successful at raising and selling other species separated them with some difficulty from their catfish and delivered them as live fish to ethnic markets in larger cities.

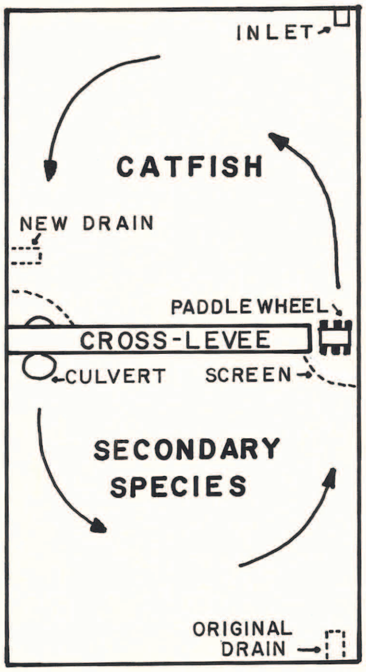
## Partitioned Ponds as an Alternative Production System

The potential economic advantages of raising more than one species of fish in the same water body stimulated interest in developing ways to modify ponds to make them easier to manage and to accommodate polyculture. In 1982, I conceived a production system that appeared to solve the problem of sorting and separating species in polyculture. I proposed dividing an existing pond with an earthen embankment (Fig. 1). The embankment would have two open channels or culverts fitted with screens to prevent fish from moving from one side to the other. Catfish would be stocked in one half and one or more secondary species stocked in the other half. Electric paddlewheel aerators would be placed in the open channels for aeration and to circulate water between the two sections. Hand-sorting of species would be eliminated because catfish and the secondary species would be physically separated and could be grown under independent production periods.

The main purpose of the system was to facilitate polyculture, so I called it the "Polyculture Production System" or PPS. The concept was published in Arkansas Aquafarming (Torrans 1984) and I received an Innovation Award from the Catfish Farmers of America for the idea. Although my initial concept indicated a 50:50 split of the two sides with catfish stocked at twice the normal rate, I speculated that, "Given a rapid enough water exchange, catfish could, in theory, be confined at raceway densities."

I proposed this concept to Kelly and Harold Farmer, of Edgar Farmer and Sons, in Dumas, Arkansas, in 1982. They divided a 12-ha pond into approximately 3-ha and 8-ha sections. Water was circulated at about 7.5 $m^3$/min between sections through a large culvert using a screw-type pump. Channel catfish were stocked in the 3-ha section and bighead carp *Aristichthys nobilis* and bighead × silver carp *Hypophthalmicthys molitrix* hybrids in the larger section. The system was used for two years until accumulation of large amounts of sediment in the catfish section made harvest difficult and forced the Farmers to consider alternative designs.

Their solution to problems related to sediment accumulation was to dramatically intensify production by confining catfish in concrete raceways. Their interest in raceway culture of catfish was stimulated by the success of Leo Ray, owner of Fish Breeders of Idaho, near Hagerman, Idaho. Leo Ray was growing channel



TOP, FIGURE 1. *The original drawing of the Partitioned Polyculture System as it appeared in the 1984 issue of Aquafarming, the University of Arkansas Cooperative Extension Service newsletter.*

BOTTOM, FIGURE 2. *Raceways at Edgar Farmer and Sons fish farm, in Dumas, Arkansas, in 1986. Water from an 8-ha "header" pond flowed through the raceways and discharged into a series of two linked ponds. Water was then lifted 3 m using large pumps into a series of ponds that eventually flowed by gravity back into the "header" pond.*

catfish, blue catfish *Ictalurus furcatus*, and tilapia (*Oreochromis niloticus* and *O. mossambicus*) in a raceway system supplied with geothermal water from artesian wells (Losordo *et al*. 2004). Fish Breeders of Idaho continues to produce warmwater fish in this facility.

The Farmers built their raceway system in 1986 as a means of better controlling production (Fig. 2). Kelly Farmer summarized his motivation by saying, "A pond has control of you. I wanted to manage growout better" (Mattei 1984). The system consisted of 40 raceways (8 parallel raceway systems, each with 5 raceways in a series) provided with gravity-flow water from an 8-ha "header" pond. Raceways discharged effluent into a large pond and water flowed into a second large pond before being lifted 3 meters into the highest-elevation pond on the farm by high-volume (83 $m^3$/min) pumps powered by two diesel engines. The engines used 42 L/min of fuel, but diesel fuel cost only $0.079/L when the system was built. Water then flowed through three other ponds through culverts before being pumped to the header pond. The seven ponds tied into the raceway system totaled 44 ha. The raceway system produced about 220,000 kg of channel catfish annually. A variety of other species, including bighead carp, silver carp, and paddlefish *Polyodon spathula*, were grown in the system's large reservoir ponds. Several ponds were also stocked with channel catfish and produced an additional 122 t annually, for a total annual net catfish production of approximately 7.7 t/ha for the entire system.

In contrast to Leo Ray's geothermal water supply, water temperatures in the Arkansas pond-raceway systems varied greatly throughout the year, from more than 30°C in summer to less than 10°C in winter. Channel catfish grew little, if at all, for several months during winter and cold temperatures predisposed fish to infectious diseases. As such, catfish could not be overwintered in raceways without large losses and could not be stocked in raceways for growout before mid-May. However, the concept showed promise because fish grew quickly—100-g fish stocked in mid-May reached market-size in one growing season.

Dick Pratt and his son Jon built a similar system of raceways and linked ponds in 1988 at Beouf River Fish Farm, Eudora, Arkansas. The Pratt's system consisted of 108 raceways (36 parallel series of 3 raceways in a series) linked to seven ponds totaling 55 ha. Water flowed through the system at 115 $m^3$/min. As in the Farmers' system, channel catfish were grown using manufactured feed in raceways and blue tilapia *O. aureus*, paddlefish, silver carp, or bighead carp were grown in ponds receiving catfish wastes and with abundant natural foods. The Pratt system operated as described only for a few years, suffering some of the same problems encountered by Kelly and Edgar Farmer. Annual net catfish production from raceways was about 320 t, which, when divided by the pond area used in the system, is roughly the same achieved in well-managed traditional ponds at that time (5-6 t/ha).

Although Arkansas farmers were pioneers in partitioned pond aquaculture, neither of the two linked pond-raceway systems remains in operation. Frequent disease outbreaks and growing-season limitations related to lack of temperature control contributed to poor profitability. But the primary economic limitation was caused by the flat topography of the Mississippi River floodplain where those farms were located. Achieving gravity flow through the system of linked ponds and raceways required large volumes of water to be pumped against considerable hydraulic head (~3 m). The concept made sense in an era of low energy costs, but when faced with rapidly increasing fuel costs, the systems were abandoned. The relatively high hydraulic head was a common feature of those early systems. This limitation can be contrasted with Leo Ray's hillside raceways supplied with geothermal artesian water (no head considerations) and the partitioned aquaculture system and its derivative, the split-pond, where water is cycled through the system against very low hydraulic head.

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LEFT, FIGURE 3. *The first four, 100-m$^2$ prototype PAS units installed at in 1989 at Clemson University. The slow-rotating paddlewheel circulated water through the fish-holding raceways on the right and the algal basin on the left.* RIGHT, FIGURE 4. *Six, 0.13-ha PAS units installed 1994 at Clemson University.*

## THE PARTITIONED AQUACULTURE SYSTEM

*David E. Brune*

My involvement with the partitioned pond concept consisted of experiences and interactions with a number of engineers, aquaculturists and producers over 30 years. As an assistant professor of Aquacultural Engineering, beginning in 1978 at the University of California, Davis, I became aware of William Oswald's work at Berkeley with a "high-rate algal pond" for municipal wastewater treatment. His work stimulated my thinking about using photosynthetic systems to treat aquaculture wastewater.

In 1980 Benard Colvin visited Davis, where he presented a seminar on his experiences with the Puerto Peñasco (Mexico) shrimp culture project. The culture system at Puerto Peñasco consisted of small raceways for growing penaeid shrimp at annual yields equivalent to 10 to 20 t/ha. At the time, typical fish and shellfish aquaculture annual yields from ponds were roughly 2 to 4 t/ha. The increased production potential was made possible by pumping clean seawater from shallow saline wells into raceways at rates needed to maintain good water quality. Water exiting the raceways was discharged to sandy lagoons, ultimately seeping into the Gulf of California. Obviously, such discharge would not be a sustainable practice on a larger scale. At this point I first got the notion to combine shrimp or fish raceway culture with Oswald's high-rate pond for water treatment and reuse.

By 1982 I had moved to Pennsylvania State University, where I worked on a variety of wastewater-treatment system designs. I was interested in exploring fish culture integrated with some kind of zero-discharge water treatment. Working with students in the Penn State Agricultural Engineering and the Environmental Resource Management departments, I developed a new design for a rotating biological contactor that we installed in a greenhouse-enclosed trout raceway located at the Northeast Fisheries Center in Lamar, Pennsylvania. We successfully demonstrated zero-discharge trout culture using this bacterial technique, but it was obvious that capital and operating costs of these systems could not compete with conventional flow-through raceway aquaculture.

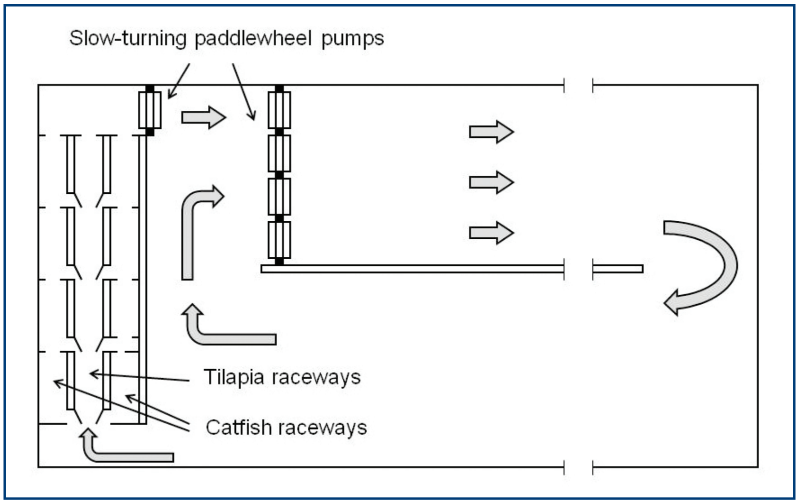
In 1987, I relocated to Clemson University in South Carolina and installed the first operating system fully utilizing algal growth as the basis of aquaculture waste treatment. I called this approach the "Partitioned Aquaculture System," or PAS, because it consisted of separating, or partitioning, raceway fish culture (requiring only 5 percent of water surface area) from the algal-driven water-treatment process. Initial work was targeted at reducing an environmental impact of aquaculture by reducing or eliminating discharge of pond effluent to public waters (Brune *et al*. 1999).

### The PAS Concept

Optimizing a photosynthetically supported fish-culture system required a radical departure from traditional pond design. Because fish need only a small portion of the pond area to live and grow, the system could use raceways to confine animals so they would be easy to feed, harvest and protect from predators. Also, by confining fish at high density, they became the dominate consumers of dissolved oxygen in the raceway, making localized aeration in the raceway more cost-effective than in traditional ponds where the standing crop of fish often represents less than 25 percent of the total oxygen demand. Raceways were coupled to a high-rate algal pond, optimized for algal productivity (Brune *et al*. 2003, 2004).

Maintaining high algal productivity rates, while simultaneously stabilizing algal density and controlling algal species composition, are the keys to greater aquaculture production in the PAS compared to traditional ponds. Pond aquaculture production is ultimately limited by the rate at which ammonia and carbon dioxide—two potentially toxic byproducts of aquatic animal metabolism—are removed from the system. In outdoor systems, phytoplankton remove ammonia and carbon dioxide from water to support algal growth. The waste-treatment capacity of ponds (and therefore the upper limits on fish or shrimp production potential) can be increased by improving conditions for algal growth because carbon dioxide and ammonia assimilation rates are proportional to phytoplankton productivity.

Net primary productivity depends on water temperature,



LEFT, FIGURE 5. *Diagram of the 0.8-ha PAS unit at Clemson University.*
RIGHT, FIGURE 6. *The 0.8-ha PAS unit installed in 2000 at Clemson University.*

sunlight intensity and duration, transmission of underwater light, nutrient availability and average algal cell age. Water temperature and sunlight depend on geographic location, climate, and season—factors that cannot be controlled by the culturist except through site selection. Nutrient availability seldom limits algal productivity in intensive pond aquaculture because large amounts of waste nutrients are generated as a byproduct of feeding. Underwater light conditions and cell loss can, however, be manipulated in the PAS to increase phytoplankton productivity.

The PAS algal basin is shallow (~0.5 m) so that phytoplankton cannot sink below the well-lit photic zone. A slow rate of mixing throughout the algal basin allows algal cells to avoid light limitation of growth, a common feature of static, hypereutrophic fish ponds. Mixing also enhances nutrient dispersion throughout the basin, thereby insuring that the pond volume can be fully utilized.

Although algal growth generates oxygen as a byproduct of photosynthesis, subsequent aerobic decomposition of algal biomass consumes an approximately equivalent amount of oxygen. Aerobic decomposition also releases the same amount of carbon dioxide and ammonia initially assimilated by algae during growth. To provide net oxygen input and net nitrogen and carbon removal, algal biomass must be either removed or decomposed anaerobically. Algal biomass can be removed directly or indirectly by incorporating it into other life forms that are eventually harvested from the pond. Biomass can be decomposed anaerobically in pond sediments or isolated tanks or reactors.

Controlled removal rates can increase algal productivity by decreasing average algal cell age, insuring a fast-growing algal culture that rapidly assimilates nutrients. Algal cell age can be manipulated by providing some method to continually crop or harvest algal biomass from the pond. Controlled algal harvest also prevents excessive algal abundance, thereby decreasing water column respiration and increasing light availability.

Phytoplankton communities in the PAS are continually "cropped" using co-culture of filter-feeding fish such as tilapia (Turker *et al*. 2003a), or by using physical processes such as coagulation and precipitation of algal biomass. The primary objective of growing tilapia in the Arkansas ponds described earlier was to produce a secondary fish crop on otherwise unused food base in catfish ponds. In contrast, the primary objective of growing tilapia in the PAS was to provide a grazer to harvest phytoplankton and zooplankton. Tilapia must be confined in raceways or net pens, isolating them from other feed sources such as uneaten feed, fecal waste, or pond sediments; otherwise, plankton-grazing efficiency was reduced. We referred to this technique as "co-culture" to distinguish the practice and intended effect from polyculture. Field trials demonstrated that tilapia co-culture could be used to maintain algal standing crops equivalent to a water transparency of 12 to 15 cm while ensuring high rates of algal productivity and substantially reducing the occurrence of undesirable cyanobacteria (Turker *et al*. 2003b).

The combined use of shallow basins, pond-wide mixing, and continuous cropping of phytoplankton and zooplankton biomass provided a 3- to 4-fold increase in phytoplankton production compared to traditional ponds, allowing a proportional increase in the upper limits of fish carrying capacity and production.

Continuous water flow throughout the PAS is critical. Water is directed through the culture raceways to maintain good water quality and ensure optimal fish growth. Uniform flow in the algal basin assures well-mixed conditions, resulting in more predictable and consistent phytoplankton productivity and community structure. To insure uniform continuous water movement, a device was needed that could move large water volumes at low energy input with minimal capital investment and low maintenance cost. Slowly rotating (1-3 rpm) paddlewheels moving very large water volumes at hydraulic heads of only 2-5 cm were found to be best suited for this application (Fig. 5).

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## The Clemson PAS

With help from faculty, students, and staff at Clemson, including John Collier, Tom Schwedler and Arnie Eversole, we built four, 100-m$^2$ PAS prototypes (Fig. 3). During the first years of operation we focused only on growing algae in the system, simulating fish metabolic nitrogen production by adding ammonia fertilizer. During this time, we determined optimum operating water depth, paddlewheel speed, and potential fish carrying capacity (Drapcho and Brune 2000).

By the early 1990s, Tom Schwedler, the fish culturist at Clemson, had become convinced of the fish production potential of the PAS. At that point, we designed, installed, and began operation of the first fully operational PAS units for channel catfish production. These prototypes consisted of six, 0.13-ha units (Fig. 4). We later built a 0.8-ha unit using a slightly different design (Figs. 5, 6 and 7).

Over 7 years, we systematically increased annual production to 20 t/ha of channel catfish with co-production of 5 t/ha of Nile tilapia. The costs of producing channel catfish in the PAS were comparable to those for conventional pond culture (Goode *et al*. 2002). In 2000, we installed a greenhouse-covered version of the PAS at Clemson dedicated to penaeid shrimp aquaculture and produced 12 to 35 t/ha of Pacific white shrimp *Litopeneaus vannamei* (Fig. 8; Brune et al. 2012). From 2005 through 2009, we also produced 5.2 t/ha of large (110 g) catfish fingerlings in single summer seasons in net-pens contained in the 0.8-ha PAS unit (Wells 2009). Clemson University was granted a United States patent for the PAS (Brune *et al*. 2001).

## Recent PAS Developments

During my years at Clemson, I also worked with Kent Bioenergy, in southern California, looking at ways to take advantage of and add value to the high rate of algal biomass production in the PAS. We examined the possibility of converting algal biomass into a variety of higher-value products, from biofuels to pharmaceuticals (Brune and Beecher 2009; Brune *et al*. 2012).

For the last 3 years, I have been operating a zero-discharge marine shrimp culture system at the University of Missouri (Fig. 9). The system is based on the original PAS design, using both tilapia and brine shrimp co-culture to harvest and convert excess algal and bacterial biomass into higher-value co-products, including fish food, fishmeal replacement, biofuels and bioenergy products. This approach could potentially reduce the fossil-fuel requirement of fed fish and shrimp production. These systems can produce marine shrimp at costs competitive with Asian semi-intensive shrimp production, with no water discharge, while replacing 30 to 100 percent of the feed required in conventional fish or shrimp culture with

TOP, FIGURE 7. *Aerial photograph of Clemson University partitioned aquaculture systems. Six, 0.13-ha units are located at the bottom of the photo and a single 0.8-ha unit is at the top. The design of the larger unit is shown in Figures 5 and 6.* MIDDLE, FIGURE 8. *Greenhouse-covered PAS culture of marine shrimp at Clemson University, 2001-2009.* BOTTOM, FIGURE 9. *Greenhouse-covered 200-m$^2$ PAS units at University of Missouri (2010-2014) for co-culture of marine shrimp, brine shrimp and tilapia.*

co-products (e.g. brine shrimp) grown in the system.

During the 1990s and early 2000s, we interacted with fish farmers throughout the world who were interested in the PAS approach. Interest usually focused on the fish-management advantages of high-density raceway culture compared to traditional pond culture. Of course the potential for eliminating water discharge while maintaining high yields was also attractive. A few individuals in Georgia and California installed commercial-scale PAS units, although most catfish farmers in the southern United States were reluctant to re-capitalize their existing fish farming operation using an unfamiliar technology.

## Split-Ponds

*Craig S. Tucker*

Tom Schwedler and I worked together in the Mississippi State University catfish research program at Stoneville before he moved to Clemson University in 1985. Through Tom, I met David Brune and John Collier, and I was aware of their work on the PAS from its earliest stages in the late 1980s. From the outset, I was impressed by the sound ecological and engineering theory of the PAS but, based on my experiences with commercial catfish farming in Mississippi, I had concerns about large-scale implementation of the technology on existing farms.

Mississippi catfish farmers already had considerable investment in infrastructure (earthen ponds, wells, aerators, and so on) and I doubted that many farmers would consider making wholesale changes to their production system. David drafted a design based on a simplified PAS configuration he had originally proposed in 1999 (Brune *et al*. 1999). The new design could be built inside existing ponds, using large, slow-turning paddlewheels to circulate water throughout the pond and a smaller paddlewheel to pump a sidestream flow of water through concrete raceways. This configuration functionally resembled in-pond raceways constructed on some catfish farms in Alabama in the late 2000s (Brown *et al*. 2011).

Although the new PAS design used existing ponds as the starting point for construction, I was also concerned about the willingness of Mississippi farmers to accept two other features of the PAS: the very high fish biomass loadings in raceways and the apparent requirement for continuous cropping of algal biomass to sustain high algal productivity. Fish farms in Mississippi experience frequent electrical power outages, and dissolved oxygen concentrations could decline to lethal levels within minutes after loss of power for aeration and water flow at the high fish biomass loadings used in PAS raceways. Although the solution is simple—installation of emergency electrical generators—I doubted whether many farmers would make that additional investment.

Also, the extra effort involved in algal management with tilapia would not be acceptable to most Mississippi farmers. Tilapia must be overwintered in heated facilities and, although a few farmers might be able to hand-process and locally market some tilapia, infrastructure was lacking to process large quantities of tilapia if catfish-tilapia co-culture was widely adopted.

These concerns led me to build a simplified version of the PAS in 2001 that would make use of existing catfish ponds, confine fish at lower densities than in PAS raceways but greater than those in traditional ponds, and not incorporate tilapia or other algal-cropping methods. The new system physically resembled the Polyculture Production System (PPS) described by Les Torrans, but it functioned more like a PAS.

TOP, FIGURE 10. *A slow-rotating paddlewheel used to pump water between basins in a 2-ha split-pond. The paddlewheel is 3.7-m long and 1.8-m in diameter and turns at 2-3 rpm with paddles immersed to a depth of 1.2 m. The paddlewheel pumps approximately 50 m$^3$/min and is powered by a 1.1-kW electric gearmotor. Screens in the open channel to the right prevent fish from escaping the fish-holding area.* BOTTOM, FIGURE 11. *The 2-ha split-pond at Stoneville, Mississippi. The 0.4-ha fish-holding basin is in the foreground and the 1.6-ha algal basin is in the distance. The two basins are separated by an earthen levee that is breached in two places. The slow-rotating paddlewheel on the far right pumps Water is pumped out of the fish-holding basin by the slow-rotating paddlewheel on the far right and returns through the channel on the far left. Two, 7.5-kW paddlewheel aerators provide supplemental dissolved oxygen at night.*

The initial, pilot-scale system was constructed at Stoneville, Mississippi, by building an earthen levee across an existing 0.4-ha pond to divide the pond into two unequal sections (hence the name 'split-pond'). The pond had a proportionately smaller algal basin (about 80-85 percent of the total pond area) and a larger fish-holding basin than the PAS. The levee dividing the two basins was breached with two open channels and water was circulated between the two sections using a large, slow-rotating paddlewheel (Fig. 10, Brown and Tucker 2013). Barriers or screens in each channel prevented fish escape. Two larger split-ponds based on this design were built at Stoneville: a 2-ha system in 2008 (Fig. 11) and a 3.2-ha system in 2012. Three additional 3.2-ha split-ponds are currently under construction at Stoneville.

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Unlike the Clemson PAS, water does not circulate continuously in the split-pond. During daylight and early evening, oxygenated water from the algal basin is pumped through the fish-holding basin and return flow to the algal basin removes fish metabolic wastes. At night, when dissolved oxygen concentrations decrease in the algal basin, circulation between the two basins ceases and oxygen is provided by mechanical aerators in the fish-holding area. Similar to the PAS, no attempt is made to manage dissolved oxygen in the algal basin and dissolved oxygen concentrations usually fall to 0 mg/L each night during summer months. Slow-rotating paddlewheel and aerator operation are controlled by oxygen sensors located in both sections of the split-pond.

The two critical design parameters for split-ponds are 1) amount of aeration required in the fish-holding area and 2) water flow rate between the two basins (Brune *et al*. 2012). Split-pond aerator requirements are estimated by determining the aerator oxygen transfer needed to offset fish respiratory demands at the maximum projected fish biomass loading. Other sources and sinks of oxygen, such as air-water gas exchange and plankton and benthic metabolism are assumed to be insignificant at the high fish biomass loading rates in the small fish-holding area. Pumping rate estimates are based on the assumption that fish oxygen requirements are primarily met during daylight and early evening by oxygen in water pumped into the fish-holding area from the algal basin. An oxygen mass balance is used to calculate flow rate (volume/time) by dividing fish respiratory rate (oxygen mass/time) by the minimum desired dissolved oxygen concentration (oxygen mass/volume). Required water flow varies with time as fish grow and water temperature changes.

The original goal of the split-pond was to take advantage of the fish-confinement benefits of the PAS, such as facilitation of feeding, inventory, harvest, health management and protection from predators. Because the system appeared to lack processes needed for enhanced algal productivity (shallow basin, turbulence throughout the system, and algal cropping), I did not expect maximum allowable feed input to be much greater than for catfish traditional ponds. However, within three years of use, it was evident that some set of ecosystem processes were operating that allowed higher feed inputs than expected. Net annual production (based on the combined water surface of algal basin and fish-holding areas) in experimental split-ponds at Stoneville has ranged from 15 to more than 20 t/ha, which is marginally less than production from the PAS but two or three times greater than from most traditional catfish ponds.

The potential for better fish production stimulated rapid commercial adoption, and more than 600 ha of split-ponds have been built by farmers in Mississippi, Arkansas, Alabama, and California. As farmers adopted the split-pond concept, pumps other than slow-rotating paddlewheels (such as high-speed screw pumps, axial-flow pumps, and others) have been used to reduce initial investment costs and facilitate system installation. Catfish production in commercial split-ponds is less than that achieved in experimental ponds, but is nevertheless impressive, with net annual production of 12 to more than 16 t/ha. Two regional studies are currently underway to examine production and economics of different split-pond designs.

## Partitioned Ponds and Drivers of Innovation

Partitioned ponds are a significant development in pond aquaculture, with the potential to increase aquaculture production several-fold over that achieved in traditional ponds and little or no discharge of effluent or wastes into public waters. One variant, split-ponds, has been rapidly adopted by farmers in the southeastern United States for catfish aquaculture. Time will tell whether partitioned ponds find a place in the aquaculture mainstream, although we believe the concept offers a number of advantages over large earthen ponds for commercial production of some species.

Use of filter-feeding organisms to harvest algal biomass in the PAS can produce co-products that provide significant secondary sources of income for fish farmers. Current fishmeal, fossil fuel, and electricity costs seem to favor simpler partitioned pond designs—such as the split-pond—that do not involve controlled algal harvest and recovery. However, as fishmeal and fossil energy prices increase, recovery and utilization of otherwise wasted feed nitrogen is likely to grow in importance. Fish farmers may soon find themselves forced by economics to install and operate “designed ecosystems” in which photosynthetic algal co-production will become essential to profitable fish and shrimp production.

The developmental history of partitioned ponds is an interesting example of innovation in science. Independent, contemporaneous development of partitioned ponds is an example of “multiple discovery,” where similar innovations are made more or less simultaneously by different people. The common perception is that science advances mainly through unique contributions made by individuals or groups with a singular combination of training, personality, and insight. In actuality, multiple independent discoveries are thought to be the common pattern of innovation (Merton 1961). Although innovation of partitioned ponds does not rise to the level of simultaneous development of calculus by Leibniz and Newton, it does represent a significant development in pond aquaculture, and has an interesting twist in that the two independent evolutionary lines of partitioned ponds were stimulated by different goals.

The common occurrence of simultaneous discovery has been the subject of considerable study and speculation to explain why “multiples” are so prevalent in science (Simonton 1979, 1986, Garfield 1980). Frequent occurrence of multiple discoveries is attributed either to chance or to the concept of “zeitgeist.” Zeitgeist means “spirit of the times” and the zeitgeist theory of innovation is based on the idea that simultaneous discoveries arise from an existing set of cultural circumstances that make discovery inevitable. These circumstances (the prevailing zeitgeist) may be an acute need for the technology, the development of a body of knowledge to the point where the next discovery is unavoidable, or—usually—both.

So what was the aquaculture “zeitgeist” in the 1980s that led to independent development of partitioned pond concepts? It was a decade of amazing growth of aquaculture throughout the world. In the United States, channel catfish production nearly doubled, increasing from 90,000 t in 1980 to almost 175,000 t in 1990. As the demand for aquaculture products increased, aquaculturists sought ways to intensify production and increase economic returns. Fish feeds were developed that satisfied all nutritional requirements. Supplemental aeration, which was relatively rare prior to the mid-1970s, became commonplace by the early 1980s. Feeding and aeration allowed large increases in stocking densities, feeding rates, and productivity but revealed other limitations and inefficiencies of large, static ponds as fish culture systems. The 1980s were also a time of increasing awareness of the environmental impacts of aquaculture and the need to develop more sustainable cultural practices. In short, the time was ripe for innovation. Meanwhile, as interest in aquaculture grew, new opportunities attracted students and scientists with diverse backgrounds and expertise, bringing unique perspectives on problems and potential solutions.

The partitioned pond concept evolved over 30 years, driven by investigators with differing goals and objectives. Early partitioned ponds in Arkansas and newer split-ponds were developed to facilitate fish management. In contrast, PAS development was initially driven by the need to reduce aquaculture waste discharge. The common element in these divergent goals was the desire to gain control over the production system. And the common solution to controlling the ecosystem was to divide the pond into smaller sections so that various functions (fish confinement, culture of secondary species, waste treatment, and so on) were optimized or more easily managed. As such, partitioned ponds were developed by different people with different goals and perspectives, but the shared driver of innovation—the desire to achieve better control of the ecosystem—resulted in new systems that inevitably shared common functions and design features.

## *Notes*

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