DESIGNING EFFICIENT INDOOR SHRIMP PRODUCTION SYSTEMS: A BIOECONOMIC APPROACH

Peter M. Van Wyk
Shrimp Research Program Manager, Harbor Branch Oceanographic Institution
5600 Highway U.S. 1 North, Fort Pierce, FL 34946 USA

ABSTRACT

In recent years researchers have been attempting to develop shrimp production technologies that are better suited to the conditions in the United States than the traditional semi-intensive shrimp production systems. Much of this effort has been devoted to the development of indoor recirculating systems for *Litopenaeus vannamei*. These systems are attractive to U.S. shrimp producers because they allow the shrimp to be cultured year round, and minimize environmental impacts. In addition, these systems provide a degree of biosecurity that is impossible in open ponds. Despite these apparent benefits, no one has yet built a commercially successful recirculating shrimp production facility. The capital requirements for building indoor recirculating production systems are high relative to their annual productivity. In addition, the energy costs and labor requirements are much higher than for the typical pond production operation. The challenge for shrimp recirculating system designers is how to increase system productivity while reducing capital, energy and labor costs. One approach that may be used to guide system designers and project planners in designing more efficient production systems is to analyze how the cost per unit of production can be minimized for each type of production input. While the concept of minimizing production costs while increasing production may not seem very profound, systematic analysis of how this may be accomplished for each input yields some interesting insights.

Management cost per unit of production is the total value of salaries paid divided by the number of pounds of shrimp produced and sold. Management costs per unit of production are minimized by maximizing the total amount of production per dollar of salary paid. Clearly, it is inefficient to produce on a very small scale because per unit management costs will be excessive. The efficient business will increase in size until the manager cannot manage more production units profitably. Labor costs per unit of production are minimized by minimizing the amount of labor required to produce a pound of shrimp. There are several strategies that may be used to accomplish this goal, including automation of routine maintenance tasks and water quality monitoring. With many labor saving devices there is a tradeoff between labor cost and capital cost. There is one strategy for reducing labor costs per unit of production, however, that generally reduces capital costs, as well as labor costs. This strategy is to increase the size of the rearing units. Systems should be designed as large as the structure of the building will practically permit.

Capital cost per unit of production is minimized by maximizing annual production per dollar of capital investment. One strategy that has often been employed has been to increase the stocking density to extremely high levels, hoping that increased production will more than offset any increases in capital costs. However it is not always clear whether additional capital spent to extend carrying capacities will result in lower production costs. For this to be the case, each additional dollar of capital investment must result in greater than one dollar of additional revenues. An alternative strategy for increasing system productivity is to utilize a multi-phase production system. Annual productivity of multiphase production systems is higher than in single-phase production systems because they minimize the amount of time the shrimp are held at a low density relative to the system carrying capacity. An advantage to this production strategy is that it allows annual production to be significantly increased with minimal impact on the capital investment or requirements or on the total operating expenses.

There are many other promising strategies for improving the efficiency of indoor shrimp recirculating systems. Low-head designs will reduce energy costs. Artificial substrates can be used to improve survival and growth rates. Greenwater or heterotrophic production systems may improve growth and feed conversion rates. Striving to maximize the efficiency of a system in every aspect of its design will greatly improve the likelihood that shrimp will someday be profitably produced in indoor recirculating production systems.

INTRODUCTION

In recent years researchers have been attempting to develop shrimp production technologies that are better suited to the conditions in the United States than the traditional semi-

Craig L. Browdy and Darryl E. Jory, editors. The New Wave, Proceedings of the Special Session on Sustainable Shrimp Culture, Aquaculture 2001. The World Aquaculture Society, Baton Rouge, LA USA.

intensive shrimp production systems. Much of this effort has been devoted to the development of indoor recirculating systems for *L. vannamei* (Davis and Arnold 1998, Van Wyk 1999). These systems are attractive to U.S. shrimp producers because they allow the shrimp to be cultured year round. Year round production smoothes out the annual cash flow and facilitates a direct marketing strategy (Van Wyk 2000a). Recirculating systems are attractive from an environmental standpoint because the volume of effluent is reduced, facilitating waste recovery in retention ponds. The ability of *L. vannamei* to thrive and grow in hard, freshwater conditions makes it feasible to grow this shrimp on non-coastal agricultural land. Recirculating freshwater production systems may someday permit shrimp to be produced close to large non-coastal population centers, facilitating access to large markets for fresh shrimp. Another reason for the recent interest in indoor recirculating systems is the high degree of biosecurity these systems provide (Leung and Moss 1999, Ogle and Lotz 1998).

Despite these apparent benefits, no one has yet built a commercially successful recirculating shrimp production facility. The capital requirements for building indoor recirculating production systems are high relative to their productivity. In addition, the energy costs and labor requirements are much higher than are typical for most pond production operations. The challenge for shrimp recirculating system designers is to increase system productivity while reducing capital, energy and labor costs. In short, more efficient production systems must be developed.

Shrimp recirculating system designers and project planners have many decisions to make about the systems they are planning to build. Key decisions must be made regarding the type of production system that should be used, the number and size of greenhouses that should be built, and the number and size of the production systems that should be enclosed in each greenhouse. The objective should be to choose the production technology and production scale that will minimize the average cost per unit output and maximize profits. An enterprise budgeting approach was used to illustrate how some of these system design choices affect the production cost and profit potential of a recirculating shrimp production facility.

METHODS AND MATERIALS

Enterprise budgets were developed for a variety of different scenarios to illustrate how the choice of production system, the number of greenhouses, the size of the greenhouses, and the number of systems per greenhouse affect the cost of production and profit potential of an indoor shrimp production facility. All enterprise budgets were based on a common set of assumptions regarding key production variables such as stocking density, survival, growth rates, length of the production cycle, size of shrimp harvested, and harvest densities (Table 1).

Table 1. Production assumptions common to all enterprise budgets.

Parameter	Assumed Value
Stocking Density (shrimp/m^2 final growout area)	214
Average Stocking Weight (g)	.002
Survival From PL to Harvest (%)	70
Average Harvest Weight (g)	18
Average Harvest Density (shrimp/m^2)	150
Biomass at Harvest (kg/m^2)	2.70
Length of Production Cycle (days)	150
Feed Conversion Ratio	1.75

System Description

All of the systems analyzed in the budgets are based on a common production technology developed at Harbor Branch Oceanographic Institution (Van Wyk 1999). The shrimp production systems are enclosed in greenhouses covered with a double-wall polyethylene covering. Each greenhouse is provided with a ventilation system consisting of exhaust fans and shuttered windows, and a propane space heater. The shrimp are grown in rectangular culture tanks consisting of a black 30-mil HDPE liner supported by a wooden frame. The average depth of water in the tanks is 0.85 meters. All tanks are set up in a "racetrack" configuration, in which water is circulated around a central baffle. Drain outlets are positioned at opposite ends of the central baffle. The water in the culture tank flows in an elongated oval pattern, circling around the drain outlets at the ends of the tank. The semi-circular flow pattern around the drain outlets concentrates the solid wastes around the drain where they exit the tank. Corner baffles prevent solids from collecting in the corners of the tank. The racetrack configuration provides the efficient space utilization of a rectangular tank and the good mixing and solids removal characteristics of a circular tank. Regenerative blowers supply air to the culture tanks and biofilter. The blowers for the various systems were selected to be able to provide 0.16 CFM of air per kilogram of anticipated shrimp biomass. The systems feature a low-head filtration system consisting of a solids filter tank and an aerated submerged bed biofilter, both filled with plastic Kaldnes biofilter media. Water flows by gravity from the culture tank to the solids filter and then through the biofilter. The water is pumped from the biofilter tank back to the culture tank using a low-head centrifugal pump. The entire volume of each culture system is circulated through the filtration system 10 times per day. The solids filter is backwashed every third day. Three percent of the system volume is discharged during the backwash procedure. This volume is replaced with an equal volume of makeup water. The rate of water exchange averages 1% of the system volume per day. The effluent from the culture tanks is discharged into a retention pond in which solid wastes are settled out and aquatic plants and algae sequester ammonia and phosphorus. Approximately 0.1 ha of earthen retention ponds are required for every four greenhouses. Make-up water is supplied by well-water that must be treated prior to use in a water treatment system consisting of a degassing tower, biofilter, water storage tank and a water distribution pump. Other infrastructure required by all of the facilities modeled in the budgets included a postlarvae quarantine/acclimation system, a feed storage shed, an office, and a 1/2-ton pickup truck. Each of the budgeted shrimp production facilities was assumed to have been built on a 5-acre parcel of property purchased for $7,500/acre.

Choice Of Production System

The choice of whether to use a single-phase or a multiphase production system is an important decision for the project planner because of the impact the production system can have on annual system productivity. In a single-phase production system, post-larval shrimp are stocked into a non-partitioned culture tank and remain in that same area until harvested for market. In a multi-phase production system, postlarvae are stocked into a nursery tank at a relatively high density. When the biomass of the nursery tank approaches the carrying capacity for that tank, the shrimp are transferred to a larger culture tank (or section of the same tank) so that they may continue to grow. In a two-phase production system, the growout takes place in a nursery phase and a final growout phase. The nursery phase may be shorter than the final growout phase, or the total culture period may be equally divided between the nursery and final growout phases. In a three-phase production system, the culture period is divided into three phases, with the shrimp typically spending equal periods of time in the nursery, intermediate, and final growout phases. Multi-phase systems with more than three phases are theoretically possible, but are rarely used for practical reasons. In theory, multi-phase production systems are more productive than single-phase production systems (Parker et al., 1974). This is because the biomass is maintained closer to the carrying capacity for a greater percentage of the production cycle, resulting in a more efficient use of the production area.

A spreadsheet analysis was performed to show how the choice of production system could affect annual productivity (Table 2). Three two-phase production systems and a three-phase production system were compared to a single-phase pro-

Table 2. Comparison of annual production potential of single-phase, two-phase, and three-phase production systems, assuming a fixed amount of total production area.

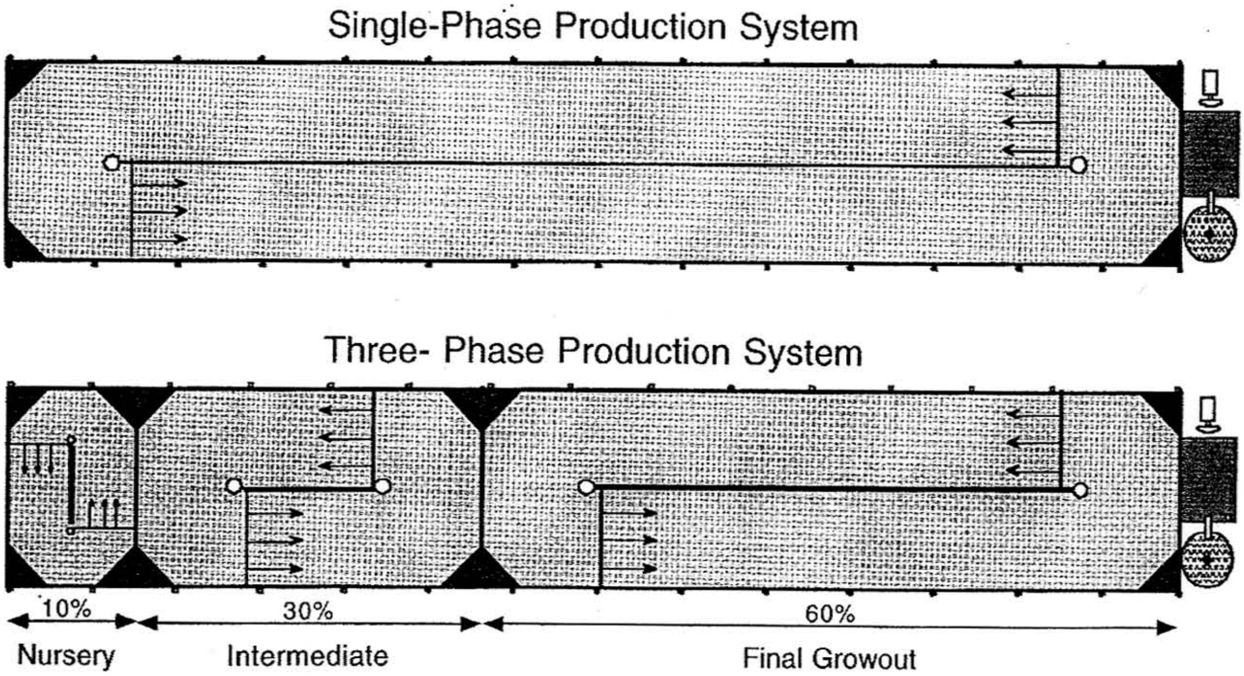
Production Parameter	1-Phase (150 days)	2-Phase (30 /120)	2-Phase (50/100)	2-Phase (75/75)	3-Phase (50-50-50)
Length of nursery phase (days)	—	30	50	75	50
Length of intermediate phase (days)	—	—	—	—	50
Length of final growout phase (days	150	120	100	75	50
Area required for nursery phase (%)	0%	7%	14%	25%	10%
Area required for intermediate phase (%)	0%	0%	0%	0%	30%
Area required for final growout phase (%)	100%	93%	86%	75%	60%
PLs stocked per crop / m^2 final growout area	214	214	214	214	214
Postlarvae stocked per crop / m^2 total area	214	199	184	161	129
Final survival (%)	70%	70%	70%	70%	70%
Shrimp harvested per crop / m^2 final growout	150	150	150	150	150
Shrimp harvested per crop / m^2 of total area	150	140	129	113	90
Final harvest weight (g/shrimp)	18	18	18	18	18
Kg harvested per crop / m^2 of total area	2.7	2.5	2.3	2.0	1.6
Number of crops per year	2.4	3.0	3.7	4.9	7.3
Kg harvested per year / m^2 of total area	6.6	7.6	8.5	9.9	11.8
Annual productivity relative to 1-phase system	100%	116%	129%	150%	180%

duction system. The total length of the production cycle was assumed to be 150 days for each scenario. The two-phase systems differed in the relative duration of the nursery and growout phases. The nursery phases for the three, two-phase systems were assumed to last 30 days, 50 days, and 75 days, respectively. Each phase in the three-phase system was assumed to last 50 days. The stocking density for each system was based on the area of the final growout phase, and was assumed to be 214 postlarvae/m^2 of final growout area. The analysis assumed that growth rates and survival rates were not affected by the choice of production system. The average weight of shrimp harvested was assumed to be 18 grams, and the overall survival was assumed to be 70%. Standard growth and survival curves were used for all scenarios to predict the average weight and number of shrimp surviving at the end of each phase. The analysis assumed that the choice of production system did not influence the carrying capacity of the system. The carrying capacity for all phases of each production system was assumed to be 2.7 kg/m^2 of shrimp biomass. The percentage of the total production area devoted to each phase of the production cycle was calculated so that the shrimp biomass would reach 2.7 kg/m^2 at the end of the time allotted for that phase. With growth, survival, and carrying capacity all held constant, differences in annual productivity between systems were functions of the type of production system used.

Enterprise budgets were used to analyze how the choice of production system can affect production costs and profitability. Enterprise budgets were developed for two enterprises that were identical except for the type of production system used. One enterprise budget was based on a facility that employed a single-phase production system, while the other was based on a facility that employed a three-phase production system. In each case, the facility consisted of sixteen 30'x152' greenhouses, with each greenhouse enclosing two production systems. The single-phase systems consisted of a non-partitioned 189-m^2 culture tank and filtration system, as described above (Figure 1). The three-phase systems were identical to the single-phase systems, except that the culture tank was partitioned into a nursery section, occupying 10% of the culture area, an intermediate section, occupying 30% of the culture area, and a final growout area, occupying 60% of the total area (Figure 1). Drainage structures at the base of the partitions allowed shrimp to be transferred from one section into another by draining the volume one section into the next. Eliminating handling of the shrimp during transfers minimizes transfer-related mortality.

The baseline production assumptions for both systems are summarized in Table 2. The only operating input affected by the choice of production system was labor. For this analysis, it was assumed that the labor requirement for a single-phase sys-

Figure 1. Schematic diagram of a single-phase production system and a three-phase production system.



tem was 40 man-hours/crop, while the requirement for three-phase system was 50 man-hours/crop. The only difference in capital cost between the two types of systems was the additional cost associated with the partitioning of the culture tanks (about $300 per system).

Facility Size

The relationship between facility size and profit potential was evaluated by comparing enterprise budgets for facilities consisting of one, two, four, eight, and sixteen 30-ft x 152-ft greenhouses (Table 3). The capital requirements for each facility are summarized in Table 4. As the number of greenhouses was increased, certain economies of scale were realized.

Retention pond construction costs per unit area declined as the size of the retention pond increased. A 1,500-m^2 retention pond was constructed for the projects with four or fewer greenhouses. A 3,000-m^2 pond was constructed for the eight-greenhouse facility, and a 4,500-m^2 pond was constructed for the sixteen-greenhouse facility. The construction cost was $3,000 for the 1,500-m^2 pond, $4,000 for the 3000-m^2 pond, and $4,500 for the 4,500-m^2 pond. Construction costs for ponds are proportional to the volume of earth moved, which in turn, is a function of the perimeter of the pond (Allen, et al., 1984). As a general rule, the cost per unit of pond area is inversely related to the area of the pond.

The cost of the water treatment system also declined as the capacity of the system was increased. The capacity of the water treatment system for the one- and two-greenhouse facilities was 8,000 liters/day and cost $4,000. The capacity of the four-greenhouse facility's water treatment system was 16,000 liters/day, and cost $6,000. The capacity of the 8-greenhouse facility was 32,000 liters/day, and cost $8,000. The 16-greenhouse facility was equipped with two 32,000 liters/day treatment systems.

The postlarvae acclimation system for the four-greenhouse and smaller enterprises was assumed to cost $3,000, while the acclimation system for the larger enterprises was assumed to cost $5,000. An air-conditioned feed storage shed ($2,400) was provided for all enterprises. The enterprises with eight or more greenhouses also required separate equipment storage sheds ($1,200). The enterprises with eight or fewer greenhouses were provided with one 1/2-ton pickup truck ($18,000), while the larger enterprises were provided with two pickup trucks.

The baseline price for a 30'x152' greenhouse with extractor fans and mechanical shutters was $13,600. Discounts are often available when four or more greenhouses are purchased at the same time. For this analysis, greenhouse cost was discounted by 10% for the four-greenhouse facility, by 12% for the eight-greenhouse facility, and by 15% for the sixteen-greenhouse facility.

Shrimp sales price and the prices of all operating inputs (except feed) were assumed to be constant (Table 5). Delivered feed price was a function of the volume of feed purchased in a single order. Some feed manufacturers offer volume discounts on feed purchases. In addition, shipping costs are inversely proportional to shipping volume. The best prices can be obtained when feed is shipped in truckload quantities. Shrimp feed is a perishable product with a shelf life of approximately three to four months when stored in an air-conditioned feed storage shed. A facility using twenty tons of feed in this time period can purchase full truckloads of feed and obtain the minimum price. In this analysis, the 8-greenhouse facility was the minimum facility size that consumed enough feed to be able to purchase feed by the truckload. Higher feed delivery prices accounted for the differences in feed prices for the smaller facilities.

Fixed costs included salaries for managers, depreciation, and interest on loans. All of the facilities, regardless of size, were assumed to require a production manager. The salary of the production manager was assumed to be $48,300 per year, including fringe and benefits. It was also assumed that the eight- and sixteen-greenhouse facilities would require an assistant manager. The salary of the assistant manager was assumed to be $34,500 per year, including fringe and benefits. Depreciation on capital items was calculated using the straight-line depreciation method (Shang 1990). Capital items with a useful life of 15 years (e.g. retention pond, buildings, and tanks) were assumed to have been purchased with a long-term loan (15-year term, 7% interest rate). Items with a shorter useful life (e.g. machinery and equipment) were assumed to have been purchased with a medium-term loan (5-year term, 10% interest rate).

Size and Number of Production Units

The size and number of culture tanks used in an operation may affect both labor costs and capital costs. The amount of labor involved in managing a culture tank is, to a large degree, independent of the size of the tank. Water quality monitoring and filter maintenance time requirements are the same, whether the tank volume is 10 cubic meters or 100 cubic meters. The time requirement for feeding increases only marginally with increases in tank size. For a given amount of production capacity, the labor requirements should be less for a system with a few, large culture tanks, than for a system with many, small culture tanks.

Table 3. Enterprise budget summaries for seven scenarios. The first five scenarios are for 30'x152' greenhouses housing two 3-phase production systems. The sixth scenario is for a 30'x152' greenhouse housing two single-phase production systems. The seventh scenario is for a 36'x200' greenhouse housing one large 3-phase production system.

Item	1- 30'x152' greenhouse 2 -3-phase systems	2- 30'x152' greenhouse 2 -3-phase systems	4- 30'x152' greenhouse 2 -3-phase systems	8- 30'x152' greenhouse 2 -3-phase systems	16- 30'x152' greenhouse 2 -3-phase systems	16- 30'x152' greenhouse 2 -1-phase systems	12- 36'x200' greenhouse 2 -1-phase systems
Revenues							
Shrimp Produced (kg)	4,462	8,924	17,849	35,698	71,396	39,664	80,953
Gross Receipts for shrimp sold	**$51,316**	**$102,631**	**$205,262**	**$410,525**	**$821,050**	**$456,139**	**$930,961**
Variable Cost							
Shrimp Postlarvae ($10/1000)	$3,541	$7,083	$14,166	$28,332	$56,663	$31,480	$64,249
Feed	$7,809	$14,056	$26,550	$46,853	$93,707	$52,059	$106,251
Labor	$22,963	$22,963	$45,926	$68,890	$114,816	$114,816	$68,890
Electricity	$5,037	$8,701	$17,080	$31,794	$61,486	$61,486	$63,025
Fuel	$3,806	$7,112	$13,724	$26,948	$53,396	$50,281	$59,318
Office Rental	$6,000	$6,000	$6,000	$6,000	$6,000	$6,000	$6,000
Maintenance & Repairs	$3,635	$5,210	$8,338	$15,002	$28,876	$28,572	$28,218
Operating Supplies	$365	$730	$1,460	$2,920	$5,840	$3,115	$4,380
Harvest, Shipping & Sales	$892	$1,785	$3,570	$7,140	$14,279	$7,933	$16,191
Marketing	$446	$892	$1,785	$3,570	$7,140	$3,966	$8,095
Miscellaneous	$446	$892	$1,785	$3,570	$7,140	$3,966	$8,095
Contingency	$5,494	$7,542	$14,038	$24,102	$44,934	$36,367	$43,271
Total Variable Costs	*$60,435*	*$82,967*	*$154,422*	*$265,120*	*$494,276*	*$400,042*	*$475,982*
Income Above Variable Cost	**($9,120)**	**$19,664**	**$50,840**	**$145,405**	**$326,774**	**$56,096**	**$454,979**
Fixed Cost							
Salaried Staff	$48,300	$48,300	$48,300	$82,800	$82,800	$82,800	$82,800
Interest Long-term Loan (15 yr @ 7%)	$6,601	$8,876	$13,395	$22,956	$41,430	$41,005	$40,439
Interest Intermediate Loan (5 yr @ 10%)	$3,543	$4,591	$6,685	$11,123	$21,772	$21,427	$19,574
Depreciation	$10,484	$14,682	$23,048	$40,777	$79,169	$78,073	$73,888
Total Fixed Cost	*$68,929*	*$76,448*	*$91,428*	*$157,656*	*$225,171*	*$223,306*	*$216,700*
Total Cost	**$129,474**	**$159,525**	**$245,960**	**$422,925**	**$719,601**	**$623,502**	**$692,836**
Net Returns	**($78,158)**	**($56,894)**	**($40,698)**	**($12,400)**	**$101,448**	**($167,363)**	**$238,125**
Total Fixed Cost/Lb	**$7.02**	**$3.89**	**$2.33**	**$2.01**	**$1.43**	**$2.56**	**$1.22**
Total Variable Cost/Lb	**$6.17**	**$4.23**	**$3.94**	**$3.38**	**$3.15**	**$4.59**	**$2.67**
Total Cost/Lb	**$13.19**	**$8.13**	**$6.26**	**$5.39**	**$4.58**	**$7.15**	**$3.89**

Table 4. Facility capital requirements as a function of the number of 30'x152' greenhouses. Each greenhouse encloses two three-phase production systems.

Item	Number of Greenhouses				
	1	2	4	8	16
Infrastructure					
Land & Site Clearing- 5 acres	$42,500	$42,500	$42,500	$42,500	$42,500
Well & Water Treatment System	$7,700	$7,700	$10,200	$15,100	$27,200
Retention Ponds	$3,000	$3,000	$3,000	$4,000	$4,500
Feed & Storage Sheds	$2,400	$2,400	$2,400	$3,600	$3,600
Acclimation/Quarantine Greenhouse	$3,350	$3,350	$3,350	$5,450	$5,450
Office Furniture & Equipment	$4,850	$4,850	$4,850	$4,850	$7,100
Pickup Truck	$18,000	$18,000	$18,000	$18,000	$36,000
Infrastructure Sub-Total	**$81,800**	**$81,800**	**$84,300**	**$93,500**	**$126,350**
Greenhouses					
Greenhouses, Tanks, Filtration Equip.	$32,500	$65,000	$124,560	$246,944	$487,360
Pumps, Blowers, Plumbing	$10,488	$20,976	$41,952	$83,904	$167,808
Drain & Harvest Sumps	$3,400	$3,400	$5,900	$11,800	$23,600
Harvest Equipment	$500	$500	$500	$1,000	$1,500
Water Quality Monitoring Equipment	$1,100	$1,100	$1,100	$2,200	$3,300
Greenhouses Sub-total	**$47,988**	**$90,976**	**$174,012**	**$345,848**	**$683,568**
Total Capital Cost	**$129,788**	**$172,776**	**$258,312**	**$439,348**	**$809,918**
Capital Cost/Greenhouse	**$129,788**	**$86,388**	**$64,578**	**$54,919**	**$50,620**

Table 5. Assumed unit prices for whole shrimp sold and unit costs for operating inputs.

Item	Units	Unit Price/Cost
Whole Shrimp, 18 g/shrimp	Kg	$11.50
Postlarvae	1000 PLs	$10.00
Shrimp Feed	Kg	$0.75†
Electricity	kW-hr	$0.08
Propane	gallon	$1.00
Gasoline	gallon	$1.50
Diesel	gallon	$1.40
Labor + Fringe	man-hr	$11.04
Operating Supplies	$/Crop	$25.00
Office Rental	$/Year	$6,000
Harvest, Shipping & Sales	$/kg harvested	$0.20
Marketing	$/kg harvested	$0.10
Miscellaneous	$/kg harvested	$0.10
Maintenance	% Capital	5%
Contingency	% Variable Costs	10%

† Feed delivery price is a function of volume. The delivered feed prices were assumed to be $1.00/kg, $0.90/kg, and $0.85/kg for the one-, two-, and four-greenhouse firms. The price for firms with eight or more greenhouses was assumed to be $0.75/kg.

In an indoor production facility, culture tank size is limited by the size of the building. For a given building size, tank size is maximized by reducing the number of tanks to only one tank per building that occupies the entire area, except that which is required for the water treatment system and system access. Further increases in tank size can be achieved by increasing the size of the building. In practice, there are limits to both the length and width of a greenhouse. The maximum practical size of a single-span Quonset-style greenhouse is 11m x 61m (36'x200') (Dick Gilham, personal communication). Further increases in the width of the greenhouse can be achieved only by sacrificing wind load tolerance. Further increases in the length of the greenhouse result in ventilation problems.

The economic impact of reducing tank number and increasing tank size was evaluated by comparing enterprise budgets for facilities utilizing either sixteen 30'x152' greenhouses with two 189-m^2 three-phase culture tanks per greenhouse (small tank facility), or twelve 36'x200' greenhouses with one 570-m^2 three-phase culture tank per greenhouse (large tank facility). The total production area for the small tank facility was 6,048 m^2 divided between thirty-two culture tanks. The total production area for the large tank facility was 6,840 m^2 divided between twelve 570-m^2 culture tanks. It was assumed that five full-time hourly laborers and two salaried managers would be required for the small tank facility. The large tank facility, with less than half the number of culture systems to maintain, was assumed to be managed by three full-time hourly laborers and two salaried managers. The capacities of the biofiltration, aeration, pumping, and temperature control systems of the small and large tank facilities were proportional to the greenhouse and tank sizes of the respective facilities.

RESULTS AND DISCUSSION

Multi-phase Production Systems

One measure of system efficiency is the capital cost per unit of annual production capacity. Capital cost per unit of annual production is minimized by strategies that increase annual productivity without causing proportional increases in capital costs. For a given plant size, productivity can only be increased by improvements in management or by investing in system modifications that increase system productivity. One strategy recirculating system designers have used to reduce the cost of production has been to design systems that will support extremely high biomasses of shrimp (Reid and Arnold 1992, Davis and Arnold 1998). Often this is accomplished by increasing the capacity of the biofiltration and aeration systems. However, it is not always clear whether additional capital spent to extend carrying capacities will result in lower production costs. For this to occur, each additional dollar of capital investment must result in greater than one dollar of additional revenue. This result is not assured. Shrimp growth rates often decline as stocking densities are increased (Sturmer et al. 1992; Williams et al. 1996). Higher stocking rates may also result in lower survival rates (Williams et al. 1996) and increased risk of crop failure (Fast 1992).

An alternative strategy for increasing system productivity is to utilize a multi-phase production system. Multiphase production systems are capable of increasing annual productivity because they utilize the available production area more efficiently by operating closer to the carrying capacity of the system for a greater percentage of the culture period (Van Wyk 2000b). If the multi-phase system is created by partitioning of a single-phase system, this increase in system capacity can be obtained without significantly increasing system or operating costs. Using a computer simulation of a recirculating fish production system, Losordo and Westerman (1994) demonstrated that changes in either system capacity or overall system cost had greater impacts on the total production cost than changes in any other variable. The greatest impact on total production cost occurred when system capacity was increased without a corresponding increase in capital costs.

Table 2 shows that there is a very large potential gain in annual productivity that may be realized by adopting a multi-phase production strategy. A two-phase system with a 30-day nursery phase and a 120-day final growout phase was 16% more productive on an annual basis than a single-phase system. Annual productivity increased with the length of the nursery phase. A two-phase system with 50-day nursery phase and a 100-day final growout was 29% more productive than a single-phase system. The productivity of two-phase systems was maximized when the growout period was equally divided between the nursery and final growout phases. In that scenario, the two-phase system was 50% more productive than the single-phase system. The greatest gains in annual productivity were obtained with a three-phase production strategy, in which the growout period was equally divided between the nursery, intermediate, and final growout phases. The three-phase system was 80% more productive than the single-phase system.

The above analysis was based on the assumption that overall survival and growth were identical for each culture system. This simplifying assumption may not hold for all stocking densities. Several studies (Sandifer et al.1988, Sturmer et al. 1992. and Williams et al. 1996) have shown that shrimp growth rates are inversely proportional to stocking density. Williams et al. (1996) found the survival declined with increasing density. Wang and Leiman (2000) demonstrated that if the density-dependent inhibition of growth rates is of sufficient magnitude, a two-phase production system might be more efficient than a three-phase system. However, in field trials comparing production in single- and three-phase systems, Van Wyk (2000b) demonstrated that the annual productivity of a three-phase production system was 74% higher than that of a single-phase system of similar design. That study demonstrated that the actual improvement in annual productivity was similar in magnitude to the 80% improvement predicted by the model.

Comparison of the production costs associated with a three-phase and a single-phase production system reveals the economic benefits associated with the three-phase approach. Figure 2 shows how the choice of production system affected input costs per pound of production. Seed and feed costs per pound of production were not affected by the choice of production system because these inputs were used in amounts proportional to the level of production. Labor, energy, maintenance, and fixed costs, however, were used in amounts proportional to the number of production systems and greenhouses, and were relatively independent of the production capacity of individual systems. Therefore, increases in system production capacity reduced the cost of these inputs by an amount proportional to the increase in capacity. For example, the energy cost per pound of shrimp produced was $1.28/lb for a facility operating sixteen 30'x152' greenhouses, when each greenhouse enclosed two single-phase production systems. The energy cost was only $0.73/lb of shrimp produced for an identical facility that used a three-phase production system rather than a single-phase system. The total annual energy bill would be the same for both facilities, with the difference in the energy cost per pound of shrimp produced due the differences in annual productivity resulting from the choice of production system. The same phenomenon explains the differences in the costs per pound of production for labor, maintenance, and fixed costs. For a sixteen-greenhouse facility, the enterprise budget analysis (Table 3) showed that if a single-production system was used, the overall production cost per pound of shrimp produced was $7.15/lb. The total cost of production for an identical facility that used a three-phase production system was only $4.58/lb. This represents a 36% decrease in the overall production cost per pound.

Number Of Greenhouses

In the short run, capital resources such as land, greenhouses, and production tanks are fixed. Minimization of production costs in the short run requires efficient use of variable inputs such as seed, feed, labor and energy. In the long run, all inputs are variable, including capital inputs. The entrepreneur planning for a new enterprise is making long-run plans and must decide on what scale the operation should be built. It is a well-known economic phenomenon that the average cost of production typically decreases with increasing firm size (Jolly and Clonts 1993, Shang 1990). Economies of scale come from

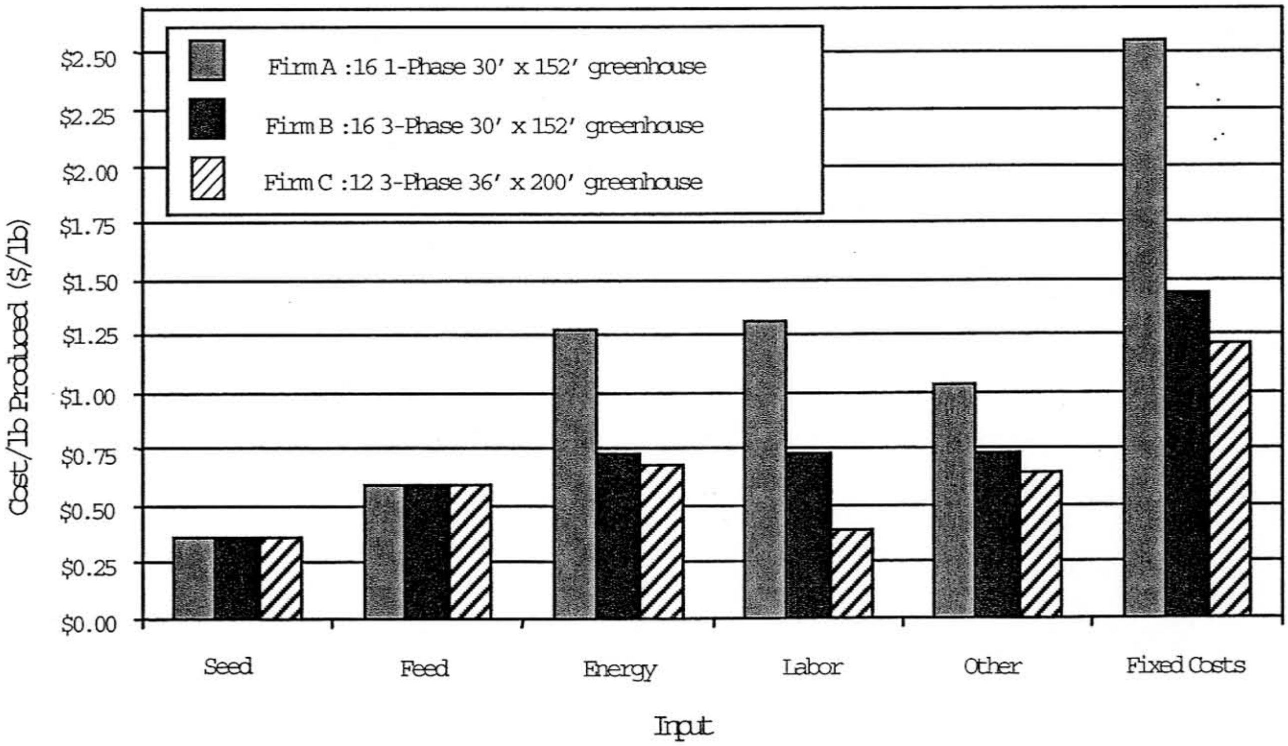


Figure 2. Input costs per pound of shrimp production for three facilities: Firm A operates 16 30'x152' greenhouses each enclosing two single-phase production systems; Firm B operates 16 30'x152' greenhouses each enclosing two three-phase production systems; Firm C operates twelve 36'x200' greenhouses each enclosing one large three-phase system.

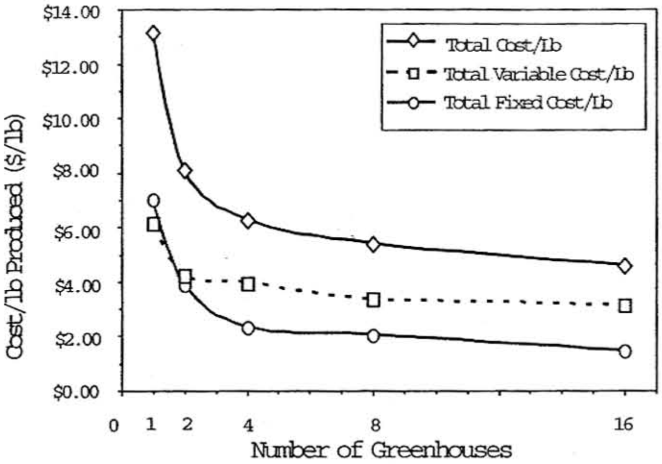


Figure 3. The relationship between the number of greenhouses operated by a firm and the average production cost per pound of shrimp produced.

a variety of sources, including the spreading of total fixed costs over a larger amount of output, and the full utilization of labor, machinery, and buildings (Kay and Edwards 1994).

Indoor shrimp production systems are often enclosed by greenhouses. For these systems, the greenhouse constitutes the basic construction unit. Farm size is increased by increasing the total area enclosed by greenhouses. Microeconomic theory tells us that the number of greenhouses should be increased as long as the addition of more greenhouses results in a lower average cost of production. Declining production costs indicate that the increases in capital and operating costs associated with the addition of production capacity are less than the increased revenue from the added production.

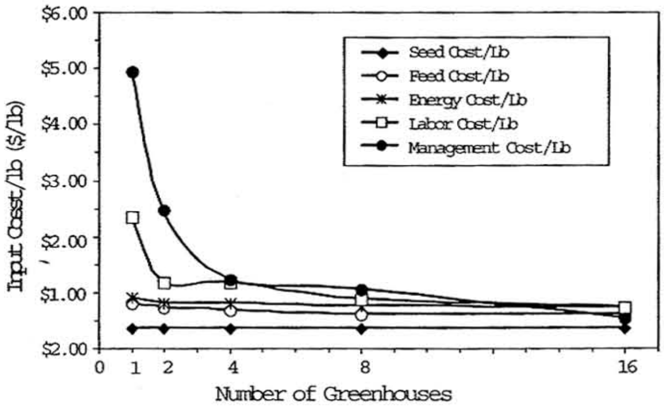


Figure 4. Input costs per pound of shrimp production as a function of the number of greenhouses operated by a facility. The greenhouses all measure 30'x152' and enclose two three-phase production systems.

The enterprise budget analysis revealed that the total cost of production per pound of shrimp harvested decreased as the number of greenhouses was increased from one to sixteen (Figure 3). Production costs were very high ($13.19/lb) for a firm operating a single greenhouse, but dropped quickly as additional greenhouses were added. The shape of the curve relating production cost per pound to the number of greenhouses is that of the classical long-run average cost curve found in microeconomics textbooks (Jolly and Clonts 1993). The extremely high cost of production for facilities operating less than four greenhouses was largely due to the fact that management and labor were under-utilized (Figure 4). The single-greenhouse facility was staffed with a manager and one hourly laborer. The total staffing cost was $71,263 per year, or $7.26 per pound of shrimp produced per year. This cost is cut in half for a two-greenhouse facility. An additional hourly laborer would be required for a four-greenhouse facility, but the staffing cost per pound of shrimp produced would still be reduced to $2.40/lb. Further increases in the number of greenhouses brought only slight savings in the hourly labor cost per pound, but the management cost per pound of production continued to decline as production capacity increased. The total staffing cost for a three-phase sixteen-greenhouse facility was $1.26 per pound of production.

The decline in production cost with increasing facility size can also be attributed to a variety of economies of scale that resulted in lower capital costs per unit of production capacity (Figure 5). Most of these economies of scale were related to a more efficient utilization of infrastructure, such as wells, wellwater treatment systems, retention ponds, postlarval quarantine systems, and vehicles (Table 4). The total capital investment for infrastructure for a sixteen-greenhouse facility

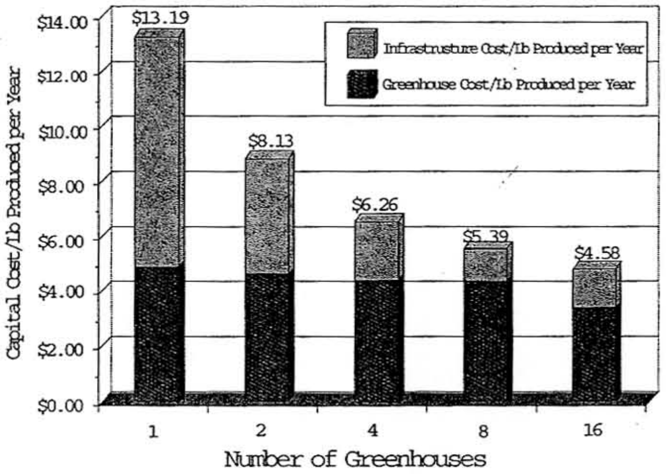


Figure 5. Capital cost per pound of annual shrimp production capacity as a function of the number of greenhouses operated by a facility. All greenhouses measure 30'x152' each and enclose two three-phase production systems.

($126,350) was only a little more than 50% higher than investment in infrastructure for a single-greenhouse facility ($81,800). Meanwhile, the production capacity of a sixteen-greenhouse facility was sixteen times that of single-greenhouse facility. Frequently the cost for items such as wells and tanks is not a linear function of capacity. For example, the cost of a well is influenced more by the cost of boring the well, than it is by the pumping capacity of the well pump. The cost of a postlarval quarantine/acclimation is not proportional to the number of postlarvae acclimated per year. The minimum size for a postlarval quarantine system is determined by the number of postlarvae received in a single shipment. If the postlarvae spend a week in the system, the system size will be the same whether postlarvae are received on a weekly basis or a monthly basis. The system will need to be enlarged when more than one shipment per week is anticipated. However, the cost of doubling the capacity of the system is less than the cost of the initial system, because the enclosure has already been built. Other capital resources, such as vehicles, are available only in indivisible whole units (Jolly and Clonts 1993). Small facilities will generally under-utilize these resources.

There is a limit to how many greenhouses a company can operate before diseconomies of scale begin to set in. As the size of the operation is increased, the production manager will be forced to delegate responsibilities and authority to subordinates. Efficiency will tend to decline as the production manager becomes more distanced from the day-to-day management decisions regarding individual production systems (Jolly and Clonts 1993). Market forces will also impose limits on the size of the facility. Most indoor shrimp production facilities are likely to market their shrimp as a fresh, premium product to restaurants, seafood distributors, and other direct markets (Van Wyk 2000b). A limited volume of shrimp can be sold at premium prices into these markets. As production volume increases, marketing costs will increase, and the price received for the product is likely to decrease. The size of the facility should only be increased as long the additional income associated with the increased production capacity (the marginal revenue) exceeds the costs associated with the addition output (the marginal cost). The average cost of production is minimized at this facility size. Increasing the size of the facility beyond this point will result in diseconomies of scale, and the marginal cost of the expansion will exceed the marginal revenue. It is difficult to predict the facility size at which diseconomies of scale begin to set in, because this depends on the managerial skills of top management and the size of the market for premium quality fresh shrimp.

Size And Number Of Production Units

The size of the greenhouses, as well as the size and number of production tanks per greenhouse, may have a significant impact on both the capital costs and operating costs for a facility. To illustrate this point, enterprise budgets were compared for facilities operating either sixteen, 30'x152' greenhouses with two, 189-m^2 production tanks per greenhouse, or twelve, 36'x 200' greenhouses with a single, 570-m^2 production tank per greenhouse.

For the sixteen-greenhouse small-tank facility, the total capital cost for the greenhouses and the enclosed production systems was $683,568, or $113.02 per square meter of culture tank area. For the twelve-greenhouse large-tank facility, the total capital cost for the greenhouses and the enclosed production systems was $647,390, or $94.65 per square meter of culture tank area. This reduction in the capital cost per unit area is due to several economies of scale. As a general rule, the capital cost of a greenhouse per unit area enclosed declines as the total area enclosed increases. In this example, the cost per square meter for the 30'x152' greenhouses was $44.50/m^2, while the cost for the 36'x200' greenhouses was $41.00/m^2. Another economy of scale was gained by using fewer, larger culture tanks. The cost per square meter for lined culture tanks often decreases as the area of the tank increases. For a given amount of enclosed area, fewer large culture tanks will have a smaller perimeter than a greater number of small culture tanks. The cost savings are due to the reduction in the amount spent on the perimeter support structure. In this example, the cost of the thirty-two, 189-m^2 culture tanks required for the sixteen-greenhouse small tank facility was $73,824, or $12.21/m^2 of culture area. The cost of the twelve, 570-m^2 culture tanks for the twelve-greenhouse large tank facility was $57,600, or $9.52/m^2 of culture area.

Fewer, larger tanks should also reduce labor costs. The time required for routine tasks such as water chemistry, filter maintenance, and feeding is primarily a function of the number of systems or tanks, rather than tank size. In this example, five hourly laborers were required to maintain 32 culture tanks in the sixteen-greenhouse small tank facility, while only three hourly laborers were required to maintain twelve culture tanks in the twelve-greenhouse large tank facility. As a result, the labor cost per pound of production was reduced from $0.73/lb to $0.39/lb (Figure 2).

Enterprise budget analysis showed that the breakeven cost of production for a twelve-greenhouse large-tank was only $3.89/lb. This was $0.69/lb less than the breakeven price for a sixteen-greenhouse small-tank facility. Theoretically, production costs will be minimized by using the largest greenhouse possible. Each greenhouse should enclose a single production system that occupies the maximum amount of available area within the greenhouse.

CONCLUSIONS

Indoor recirculating shrimp production systems have many positive qualities. They have a relatively low environmental impact, and a high degree of biosecurity. The increased environmental control that is possible in an indoor, recirculating system makes it possible to produce shrimp year-round, even in areas with cold winters. Near-freshwater shrimp production systems can be built close to inland population centers, allowing easy access to major markets for fresh shrimp. Because of these positive attributes, indoor recirculating systems have been labeled by some as a sustainable shrimp production technology. But in order for a technology to be sustainable, it must first be profitable. To date, however, no one has made a profit producing shrimp in an indoor recirculating system. Inefficient production systems have led to high production costs.

This situation may change, however, if system designers examine how alternative design choices affect production costs. Bioeconomic analysis shows that the cost of production can be significantly reduced by adopting a three-phase production strategy, and by taking advantage of economies of scale to eliminate under-utilization of capital, management, and labor.

The type of production system was demonstrated to have a very large impact on the average cost of production. Inefficient use of space in traditional single-phase production systems led to extremely high production costs per pound of shrimp produced, even for a sixteen-greenhouse facility that has taken advantage of the available economies of scale. This result suggests that indoor recirculating systems based upon a single-phase production technology are not likely to be profitable.

Only by using available space more efficiently can the prospects for profitability be improved. This can be accomplished either by investing in filtration and aeration systems to boost system carrying capacities, or by adopting a multi-phase production strategy. Boosting the system carrying capacity would likely require significant capital investment. However, if higher densities lead to lower growth rates and less stable systems, the increased carrying capacity might not result in a lower cost of production. Multi-phase production systems, on the other hand, appear to allow for increased production capacity without significantly increasing the capital investment requirements.

Another important factor affecting the cost of production is the scale of the operation. Enterprise budget analysis clearly showed that there are large economies of scale associated with increasing the number of greenhouses. By increasing the size of individual production systems and decreasing the total number of systems, significant labor savings can also be realized. The high capital cost associated with building indoor recirculating production systems prohibits many enterprises from graduating from a small-scale operation to a size that will allow them to capture important economies of scale. Some producers may feel that they can reduce their risk by remaining small. While it is true that limiting the amount of capital invested in a project limits the amount of money that will be lost if the business fails, it is also true that an undersized enterprise is almost guaranteed to fail.

The above analysis suggests that indoor shrimp recirculating systems may someday justify the excitement they have generated because of their many positive attributes. Nevertheless, businesses based on this technology will only be profitable if project planners design their facilities so that resources such as space, labor, and management are utilized as efficiently as possible. Facilities will need to take full advantage of economies of scale wherever possible, and use multi-phase production systems.

This article is Harbor Branch Oceanographic Institution Contribution No. 1409.

LITERATURE CITED

Allen, P.G., L.W. Botsford, A.M. Schuur, and W.E. Johnston. 1984. Bioeconomics of Aquaculture. Developments in Aquaculture and Fisheries Science, 13. Elsevier Science Publishers B.V., Amsterdam, The Netherlands. 351 pages.

Davis, D.A. and C.R. Arnold. 1998. The design, management, and production of a recirculating raceway system for the production of marine shrimp. Aquaculture Engineering 17: 193-211.

Fast, A.W. 1992. Penaeid ultra-intensive growout systems. Pages 391-398 *In* A.W. Fast and L.J. Lester, editors. Marine Shrimp Culture: Principles and Practices. Developments in Aquaculture and Fisheries Science, 23. Elsevier Science Publishers B.V., Amsterdam, The Netherlands.

Jolly, C.M. and H.A. Clonts. 1993. Economics of Aquaculture. Food Products Press, an imprint of The Haworth Press, Inc.. Binghamton, NY USA. 319 pp.

Kay, R.D. and W.M. Edwards. 1994. Farm Management. Third Edition. McGraw-Hill Series in Agricultural Economics. McGraw-Hill, Inc. New York, NY USA. 458 pp.

Leung, P.S. and S.M. Moss. 1999. Economic Assessment of a Prototype Biosecure Shrimp Growout Facility. Pages 97-106 *In:* R.A. Bullis and G.D. Pruder. Controlled and Biosecure Production Systems: Evolution and Integration of Shrimp and Chicken Models. Proceedings of a Special Session. World Aquaculture Society. Sydney, Australia. April 27-30, 1999. The Oceanic Institute. Honolulu, HI USA.

Losordo, T.M. and P.W. Westerman. 1994. An analysis of biological, economic, and engineering factors affecting the cost of fish production in recirculating aquaculture systems. Journal of the World Aquaculture Society 25: 193-203.

Ogle, J.T. and J.M. Lotz. 1998. Preliminary design of a closed, biosecure shrimp growout system. Pages 39-48 *In:* S. M. Moss, editor. U.S. Marine Shrimp Farming Program Biosecurity Workshop - February, 1998. The Oceanic Institute. Honolulu, HI USA.

Parker, J.C., F.S. Conte, W.S. MacGrath, and B.W. Miller. 1974. An intensive culture system for penaeid shrimp. Proceedings World Mariculture Society 5: 65-79.

Reid, B. and C.R. Arnold. 1992. The intensive culture of the Penaeid shrimp *Penaeus vannamei* Boone in a recirculating raceway system. Journal of the World Aquaculture Society 23: 146-153.

Sandifer, P.A., J.S. Hopkins, and A.D. Stokes. 1988. Intensification of Shrimp Culture in Earthen Ponds in South Carolina: Progress and Prospects. Journal of the World Aquaculture Society 19:218-226.

Shang, Y.C. 1990. Aquaculture Economic Analysis: An Introduction. World Aquaculture Society. Baton Rouge, LA USA. 211 pp.

Sturmer, L.N., T.M. Samocha, and A.L. Lawrence. 1992. Intensification of penaeid nursery systems. Pages 321-344 *In:* A.W. Fast and L.J. Lester, editors. Marine Shrimp Culture: Principles and Practices. Elsevier Science Publishers, B.V., New York, NY USA.

Van Wyk, P. 1999. Harbor Branch Shrimp Production Systems. Pages 99-114 *In*: Production of Marine Shrimp in Freshwater Recirculating Aquaculture Systems. Prepared by Harbor Branch Oceanographic Institution for the Florida Department of Agriculture and Consumer Services. Tallahasse, FL USA. vii + 222 pp.

Van Wyk, P. 2000a. Economics of shrimp culture in a freshwater recirculating aquaculture system. Pages 318-323 *In*: G. Libey, M. Timmons, G. Flick, and T. Rakestraw, editors. .Proceedings of the Third International Conference on Recirculating Aquaculture Virginia Polytechnic Institute and State University. Roanoke, VA USA.

Van Wyk, P.M. 2000b. Culture of *Penaeus vannamei* in Single-Phase and Three-Phase Recirculating Aquaculture Systems. Global Aquaculture Advocate 3(3):41-43.

Wang, J.-K. and J. Leiman. 2000. Optimizing multi-stage shrimp production systems. Aquacultural Engineering 22:243-254.

Williams, A.S., D.A. Davis, and C.R. Arnold. 1996. Density-dependent growth and survival of *Penaeus setiferus* and *Penaeus vannamei* in a semi-closed recirculating system. Journal of the World Aquaculture Society 27:107-112.