APPLICATION OF A BIO-ECONOMIC-ENGINEERING MODEL FOR SHRIMP MARICULTURE SYSTEMS

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The culture of marine invertebrates, collectively termed mariculture, has received much attention as a new and potentially lucrative industry. Much research has been devoted to molluscs (oysters, clams, and mussels) and crustaceans (shrimp, crawfish, crabs, and lobsters) (Bardach, Ryther, and McLarney). In particular, effort has been directed to the development of a technologically and commercially feasible penaeid shrimp mariculture scheme (Broom; Mock and Murphy; Neal and Latapie; Parker and Conte; Wheeler). Results of extensive research efforts show promise that the technological feasibility of penaeid shrimp farming in Gulf coastal regions of the United States is near to being a reality.

Before significant commercial investment in shrimp mariculture will be realized, however, economic relationships in addition to technical considerations must be better understood. Investors will initially want to know the vital biological and environmental elements of a shrimp culture system and how variability in those elements affects production. Investors will also want to know how much control can be exercised over these critical elements and at what cost. For penaeid shrimp mariculture to become an attractive commercial investment, these questions must be answered and the potential economic feasibility of such operations must be established and readily demonstrable to potential investors and creditors during their decision-making process.

Economic, investment, and feasibility analyses have been performed on a variety of aquacultural systems other than penaeid shrimp mariculture (Gibson and Wang; Herrick and Baldwin; MacDonald, Meade, and Gates; Roberts and Bauer; Shang; Shang and Fujimura; Smith). Studies of shrimp mariculture have been limited to itemizing fixed and variable costs and calculating per units costs of production for a given system or limited range of system sizes. Financial analyses have been performed on given hypothetical operations defined by a rigid set of assumptions (Anderson and Tabb; Phillips and Gillespie; Williams). Previous economic studies involving penaeid shrimp mariculture, although directed toward an immediate need and research goal, have failed to consolidate biological, economic, and engineering relationships and principles into a comprehensive model capable of performing analyses on an unlimited number of system designs and a continuum range of facility sizes.

Computerized models designed for application in technological assessment and determining direction of future research in aquaculture have been developed for other systems (Allen and Johnston; Polovina; Schurr, Allen, and Botsford). Though biologically oriented in terms of the output generated and audiences addressed, these models demonstrate a clear step foward in analytical power in the direction of assessing the status of economic feasibility.

Therefore, considering the purposes, applications, and limitations of previous modeling studies in aquaculture and the status of the industry, we see a distinct need for a modeling tool which will consolidate biological, economic, and engineering relationships and principles. A model of this scope is needed to provide a framework applicable to most land-based mariculture operations. The more extensive analysis of this type of model will aid the potential mariculturist (as well as creditors) in allocating financial resources and assessing investment opportunities. More specifically, because shrimp mariculture is a growing new investment opportunity with high risk, economies of size need to be identified. That information will enable an investor or creditor to identify the size of system that captures most of the economies of size and thus to keep risk capital as low as possible. Like previous modeling efforts, this type of model will also provide guidelines for the direction of future research and assessment of advancing technology.

We describe the development of a bio-economic-engineering (BEE) model for penaeid shrimp mariculture and its application to a specific system. The tool is introduced in primarily an application context.[1]

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[1]For a copy of the model and its use see Adams et al.

ANALYTICAL FRAMEWORK

Our particular application of the BEE model examines the financial feasibility of a one-crop system for a given year within the firm's planning horizon. The analysis is conducted under a given set of biological and engineering assumptions. The basic tool for economic analysis utilized within the framework of the study is budget simulation. The BEE model constructs budgets based on detailed itemization of cost and returns for selected sizes of firms on a per acre basis. The values produced in 1978 dollars are used to construct long-run cost curves and are then employed to examine economies of size for the given system design. In preparation for a discussion of the analytical results of the study, brief descriptions of the system and the engineering, biological, and cost components of the BEE model are provided.

General Systems Description

The system is a penaeid shrimp grow-out operation. The facility is assumed to be located on the northern Texas coast where the grow-out period is limited to less than one year. Juvenile shrimp are stocked in ponds where they remain until harvest.

In the analysis we assume a grow-out period (time shrimp are in pond) that begins on day 125 (May 5) and ends on day 308 (November 4), which is the maximum length of the growing season (approximately six months) that can be expected for the northern Texas Gulf Coast under normal climatic conditions.[2] We assume that viable eggs can be obtained approximately two weeks before stocking by sourcing offshore for gravid female shrimp.

Facility Design and Engineering Aspects

The system design is based on the research facility operated by the Texas A&M Extension Service in Brazoria County, Texas. The system consists of a series of individual grow-out ponds aligned on each side of a central reservoir into which water is pumped from an outside source. Once the water is pumped into the main reservoir it is gravity-fed into each pond. The desired flow-through is achieved by allowing water to escape from the other end of the pond by an adjustable valve extending through the levee. The bottom of the pond slopes gradually toward the reservoir to facilitate drainage during harvesting. Harvesting is accomplished by opening a valve on the reservoir end of the pond and allowing the water to drain through the levee into a net.

The BEE model has the ability to build an operation of any number and size of ponds. The levees are of two types, (1) those forming the perimeter of the pond system and reservoir with a roaded top and (2) those between the ponds without a roaded top. Given the dimensions of the levees and the individual pond perimeter, the model generates the volume of dirt needed to construct the levees, the water-surface acreage, and the total acreage for the facility.

Because large quantities of salt water must continually flow through the system to maintain the proper water quality, a crucial part of the model is the determination of equipment requirements and fuel costs for water-handling purposes. A single pump and driver provide the power necessary to supply water to the reservoir. In selecting a pumping system, the model estimates the volume of water in the system, applies a maximum daily exchange rate, and selects the appropriate pump size based on the maximum gallon-per-minute capacity of the pump and the maximum gallon-per-minute requirements of the system. Once the volume of water exchange and the appropriate pump size are selected, the size of pipe appropriate for handling the designated water volume is derived by the model.

Growth Relationships and Data Limitations

The biological component of the BEE model describes the growth process of shrimp in the grow-out ponds. In the development of this growth submodel, simulation techniques are applied in a restricted fashion because of limiting factors induced by the data. Linear and nonlinear equations are employed in deriving growth of individual shrimp over time. Estimates related to growth on the population level are then calculated from this information. Thus, an algorithm sufficient to generate growth over time is derived.

Data collected in 1972 and 1977 for Texas A&M's research facility in Brazoria County consist of length-weight data at weekly intervals. In 1972 six half-acre ponds were each stocked with 20,000 post-larvae which were reared for 15 weeks (3 ponds) to 17 weeks (3 ponds). In 1977, 13 half-acre ponds were each stocked with 40,000 post-larvae which were reared for 24 weeks (2 ponds) to 27 weeks (11 ponds) (Parker). In 1972 and 1977 all ponds exhibited linear growth patterns of shrimp through the growing season. Correlation between growth feeding rates and water chemis-

[2]Growing season length can be altered by the manager in two ways, (1) by locating in the desired area along the coast or (2) by physically manipulating the production scheme (i.e., using heated effluent, pond covers, etc.). The costs of altering the growing season length attributable to either of these methods were not examined.

try is found to be absent. Because both of the two stocking densities were not examined during the same year, there may be a confounding influence of years which cannot be evaluated.

Preliminary analyses of stocking densities indicated that profit at 40,000 post-larvae per acre was significantly greater than profit at a density of 80,000 per acre (Adams). Because of this finding and the lack of uniform data, we report only the growth equation based on 40,000 post-larvae per pond.

Although the data show linearity over the grow-out periods, we assume that after a length of time the growth curve must begin to increase at a decreasing rate, indicating an animal's approach toward an asymptotic weight. Therefore, for the purposes of our study, the growth curve is assumed to have a linear and curvilinear section, the linear portion being described by the data and the curvilinear portion being intuitive and supported by the literature (Klima). For the general form of the curvilinear portion, the classical von Bertalanffy growth equation given as

$$w_t = W\infty[1 - e^{k(t-t_o)}]^3$$

is suitable for describing growth of this nature.[3] In this equation W_t is the weight of the animal in week t, $W\infty$ is the asymptotic weight, k is the catabolic coefficient, and t_0 is the age in weeks when the weight is assumed to be zero.

The linear equation estimated where weight (y) in grams is a function of weeks (x) is

$$y = -2.56 + 1.01x.$$

Both coefficients are significant at the 5 percent level and the coefficient of determination is 0.98. The regression began in time period (week) 4 and ended at time period 18 when shrimp were 135 days old. The estimation of the curvilinear segments of the growth equation beyond week 18 is accomplished by forcing the von Bertalanffy equation through values of weight generated by each linear equation for weeks 4 and 18.

The resulting curvilinear equation is attached onto the "end" of the linear equation after period 18. The curvilinear equation is given as

$$w_t = 87[1 - e^{-.04(t-(-2.0))}]^3.$$

The asymptotic weight, $W\infty$, is supported by Klima's work on Gulf Shrimp growth. Although the asymptotic weight of 87 grams may be too high for pond-reared shrimp, lack of any valid estimation for cultured shrimp warrants its use.

To estimate the biomass of a population over time, the number of individuals and rate of attrition from the population over time must be estimated. No satisfactory method is available for accurate estimation of percentage survival in the research ponds at a given point in time prior to harvest. From an intuitive biological assumption and from unpublished data (Parker), survival is taken to be 75 percent (25 percent mortality) inclusive of weeks 1 through 17 and 66 percent (12 percent mortality) after week 17.

Production Costs and Prices

Various assumptions are made about prices, insurance, financing capital assets, and taxes. Current 1978 prices for fixed and variable items are used in the model. Capital investment (fixed) items (structural components, land, machinery, and equipment) are representative of Brazoria County, Texas. Variable input prices (labor, fuel, utilities, ice, etc.) are assumed constant throughout the planning horizon of the firm. The quantities utilized are commensurate with proper management under a given set of assumptions about production of a commercial operation. Physical unit requirements of both fixed and variable expenses are generated internally by the model.

Output prices represent monthly projected 1978 ex-vessel prices per pound of shrimp for the northern Gulf of Mexico. The prices were obtained by averaging 1976 and 1977 prices for the area and applying a wholesale price index.

Costs of insurance, financing, and taxes reflect the costs that would be incurred by a firm operating in the Brazoria County, Texas, area. Many of these costs are strictly local and vary with the size and organizational framework of the firm. These values are generated internally by the model.

RESULTS

The following analysis yields information about the size of operation which captures most economies of size. A unit of output is expressed as yield (pounds of shrimp) per surface acre (SA) with yield per SA held constant throughout the range of pond sizes considered. If economies of size exist, an investor will increase the size of the operation (acres of land) by increasing the size of ponds or by increasing the number of ponds to take advantage of the decreasing costs per unit of output. The analysis proceeds in two stages by performing an

[3]The von Bertalanffy equation is widely used as a tool in growth analysis, especially for aquatic organisms. We examined no other growth or production models.

economies of size analysis for pond size and then for the firm (number of ponds). In arriving at the latter value, the analysis provides projections on internal rates of return (IRR) on equity and total investment and estimation of payback period. Sensitivity analysis is performed on the final operation yielded.

In application, the issues of capital budgeting would be addressed on an after-income-tax basis for a one-enterprise firm. Though income taxes and strategies for minimizing taxes vary from region to region and over time, taxation is an inevitable cost. However, as Figure 1 and Figure 2 show, more economies of size are

FIGURE 1. ANNUAL "AVERAGE REVENUE" AND LONG-RUN "AVERAGE COST" PER SA BEFORE AND AFTER INCOME TAXES FOR A 20-POND OPERATION BY POND SIZE AND YIELD PER POUND

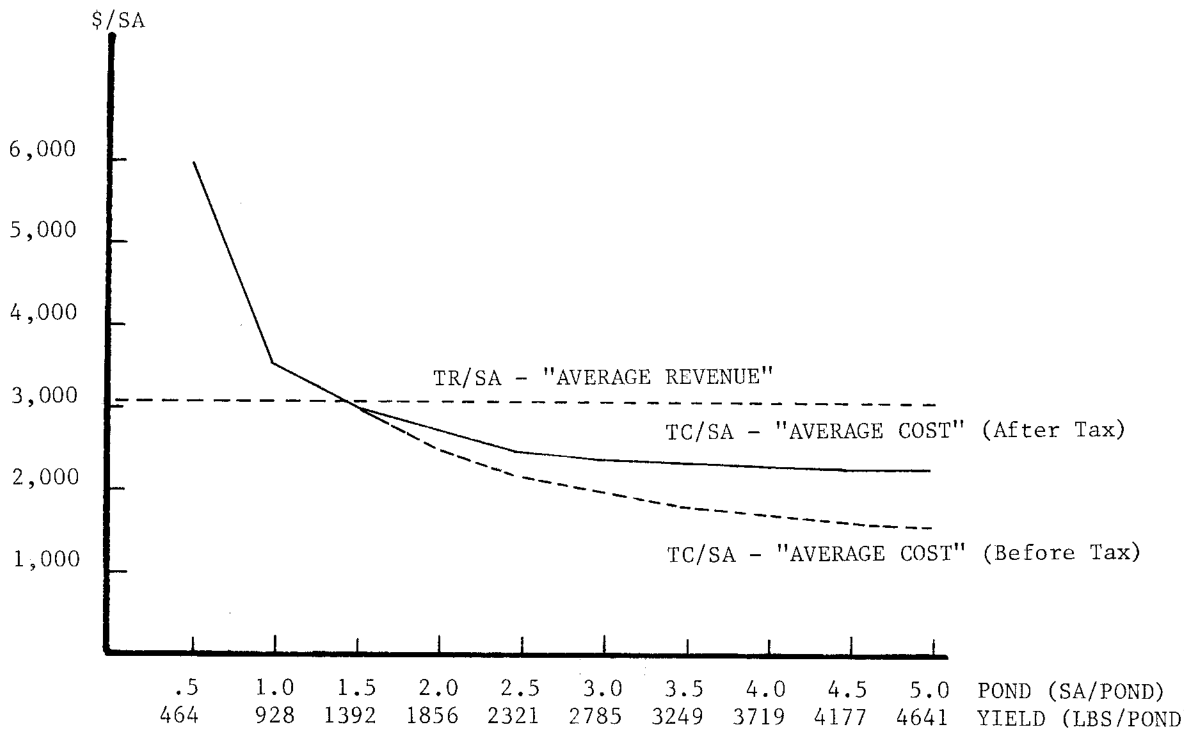
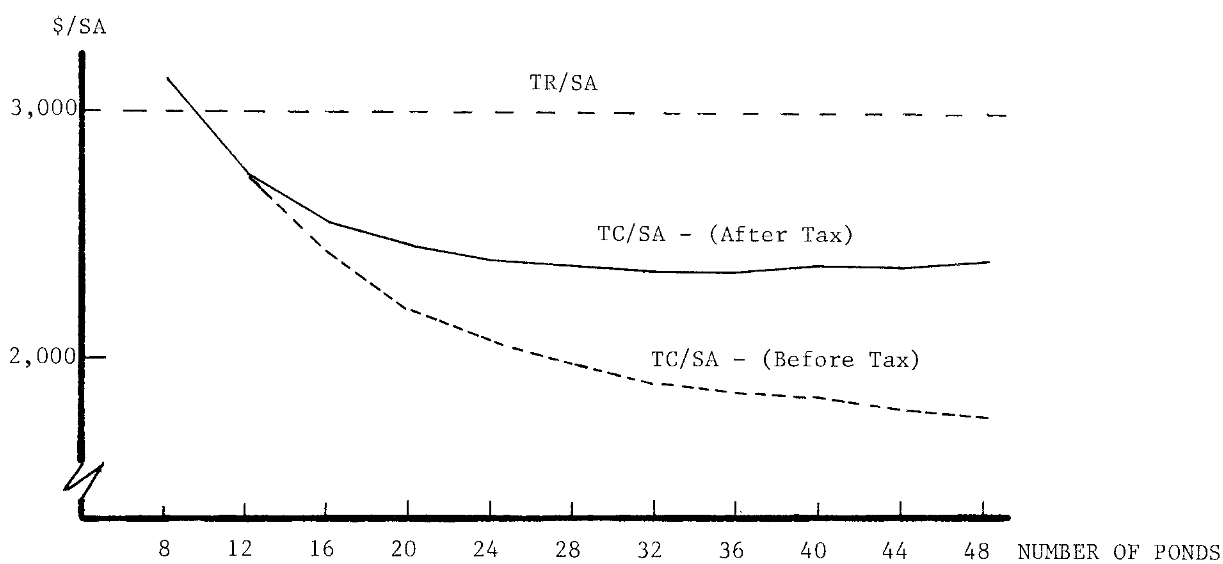


FIGURE 2. ANNUAL "AVERAGE REVENUE" AND LONG-RUN "AVERAGE COST" PER SA BEFORE AND AFTER INCOME TAXES FOR AN OPERATION EMPLOYING 2.5-ACRE PONDS BY NUMBER OF PONDS



available on a before-tax basis. A low risk venture may be extended as far as possible on the long-run average cost curve. The system examined in our study, on the contrary, is a high risk venture. Therefore, one would want to minimize risk yet capture considerable economies of size. Viewing the firm's cost structure on an after-tax basis shows the decision point for capturing most economies of size to be a smaller operation than that indicated with before-tax cost structures. We discuss costs (i.e., total costs per SA — TC/SA) on an after-tax basis, yet recognize the relationships which exists in terms of the long-run average cost curve on a before-tax basis.

INCREMENTING POND SIZE

Figure 1 shows the nature of the before and after tax "long-run" average cost curves (TC/SA) over the pond size range of .5 to 5.0 acres for a 20-pond operation.[4] For any given size of operation, fixed costs (FC) per SA depend on the ratio of SA to total acres (TA) of the operation. This ratio (SA/TA) increases at a decreasing rate as the pond size increases. The TC/SA curve decreases at a decreasing rate in part because of FC. For most machinery and equipment (which includes trucks, tractors, pumps, etc.) costs will decrease per SA as pond size increases. Also land improvement cost per SA decreases because levees, roads, and earthen foundations decrease as a percentage of SA as TA is increased. With total revenue (TR) being linear through the origin, the TR/SA ("average revenue") curve is linear and constant at $3017.

TC/SA decreases rapidly from .5-acres per pond through 1.5-acres per pond. At approximately this point, a break-even situation occurs (TC = TR). At the 2.5-acre pond size, the TC/SA after taxes has decreased to $2446. This value then decreases slightly until a value of $2311 is reached at the 5.0-acre pond size, a decrease of only an addition 4 percent in relation to the overall decline from the .5 to the 2.5-acre pond size in an after-tax situation.

Having estimated the size of the individual pond which captures most economies of size (2.5 acres), we next determine the number of these ponds which achieves most of the economies of size for the firm.

Incrementing Number of 2.5-Acre Ponds

The number of 2.5-acre ponds is increased in the analysis from 8 to 48. In Figure 2 the 24-pond operation (96 total acres) is seen to capture most economies of size in an after-tax situation when 2.5-acre ponds are used. At this point the firm's marginal decrease in TC/SA is nearing zero. Any further addition of 2.5-acre pond units results in a very slight decrease in TC/SA in relation to the decrease in TC/SA prior to the 24-pond operation.

The internal rate of return (IRR) to equity is estimated to be 71 percent for this operation. IRR to total investment is 17 percent and the payback period is two years.[5] This operation does not represent the optimum size, but rather is an estimate of a likely operation size for commercial purposes to minimize investment in a new high risk venture (as noted, the before-tax TC/SA curve is below the after-tax curve).

SENSITIVITY ANALYSIS

The sensitivity analysis examines the change in net revenue per SA (NR/SA) in relation to change in selected variables for the operation design consisting of 24 2.5-acre ponds (60 SA and 96 TA) found to be a likely size of firm. Variables subjected to 10 percent change are: (1) length of grow-out period, (2) size of tails at harvest, (3) total yield/SA, (4) hourly wage for hired labor per hour, (5) price per pound of feed, and (6) price per pound of harvested tails.

Length of grow-out period has the most dramatic effect on NR/SA. A 10 percent increase in length of grow-out period increases NR/SA 17 percent whereas the 10 percent decrease drops NR/SA from its base level of $608 to $53 or 91 percent. The longer grow-out period increases pounds harvested but the size of shrimp does not change enough to increase the price received per pound of tails. However, when the grow-out period is shortened 10 percent, both pounds of output and size are affected.

Ten percent increases in yield, tail size, and price of shrimp all result in an increase in NR/SA of 25 percent. A 10 percent decrease in either yield or price of shrimp results in a decline in NR/SA of approximately 25 percent. However, with respect to tail size, it causes a 57 percent decrease in NR/SA. The decrease in tail size causes a decrease in pounds landed (total number of shrimp held constant) and the resulting smaller shrimp sell for a lower price. Net revenue is rather insensitive to changes in feed and hired labor prices. A 10 percent in-

[4]The number of ponds is set arbitrarily at 20.

[5]Realistically, production will vary from year to year; however, data limitations warranted a typical year being assumed and held constant over the planning horizon. No stochastics have been introduced into production. On the basis of this assumption (i.e., no risk in physical production and the marketplace), we believe that the resulting cost curves and IRR values are valid. It should be noted that an unequal distribution of production over the planning horizon would have resulted in different IRR values.

crease (decrease) in feed and hired labor would cause a 5 and 1 percent increase (decrease), respectively.

CONCLUSIONS

The BEE model developed in our study is capable of integrating biological growth functions with engineering and economic relationships to examine penaeid shrimp mariculture systems through budgeting and cash flow statements. On the basis of costs and returns generated by the model, economies of size are examined by incrementing pond size and then number of ponds for a given facility design. Sensitivity analysis is performed to provide information about the responsiveness of net revenue to change in select production variables and prices.

On the basis of assumptions established and maintained with the framework of the model, large-scale penaeid shrimp maricultural operations of the assumed design and located in the Brazoria County area of Texas could be profitable. An operation containing 96 TA, 60 SA consisting of 24 2.5-acre ponds is estimated to produce an average annual net return of $608 per SA over a 10-year planning horizon. The operation would have an IRR to equity of 71 percent, an IRR to total investment of 17 percent, and a payback period of two years. This production system represents a size of operation that would capture most of the economies of size, and thus establishes a point of reference to potential investors for minimum capital investment.

As revealed by the sensitivity analysis, a much better understanding of the influencing factors involved and their control is of utmost importance. The sensitivity analysis suggests that the crux of future research should be understanding factors influencing production consistency (total yield and tail size for a given stocking density and grow-out period) and accurately predicting and manipulating these factors within a certain degree of confidence to achieve control over production.

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