3b2 Version Number : 7.51c/W (Jun 11 2001)
File path : p:/Santype/Journals/TandF_Production/Uaqm/v15n3/UAQM598213/uaqm598213.3d
Date and Time : 20/07/11 and 17:32

Aquaculture Economics & Management, 15:1–27, 2011

ISSN: 1365-7305 print/1551-8663 online
DOI: 10.1080/13657305.2011.598213

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THE ECONOMICS OF SMALL-SCALE SOFT SHELL CRAYFISH PRODUCTION

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☐ *A soft shell crayfish operation consists of an indoor molting system for immature crayfish. The molted crayfish could be sold as food or bait. Such systems have been operated on a small-scale in Kentucky and neighboring states, although traditionally the industry has been centered in Louisiana. This article investigated profit-maximizing management conditions and economic feasibility of a small-scale soft shell crayfish operation. Results showed that a minimum facility size of 25–30 culture trays was essential for realizing a profit by selling product to bait shops. This facility size was also amenable to be operated by two full-time workers, making family-run enterprises a strong possibility. Other results showed that larger facilities, with more than 50 culture trays, were necessary to reduce the minimum equity in fixed investment to be less than 70%. Direct marketing at retail prices is often the only profitable option for small-scale aquaculture; this article gives an example of a small-scale aquaculture operation that can simultaneously supply different markets at a profit.*

Keywords crayfish, feasibility analysis, linear programming, soft shell

INTRODUCTION

The aquaculture industry in Kentucky continues to be driven by the production and marketing of products that are not readily available through traditional marketing channels such as food service distributors, fish/crustacean live-haulers, and bait distributors. Because Kentucky and surrounding states have mostly small-scale aquaculture farms, receiving premium prices for unique products is essential for their profitability. Soft shell crayfish is an example of a unique product that can be produced at a small scale. Immature hard-shell crayfish of length around 7.5 cm (for *Procambarus clarkii*) are placed in shallow culture trays and fed until they molt, usually in two weeks (Culley & Duobinis-Gray, 1990). The molted

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crayfish are typically frozen and marketed as either a food item of as bait for sport fishing.

The soft shell crayfish industry in the United States has been mostly centered in Louisiana. Huner (1999) reported two soft shell crayfish associations based in Louisiana during 1987–88 with 150 known producers. He indicated that there was a "gold rush" of soft shell crayfish production in Louisiana fueled by output prices of around $17.6/kg ($8/lb) and breakeven cost of approximately $11/kg ($5/lb). However, the number of producers had rapidly fallen in Louisiana because many had higher than $11/kg production costs, and this enterprise demanded a very high labor investment, which many producers were not able to supply. Brown (1993) discussed the feasibility of having a soft shell crayfish industry using native crayfish from the Midwestern states. Kentucky had soft shell crayfish producers in recent years that used the native crayfish, and their product was sold as both food and bait.

This article investigated the economics and management of soft shell crayfish operations in Kentucky using the *Procambarus clarkii* crayfish. Although other research had investigated the economics of soft shell crayfish production (Caffey, 1988), this article is unique in that the economic results are provided for various facility sizes, in conjunction with current marketing data for soft shell crayfish from Kentucky.

Unlike Caffey (1988), this article investigated the suitability of operating a soft shell crayfish farm as a small-scale enterprise using family labor, whenever appropriate. This is important for Kentucky and neighboring states where most producers rely on equity financing, family labor, and local markets for success in their aquaculture projects. Using soft shell crayfish production technology developed in Louisiana, this article developed a linear programming model that identified various profit-maximizing strategies. This article also contains an economic feasibility analysis and addresses sensitivity of economic and management parameters to various sources of risk. Facility sizes from 1 to 70 culture trays of crayfish were evaluated. Producer data showed it to be unlikely to have more than 70 culture trays in one facility because of labor, input volume, financial, and market demand restrictions.

RELEVANT LITERATURE

The literature on the economics and management of soft shell crayfish production is sparse. Of the few examples available, Caffey (1988) had a detailed exposition of the economics of soft shell crayfish production in Louisiana during the late 1980s and 1990s. They adopted the "Culley method" for soft shell crayfish production, which could be summarized as: (1) immature hard shell crayfish were stocked in shallow culture trays in water and fed until they showed signs of molting; (2) such crayfish, called pre-molts, were moved to trays containing only molting crayfish (aka molting trays); and, (3) the molted crayfish were frozen for future sales.

Caffey (1988) investigated a 40-tray system that would have heated water circulated in a flow-through system, from an external source (e.g., pond or well), or in an indoor recirculating system that allowed more efficient energy use. Caffey (1988) indicated an initial investment of $13,254 (1988 U.S. dollars) was necessary for a 40-tray flow-through system. The corresponding investment for the recirculating system was $15,066, a 13% increase. However, it was less expensive to operate the recirculating system; the annual operating costs were $19,916 and $14,596 for the flow-through and recirculating system, respectively. These costs led to breakeven prices of soft shell crayfish to be $13.42/kg ($6.10/lb) and $11.04/kg ($5.02/lb), when the plant was operating at 100% capacity, under the flow-through and recirculating systems, respectively. The projected annual production was 1,964 kg (4,320 lb) under both management systems, with the plant operating at 100% capacity.

Brown (1993) investigated the potential of having a soft shell crayfish industry in mid-western states such as Indiana. This article indicated that Louisiana, Texas, and Arkansas were the primary producers of soft shell crayfish in the late 1980s and 1990s. If native midwestern crayfish (e.g., *Orconectes viriles*) were used, instead of the *Procambarus clarkii* crayfish, Brown (1993) postulated that Indiana could have a season that is offset from the times when fresh soft shell crayfish were available from the southern states. Brown (1993) reported successful molting of *Orconectes viriles* was optimal at lower water temperatures (20°C or 68°F), and 64% of the stocked crayfish molted within the first 10 days.

Culley and Duobinis-Gray (1987) published important research results regarding soft shell crayfish production management. This article indicated results from two crayfish molting studies. In the first study, molting and mortality patterns for commercial-scale soft shell crayfish systems over a 17-week molting cycle were quantified. This data were used in this article to characterize crayfish molting behavior. In the second study, the effects of various stocking densities of hard shell crayfish in culture trays on molting rates and mortalities were investigated. Three stocking densities 3.7 kg/m^2 (0.75 lb/ft^2), 4.9 kg/m^2 (1.00 lb/ft^2), and 6.1 kg/m^2 (1.25 lb/ft^2) were investigated. There were no statistically significant differences in the average daily molting rate for the medium and high stocking densities, but the average daily molting rate for the low stocking density was significantly smaller than the others. These results were also consistent for mortality rate of crayfish.

Huner (1999) discussed the history of Louisiana's soft shell crayfish industry. He reported that in the late 1980s soft shell crayfish culture in

Louisiana was popular with 150 known producers. This was primarily because of the reported soft shell crayfish price of $17.60/kg ($8/lb) and the average breakeven price of $12.10/kg ($5.50/lb). However, by the late 1990s there were fewer than a dozen soft shell crayfish producers in Louisiana because the market price for the product eventually settled to $13.20/kg ($6/lb), which was below breakeven price for most producers.

Huner (1999) discussed two production methods, the Culley Method and the Bodker Method. The Culley Method was based on the operator actively selecting pre-molt crayfish from culture trays and transferring them to molting trays. The Bodker Method had a self-segregation technique for separating pre-molts from other crayfish by having the culture trays with shallow and deep ends; pre-molt crayfish had a tendency to move to the shallow end of the trays where they could be scooped out by the operator. The Culley Method, reported as the industry standard, was adopted in this article. Huner (1999) reported that most immature crayfish molted within 5–10 days of stocking, and since crayfish mostly molted during daylight, very little night work was needed; this made soft shell crayfish production amenable to being a family operation.

Ogunsanya and Dasgupta (2009), Bussen and Dasgupta (2010), and Probst and Dasgupta (2010) discussed the marketing of crayfish in Kentucky. Ogunsanya and Dasgupta (2009) surveyed 94 bait shops in Kentucky, with a 50% response rate. Nine percent of respondents indicated that frozen crayfish was a regular sales item. Of these retailers, 81% sold crayfish that were 12.7 cm (5 inches) or smaller. Bussen and Dasgupta (2010) conducted a more detailed survey of 58 Kentucky bait shops. They discovered that 53% of respondents were interested in selling either soft shell or hard-shell crayfish, while 43% of bait shops were specifically interested in soft shell crayfish.

The average demand for soft shell crayfish was 14 dozen/week/shop over a spring-to-fall sport fishing season. Bait shops were willing to purchase frozen crayfish at an average price of $5.65/dozen. Probst and Dasgupta (2010) did a preliminary survey of restaurants in Lexington and Lousiville, Kentucky, and a specialty seafood retailer in Louisville, Kentucky. They provided each respondent with samples of Kentucky-produced soft shell crayfish, followed by an interview after a one-week product trial period. They discovered that the product received strong approval ratings by the respondents, with a stated willingness to pay $8–$12/dozen for frozen soft shell crayfish.

The aquaculture economics literature has other examples of economic feasibility analyses of small-scale aquaculture enterprises. Rao and Kumar (2008) investigated the economic feasibility of land-based production of marine pearls. Their article presented a non-traditional method of marine pearl culture. Data were obtained from a series of experimental results associated with hatchery, nursery, growout, feeding, harvesting, pearl size, pearl quality, and the duration of production. Rao and Kumar (2008)'s analytical methods differed from this article because they depended upon an enterprise budget and financial statement/financial ratios to evaluate the economic feasibility criteria. In our article, we developed a mathematical model to evaluate the best management practices under various resource and financial scenarios.

Another example of economic feasibility analysis is Fong et al. (2005), who investigated small-scale pearl oyster production in the central Pacific. Data for this study came from detailed interviews with two farm managers. They used enterprise budgets and financial statements to provide financial projections of this enterprise. Their results contained explicit analyses regarding capital investment, operating costs, profitability of a base model, and sensitivity analyses in which they considered the effects of varying output price, mortality, operating costs, and the percentage of equity on economic parameters.

Dey et al. (2005) took a similar approach to evaluate the economic viability of the polyculture potential of fish in flooded rice fields in Bangladesh and Vietnam. Data were obtained from observations during on-field trials at various sites in these two countries from 1998–2000. These observations included various biophysical, agricultural, and socioeconomic parameters, which were used to calculate yields and net returns from each experimental site. The results showed that the polyculture technologies added income to rural communities from fish production, without reducing any income from their traditional rice cultivation.

SOFT SHELL CRAYFISH PRODUCTION DESCRIPTION

Culley and Duobinis-Gray's (1990) exposition of a soft shell crayfish operation is adopted in this article because this technique is reported to be the "industry standard" (Huner, 1999). This production system consists of stocking immature hard shell crayfish (called inter-molts, of average weight 15 g) in culture trays under 10 cm of water at 24–27°C, and fed until they show signs of imminent molting (such crayfish are called pre-molts). Pre-molt crayfish can be recognized by a darkening of their outer shell and the shell becomes loose, i.e., when their abdomen is squeezed, there is usually a significant "give." Pre-molts usually stop eating, and are transferred to molting trays where they are allowed to molt within 24–48 hours and then are quickly frozen for future sales. Most inter-molt crayfish molt within two weeks of stocking in culture trays. Typically molting trays are 10% of the number of culture trays (Culley & Duobinis-Gray, 1990).

Soft shell crayfish farming in Kentucky starts during early summer. This is due to the availability of immature hard-shell crayfish in May, which rapidly declines until they are unavailable after 12 weeks. Immature crayfish are essential because they molt rapidly. Soft shell crayfish operations earlier than May must be accompanied by prohibitively costly heating because of low water temperatures during spring months in Kentucky. However, Kentucky water temperatures from June to August are high enough to permit normal molting, although the water needs heating during May, which is done by ambient heat from propane heaters in a greenhouse that keeps the indoor temperature at a consistent 27°C (80°F).

Facilities for a soft shell crayfish operation consist of a heated greenhouse with a large number of shallow 2.44 m × 1.22 m (8 ft × 4 ft) trays that are 15.24 cm (6 inches) deep (Fig. 1). Although trays could be made from many materials, some producers indicated that they built their own trays using pressure-treated lumber and pond liner material. This is feasible

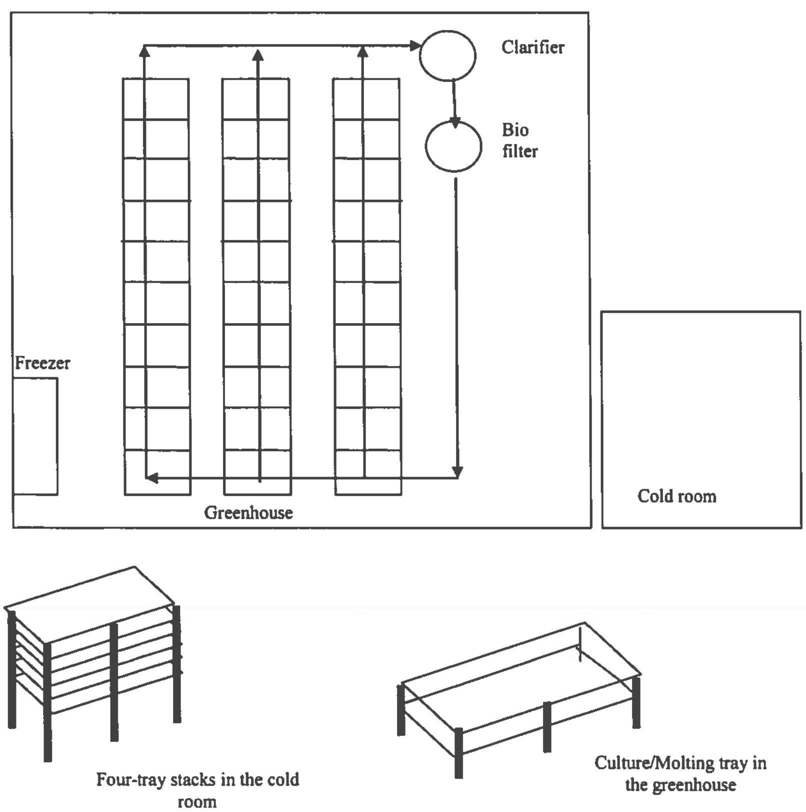

FIGURE 1 Schematic diagram of a soft shell crayfish production facility.

because the water at 25°C, held at a 10.16 cm depth in a tray with a surface area of 2.79 m^2, exerted a pressure of less than 103 kg/m^2 (21 lb/sqft), which is within the load-bearing capacity of a wooden tray with heavy lumber supports.

We assumed that water is circulated in the trays in a closed recirculating system with a biological filter. Recirculating systems allow for easier water temperature regulation than other water circulation systems. The recirculating system plumbs all trays to a clarifier and a bio filter via a water pump. The water is aerated in the biofilter using an air blower. The size of biofilter and water pump depended upon the total number of trays in the greenhouse.

As crayfish molt and/or die, they are replaced daily by other hard-shell crayfish. Since hard-shell crayfish cannot be procured daily there needs to be an inventory of hard-shell crayfish kept conveniently close. This is done by holding crayfish in a "cold room" which is a small insulated structure built next to the greenhouse in which the temperature is kept below 10°C (50°F) using an air conditioner. In this room hard-shell crayfish are held in 2.44 m × 1.22 m (8 ft × 4 ft) trays at a stocking density of 430/m^2 (40/sq ft) (Culley & Duobinis-Gray, 1987). The trays are stacked four on top of each other (Fig. 1). Crayfish in this room are cold enough to be in a temperature-induced quiescence; however, small amounts of feed are given for maintenance and there is a bio-filtration and ultra-violet sterilization system to maintain water quality.

Because crayfish replacement is done on the basis of daily mortalities and molts, our data indicated that a maximum of 4.94% of the total number of hard shells in the culture trays need to be replaced daily. Although this figure represents a maximum daily replacement rate, it also helps in determining the size of the cold room. Because hard-shell crayfish in Kentucky can be procured weekly, the daily replacement rate projected the inventory volume, large enough to supply two weeks worth of replacements. This inventory volume was calculated to be 69% of the total volume of crayfish held in the culture trays.

DATA

Data were obtained from a variety of sources (Table 1). Most data related to soft shell crayfish management were obtained from Culley and Duobinis-Gray (1987, 1990). These data include stocking densities, feeding rates, molting rates, survival rates, and water quality parameters. Average stocking density was 4.9 kg/m^2 (Culley & Duobinis-Gray, 1987) in the greenhouse and the cold room. Feeding rate of crayfish was, on average 1% of body weight per day (Culley & Duobinis-Gray, 1987), under the

TABLE 1 Summary Data of Production and Economic Parameters Relevant to a Small-Scale Soft Shell Crayfish Operation

Parameter Description	Value
Average weight of hard shell crayfish[a]	15 g
Stocking density of hard shell crayfish[b]	4.9 kg/m^2
Tray area[a]	2.98 m^2
Average daily survival rate in greenhouse[a]	99.65%
Average daily survival rate in cold room[a]	98.65%
Average soft shell crayfish demand per bait shop[c]	14 doz/week
Average price of soft shell crayfish[c]	$5.65/doz
Average price of hard shell crayfish[c]	$3.30/kg
Average feed price	$311/MT
Average electricity price[d]	$0.075/KWH
Average wage rate[d]	$7.25/hour
Average propane price[d]	$0.60/lt
Average gasoline price[d]	$0.66/lt

[a]Data obtained by interviews with soft shell crayfish producers in Kentucky.
[b]From Culley and Duobinis-Gray (1987, 1990).
[c]From Bussen and Dasgupta (2010).
[d]Values based on recent average prices from Kentucky.

assumption that the average weight of crayfish was 15 g. Data on crayfish molting rates in trays were available in Culley and Duobinis-Gray (1987) (Fig. 2).

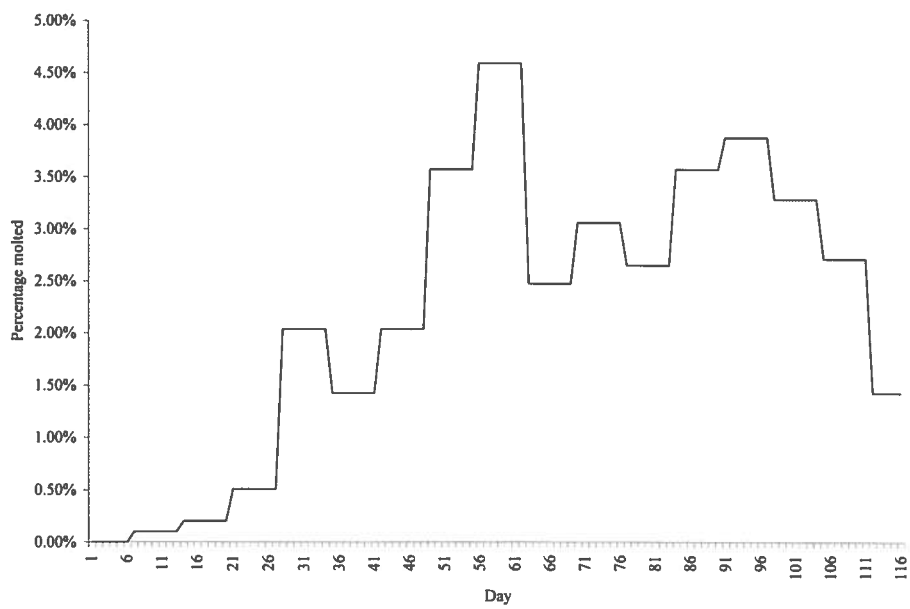

FIGURE 2 Molting rate of immature Procambarus clakii crayfish in trays. Data obtained from (Culley & Duobinis-Gray, 1987) (color figure available online).

Although the data from Culley and Duobinis-Gray (1987, 1990) were not recent, the biological information represented in the molting and mortality data remain valid. In addition, these data provided comprehensive information about a crayfish molting system that is considered to be an industry standard. There has been no literature containing molting data under soft shell crayfish production conditions since Culley and Duobinis-Gray (1987, 1990); however, Bussen and Dasgupta (2010) reported results of a soft shell crayfish production demonstration where hard-shell crayfish (average weight 14 g) were stocked, fed, and molted following the methods outlined in Culley and Duobinis-Gray (1987, 1990).

Hard-shell crayfish were stocked in three shallow trays plumbed via a recirculating system and cultured from July 1st to August 2nd 2009. Their results showed a 52% molting rate, a 40% survival rate, and the remaining 8% of hard shell crayfish remained as inter-molts. Most crayfish molted during the two weeks from June 17th to June 29th, which corroborated Culley and Duobinis-Gray (1987 and 1990), i.e., crayfish need a few days' acclimatization and growth prior to molting, and most crayfish molt in a singular window of time towards the end of the production cycle (Fig. 2).

Facility design data came from Caffey (1988), Culley and Duobinis-Gray (1990), and interviews with soft shell crayfish producers in Kentucky and Indiana. These data indicated that basic needs were an enclosed heated greenhouse containing rows of culture and molting trays and a small insulated air-conditioned room suitable for maintaining an inventory of live hard shell crayfish (called the "cold room"). Figure 1 is a schematic of such a facility and Table 2 contains a list of land, building, and equipment needs, and associated fixed costs, for a hypothetical 28-culture tray operation. Greenhouse and cold room construction costs were derived from interviews with local contractors.

All input and output price data were reported in 2010 U.S. dollars. Input price data came from current prices of hard-shell crayfish from live haul suppliers that provide crayfish in Kentucky, feed prices available from regional aquaculture feed mills, equipment costs from nation-wide aquaculture equipment suppliers, and recent labor and energy costs from Kentucky.

Soft shell crayfish are sold as bait and food in Kentucky. Marketing data were obtained from a 2009 survey of Kentucky bait shops (Bussen & Dasgupta, 2010) that discovered a strong demand for soft shell crayfish. The average price paid by bait shops was $5.65/dozen. Bussen and Dasgupta (2010) also reported an average weekly demand of 14 dozen soft shell crayfish among bait shops in Kentucky. Soft shell crayfish producers sell product throughout the entire 17-week production cycle. Due to seasonality of molting rates (Fig. 2), soft shell crayfish operations have a dearth

TABLE 2 Summary Data of Facility and Equipment Needed for a Hypothetical 28-Culture Tray Small-Scale Soft Shell Crayfish Operation

Item	Lifespan (Years)	Initial Cost	Annual Depreciation[a]	Annual Interest Forgone[b]
0.10 ha of land		$250.00		$20.00
192 m^2 greenhouse	20	$18,848.00	$462.00	$1,108.80
27 m^2 insulated cold room	20	$2,904.72	$72.62	$174.28
31 culture and molting trays	10	$3,100.00	$310.00	$124.00
5 stacked trays[c] for cold room	10	$2,500.00	$250.00	$100.00
Plumbing for trays	10	$1,481.40	$148.14	$59.26
Bio filter	20	$1,191.00	$59.55	$47.64
2 UV-sterilization systems ($887 for greenhouse, $546 for cold room)	10	$1,433.00	$143.30	$57.32
Air blower for aeration	10	$200.00	$20.00	$8.00
3 water pumps (electric) (greenhouse, cold room, and backup pump)	10	$1,444.00	$144.40	$57.76
5-hp gasoline pump	10	$540.00	$54.00	$21.60
Gasoline generator	10	$500.00	$50.00	$20.00
Pickup truck	20	$3,124.50	$156.23	$124.98
Chest freezer	10	$420.00	$42.00	$16.80
Propane heater	10	$300.00	$30.00	$12.00
Air conditioner	10	$300.00	$30.00	$12.00
Total		$38,536.62	$1,972.24	$1,964.44
Miscellaneous fixed cost[d]				$100.00
Propane tank rent				$35.00
Annual property taxes[e]				$22.85
Total annual fixed costs				$4,094.53

[a]Annual depreciation is calculated by the straight line method, annual interest is calculated based on average investment (Kay & Edwards, 1999). Salvage value is $0 in most cases.

[b]Annual interest rate = 8%, based upon the opportunity cost of investment.

[c]A stacked tray consists of 4 trays stacked vertically in a shelf system, as shown in Figure 1.

[d]This includes the costs of 208 lt plastic trash cans to be used as acclimation tanks, clarifiers and bio filters in the cold room, polyfill material, bio balls, dip nets, PVC cements, chemicals, and other small supplies.

[e]Property taxes were charged at current rates in Kentucky for agricultural land, i.e., $0.122 per $100 property value.

All prices are in 2010 U.S. dollars.

of product in May. Bait shops usually cooperate with producers because soft shell crayfish supplies are limited in Kentucky and the product is excellent fish bait (Bussen & Dasgupta, 2010).

Additional marketing data were provided by Probst and Dasgupta (2010) who did a preliminary survey of restaurants in Lexington and Louisville, Kentucky, and found a strong liking for soft shell crayfish among chefs, with a stated willingness to pay of at least $8/dozen. This market requires further characterization and is not as well developed as the bait shop market. Hence, most of the analyses in this article used the bait market as the only outlet available to soft shell crayfish producers.

MODEL DESCRIPTION

The economics and management of soft shell crayfish operations was analyzed via a linear programming (LP) model. The model represented a 17-week production cycle, adopted from Culley and Duobinis-Gray (1987). It was assumed that the owner-operator purchased all the hard-shell crayfish, although the model could be applied to scenarios where growers harvested their own hard-shell crayfish. The model's exposition is mostly descriptive; a detailed mathematical model is presented in the Appendix.

An LP model has three components: decision variables, objective function, and constraints. Decision variables are under control of producers and affect production and profits. The decision variables in our model were (1) facility size, expressed by the number of culture trays (denoted "TrayNum"), (2) amount of hard shell crayfish procured on a weekly basis (denoted "HS(τ)", where τ is a week index, varying from week 1 to week 12), (3) the number of hard-shell crayfish stocked as replacements in culture trays (denoted "N(t)", where t represented a production day), and, (4) the total number of hard shell crayfish stocked in culture trays (denoted "THS(t)", where t represented a production day).

The model selects values of the decision variables in order to maximize profit (objective function) subject to the constraints placed upon values of the decision variables due to resource and marketing restrictions, and production sequencing activities. Profit is the difference of revenue from the sum of variable and fixed costs. Revenue is the product of total output and price of soft shell crayfish. Total output is the product of the total amount of hard shell crayfish (THS (t)) and the daily molting rate (Fig. 2), summed over each day in the 17-week production cycle. Costs of stocking, feeding, electricity, gasoline, propane, labor and management, ice, packaging, telephone, maintenance, and legal fees are collectively the variable costs. Although details are in the Appendix, brief explanations of these costs are provided next.

Stocking cost was the product of hard-shell crayfish price and the total volume of hard shell crayfish procured, as shown in Appendix equation (A1). Daily feeding rate was 1% of body weight (Culley & Duobinis-Gray, 1987), and the feeding cost is given by the product of the feed price and the total amount of feed used, as shown in Appendix equation (A2). Fuel and energy costs included expenses due to electricity, gasoline, and propane use. Gasoline was used for a pickup truck delivering product to buyers and supplies from local farm supply/hardware stores. Based on interviews with producers, we assumed that most operators drove no more than 48 km per week to deliver product. Gasoline was used to pump water from a stream into the greenhouse and the cold room (typical of Kentucky's aquaculture farms), and the fuel was needed for a standby generator.

Propane was used to heat the greenhouse during May. By keeping the indoor ambient air temperature during night and early mornings at 27°C (80°F), the water in the trays remained sufficiently warm to encourage crayfish to feed and molt. Propane use was calculated using Ross (1992), which showed that heating requirement of greenhouses was determined by the surface area of the greenhouse, the temperature difference between the outside and inside air, and a heat loss factor, as explained in the Appendix equation (A4).

Electricity was used to operate water pumps, an air blower, ultraviolet (UV) sterilization systems, an air conditioner in the cold room, and lights. Two water pumps circulated water in the greenhouse and the cold storage room, respectively. The electrical load of water pump depended upon maintaining proper flow rate (determined by the entire volume of water in trays circulating in one hour), which increased with the number of trays. Appendix equation (A3) outlines the electricity cost.

Labor and management costs were charged at a current minimum wage rate. Labor hours were calculated by assuming that the operator spent 0.5/day/tray to feed crayfish, check for pre molts, and freeze molted crayfish. In addition, 5.5 hours/week was devoted to other tasks, such as cleaning, maintenance, purchasing feed and supplies, and transporting soft shell crayfish to local buyers. These costs appear in Appendix equation (A5).

Annual maintenance costs were charged at the rate of 2% of original value of equipment needing maintenance. Other operating costs included telephone ($10/month), legal fees (a $50/year propagation permit), and packaging ($0.10/zipper-type bags containing one dozen soft shell crayfish per bag).

Fixed costs included depreciation and forgone interest associated with investment in land, buildings, and equipment (Appendix). Other fixed costs included annual rent for a propane tank, property taxes, and a $100 miscellaneous fixed cost for items such as gloves, 208 lt. plastic trash cans, dip nets, polyfill material, bioballs, PVC cement, etc.

The above exposition makes it clear that profit depends upon the values of the decision variables. However, decision variable values are constrained by resource availability and production sequencing issues. Although mathematical details of constraints are in the Appendix, a descriptive presentation of the decision variable constraints is provided below.

Facility size (i.e., TrayNum) is dependent on resources such as labor and market demand. Soft shell crayfish management requires labor trained in choosing pre-molt crayfish from inter-molt crayfish. Consequently, many producers use only family labor, because family members could provide reliable labor year after year, while part-time laborers might leave the region requiring managers to re-train new hires, and family labor helps with cash flow because it is easier to "make the payroll" with family labor, i.e., wages can be more easily deferred to the end of the season and all income attributed to labor stay within the family. Labor requirements were outlined above and the relation with facility size and labor resources is mathematically represented in Appendix equation (A5).

Examples of production sequencing constraints include the dependence of the number of crayfish stocked in day 1 (i.e., $N(t=1)$) on the number of culture trays, size of culture trays (a pre-determined parameter) and the stocking density (pre-determined parameter), as shown in Appendix equation (A10). In subsequent days (i.e., $t > 1$), the number of replacement crayfish per day were related to the number of crayfish that have died or molted the day before, as shown in Appendix equation (A11).

A set production sequencing constraints related the amount of hard shell crayfish procured per week ($HS(\tau)$) to the amount of crayfish initially stocked in trays and replaced during the production season (represented by $N(t)$). The procurement of hard shell crayfish is complicated by the need to have an inventory because these crayfish were available infrequently. Hence $HS(\tau)$ must exceed the need for replacements because some of mortality of the hard shell crayfish held in storage. Appendix equation (A12) expresses $HS(\tau)$ in terms of the demand for replacement animals (indicated by $N(t)$) and mortality during holding (indicated by DSRCT).

RESULTS

Base Scenario Results

A 28-culture tray operation was selected as the base scenario because the corresponding labor and management requirements could be supplied by two full-time workers over a 17-week production cycle, which was feasible for most family-labor situations. Table 2 delineates the fixed investments associated with such an operation. Construction costs for the greenhouse and cold room were significant: Table 2 indicates that construction cost was 56% of total fixed investment. In contrast, total equipment cost was 43% of total fixed investment.

Table 3 outlines the variable costs associated with a 28-culture tray system. Labor and management cost accounted for 64% of total variable cost indicates the importance of labor in soft shell crayfish operations. Hard-shell crayfish was the next costly item accounting for 17% of the total variable cost. The average production from the 28-culture tray system was 4,650 dozens of soft shell crayfish, leading to a projected breakeven price of \$5.56/dozen. Bussen and Dasgupta (2010) reported an average price of \$5.65/dozen for frozen crayfish paid by bait shops in Kentucky. Hence,

TABLE 3 Variable Costs per Season for a Hypothetical 28-Culture Tray Small-Scale Soft Shell Crayfish Operation

Item	Quantity	Unit	Price	Total
Hard-shell crayfish	1,114.00	Kg	$3.30	$3,677.35
Feed	383.75	Kg	$0.31	$119.00
Labor and management	1,904.00	Man hours	$7.25	$13,804.00
Electricity	7,427.04	KWH	$0.075	$599.28
Gasoline	2,041.84	Liters	$0.66	$1,350.42
Propane	733.62	Liters	$0.60	$436.68
Maintenance[a]				$300.43
Packaging[b]	4,594	Bags	$0.10	$459.40
Telephone	5	Months	$10.00	$50.00
Legal fees	1	Permit	$50.00	$50.00
Total variable costs				$20,846.56
Interest on variable costs[c]				$687.94
Total				$21,534.50

[a]Maintenance is charged annually at 2% the value of buildings, trays, and equipment.
[b]Packaging includes the cost of zipper-type bags contain one dozen soft shell crayfish per bag. The 28-culture tray system produces, on average, 4,650 dozen soft shell crayfish per season.
[c]Calculated using an 8% annual rate, charged to 5 months' operation.
Rounding errors account for discrepancies between the product of quantity and price from the corresponding cost. All prices are in 2010 U.S. dollars.

the projected annual profit for a 28-culture tray system was $419. Although the profit is modest, one must consider that the scenario requires a 2-person labor and management team, which, in case of family labor, will cause the farm family to receive additionally an average of $2,792 per month over a 5-month period.

Effects of Facility Size

The LP model allowed selection of the optimal size of a soft shell crayfish operation based on resource and market limitations. We assumed that operators would consider their labor, financial, and marketing situation prior to determining a facility size. Although facilities could be expanded in the future as more resources and markets become available, from the perspective of this article, it would be more useful to provide results that assist producers to choose a size that is best suited to their current and expected future situation.

Operation size was expressed by the number of culture trays and depended upon a number of factors, such as the availability of labor, financing, and markets. Figure 3 illustrates the effect of increasing number of culture trays on output, input use, and the corresponding breakeven price. If the product were sold as bait at $5.65/dozen (Bussen and Dasgupta 2010), a minimum facility size of 25 culture trays was essential.

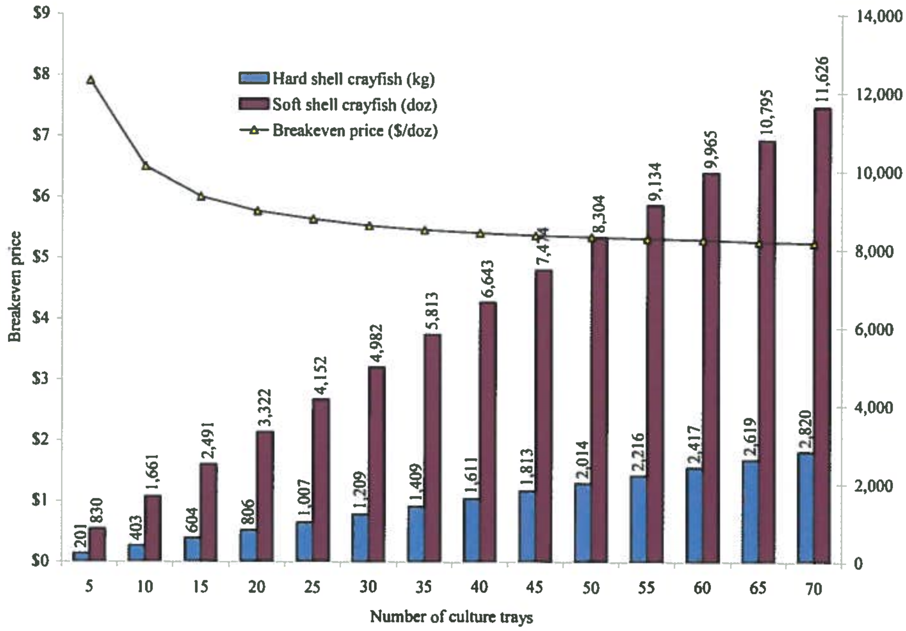

FIGURE 3 Effect of increasing facility size on amount of hard shell crayfish used (kg), amount of soft shell crayfish produced (dozens), and breakeven price ($/dozen) (color figure available online).

Table 4 indicates the optimal size for various levels of labor and management availability. Three labor scenarios were investigated: average labor supply of either 8 man-hours/day, 16 man-hours/day, or 24 man-hours/day, over the entire season. These labor levels were chosen to represent limited availability of family labor. Table 4 shows that at the lowest labor availability, only a 13-culture tray system could be managed and the projected breakeven price of soft shell crayfish exceeded $6/dozen, making the product too expensive to be sold to bait shops in Kentucky (Bussen & Dasgupta, 2010).

TABLE 4 Production and Economic Parameters Associated with a Soft Shell Crayfish Operation under Labor Constraints

Available Labor[a]	Culture Trays	Hard-Shell Crayfish Used (kg)	Soft Shell Crayfish Produced (doz)	Breakeven Price ($/doz)	Total Variable Cost[b]
8 hr/day	13	528	2,178	$6.13	$10,482
16 hr/day	28	1,114	4,594	$5.56	$20,847
24 hr/day	42	1,700	7,010	$5.39	$31,192

[a]Refers to the average labor use on a per day basis for the entire 17-week season.

[b]Excludes the interest forgone on variable costs. Labor and management costs were 65% of total variable costs.

All prices are in 2010 U.S. dollars.

TABLE 5 Production and Economic Parameters Associated with a Soft Shell Crayfish Operation under Labor Constraints

Bait Shops Supplied[a]	Culture Trays	Hard-Shell Crayfish Used (kg)	Soft Shell Crayfish Produced (doz)	Breakeven Price ($/doz)	Labor[b] (Man-hr/day)
5	7	289	1,190	$7.01[c]	5
10	14	577	2,380	$6.03[c]	9
15	21	866	3,570	$5.71[c]	13
17	24	981	4,046	$5.62	14
20	29	1,155	4,760	$5.55	17
25[d]	36	1,443	5,950	$5.45	21

[a]Bussen and Dasgupta (2010) reported average demand for soft shell crayfish by Kentucky bait shops to be 14 dozen/week.

[b]Refers to the average labor use on a per day basis for the entire 17-week season.

[c]Unprofitable scenario, because the breakeven price exceeds the average price paid by bait shops (i.e., $5.65/dozen).

[d]Bussen and Dasgupta (2010) reported 25 bait shops were interested to purchase soft shell crayfish for Kentucky producers.All prices are in 2010 U.S. dollars.

A 28-culture tray operation, requiring an average of 16 man-hours/day of labor and management, allowed the breakeven price to be sufficiently low for the product to be profitable if sold to bait shops. Hence, if the scale of operations was defined by the availability of only one full-time worker, one should not plan to sell soft shell crayfish to bait shops. In such cases, restaurants (Probst & Dasgupta, 2010) or bait sold directly to sport fishers at retail prices could be the only viable options.

Small-scale producers in Kentucky usually sell product in their county and surrounding counties, which means that limited product demand can determine facility size. Table 5 projects the size of a soft shell crayfish operation that is optimal for supplying a certain number of bait shops. The results indicate the breakeven prices all exceeded $5.65/dozen, unless at least 17 bait shops were supplied. Bussen and Dasgupta (2010) surveyed 58 Kentucky bait shops, out of which 25 were strongly in favor of purchasing soft shell crayfish from local suppliers. Table 5 indicates that a 36-culture tray facility size was necessary to supply 25 bait shops, resulting in a profit margin of $0.20/dozen for selling 5,950 dozen soft shell crayfish.

Economic Feasibility Results

Soft shell crayfish production is an expensive proposal: Figure 4 shows the initial startup costs with increasing number of culture trays. Figure 4 also provides measures of economic feasibility, such as an internal rate of return and the estimated payback period (in years), with increasing number of culture trays.

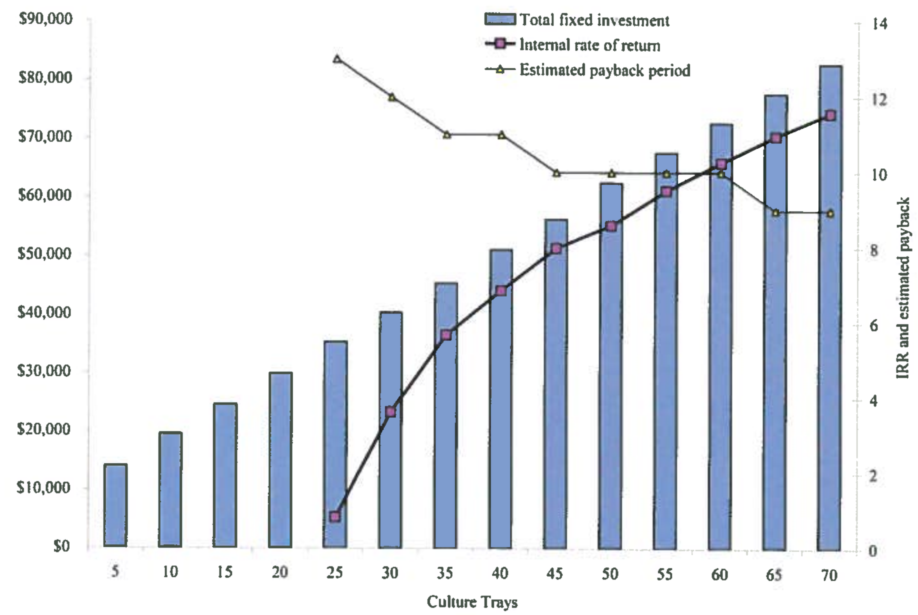

FIGURE 4 Effect of increasing facility size on the total fixed investment, a 20-year internal rate of return, and the expected payback period (years) for a soft shell crayfish operation (color figure available online).

The high startup costs imply that many farmers will not be able to enter the industry unless they receive external financing. Banks willing to lend money for aquaculture will typically do so only if the borrowers provide a certain percentage equity, which can vary depending upon the income potential and risk associated with the enterprise. The percentage of equity can be calculated by comparing the annual amortized payments for a bank loan with business' repayment capability, as measured by the annual economic and accounting profit. Table 6 indicates that minimum equity that producers must have to be able to afford to pay back a loan for the fixed investment. As expected, the minimum equity levels decreased when considering accounting profit and as the facility size grew. Table 6 shows that, using economic profit as the method of payback, the minimum equity exceeds 60%, which is similar to the current requirement for banks lending to catfish producers in the U.S. south (Engle, personal communication).

Comparing the economic performance of the current enterprise with alternative enterprises is important for an economic feasibility analysis. Soft shell crayfish production is a summertime activity, intended for local sales. Hence, alternative enterprises should have similar attributes. In Kentucky and the neighboring region, producers have the option of freshwater prawn aquaculture, which is a small-scale summertime enterprise supplying local markets (Dasgupta, 2005). An economic comparison of freshwater

TABLE 6 Effect of Facility Size on the Minimum Equity Needed to Secure a Loan for Investing in Land, Buildings, and Equipment

Culture Trays	Fixed Investment	Economic Profit	Accounting Profit	Minimum Equity[a]
30	$40,354	$622	$3,437	90%, 41%
35	$45,392	$1,151	$4,361	83%, 35%
40	$51,107	$1,596	$5,288	79%, 30%
45	$56,336	$2,092	$6,126	75%, 26%
50	$62,560	$2,521	$6,996	73%, 24%
55	$67,660	$3,055	$7,924	69%, 20%
60	$72,700	$3,565	$8,832	67%, 17%
65	$77,737	$4,099	$9,761	64%, 14%
70	$82,775	$4,635	$10,691	62%, 12%

[a]This is the minimum percentage equity an operator has to provide to feasibly pay a 10-year loan on the remainder of the fixed investment, borrowed at an annual interest rate of 8%. The equity percentages were obtained via calculations based upon economic profit and accounting profit, respectively.

Output price is kept at $5.65/dozen. All prices are in 2010 U.S. dollars.

prawn and soft shell crayfish production focuses on base scenario models for both enterprises: a 0.4 water-hectare freshwater prawn farm versus a 28-culture tray soft shell crayfish farm.

Dasgupta (2005) reports that startup costs for a freshwater prawn operation at $9,000–$10,000, which is one-fourth of a basic soft shell crayfish operation. Similarly, operating costs for a semi-intensive freshwater prawn farm was 21% of operating costs of a soft shell crayfish farm. Labor and management requirement for freshwater prawns was only 11% of the corresponding figure for the soft shell crayfish operation. Hence, it is obvious that soft shell crayfish operations are significantly more expensive than freshwater prawns.

However, the difference in marketing possibilities between the two enterprises is crucial to their comparison: in a 28-culture tray soft shell crayfish operation the breakeven price was low enough to allow sale to bait shops, which is a readily-available market for the product (Bussen & Dasgupta, 2010). However, breakeven price of freshwater prawns was too high to be sold to wholesalers, restaurants, and retailers (Dasgupta, 2005), i.e., direct marketing to end users was the only profitable option. This difference is key because direct marketing naturally limits the volume of product that could be sold which had contributed to restricting the expansion of freshwater prawn farming in the United States (Philips et al., 2010). Conversely, the ability to sell soft shell crayfish profitably to bait shops, even at a small-scale, holds potential for expansion of this industry.

The above comparisons could be extended to another popular small-scale aquaculture enterprise: channel catfish farming. Although channel catfish is farmed year-round, its popularity makes it an useful comparison in our economic feasibility analyses. This article focuses on small-scale soft shell crayfish operations; thus, comparison with channel catfish farming must be conducted in the "small scale" framework. Engle and Stone (2002) provided an example of a 4.8 water-hectare small-scale catfish farm where the total initial investment was $94,497, nearly 2.5 times the initial investment in a small-scale 28-tray soft shell crayfish operation.

Annual operating costs for channel catfish farming were 1.73 times the operating costs for soft shell crayfish farming; however, labor requirements of channel catfish, at 1,035 Man-hours was only 54% of the corresponding figure for soft shell crayfish. Difficulty with small-scale catfish production arose in the investigating breakeven price ($2.16/kg) for whole catfish, which substantially exceed the wholesale price for whole catfish which varied between $1.65–$1.87/kg during 2009–2010 (USDA 2010).

This implies that small-scale channel catfish farming is limited by the having direct markets as their only profitable outlet, which is not the case for small-scale soft shell crayfish operations. The upshot of the preceding comparisons is that soft shell crayfish produced at a small scale could profitably access markets with substantial, widespread demand (e.g., the bait market) unlike other small-scale aquaculture products which cannot be sold profitably in wholesale markets due to price competition, and depend upon direct marketing for their survival.

Sensitivity Results

Data used for this study could change under various circumstances. Table 7 indicates the sensitivity of key economic and production parameters such as the breakeven price and the product volume to changing production and economic conditions. The facility size chosen for Table 7 was a 28-culture tray system that could be managed by two full-time workers. The results showed that a soft shell crayfish operation was very sensitive to changes in the survival rate of crayfish in the culture and molting trays, but much less sensitive to changes in survival rate in the holding trays located in the cold room. Reducing survival rates in the greenhouse initially increased the amount of hard-shell crayfish purchased and the breakeven price, but more than a 1% reduction in the daily survival rate soon made the enterprise unprofitable.

Culley and Duobinis-Gray (1987) considered the stocking density of crayfish in Table 1 to be typical; however, they indicated that increasing stocking density up to 26% did not significantly affect molting rates or survival rates. Hence, Table 7 showed the effect of a 26% increase in stocking density, which led to a 15% reduction in breakeven price.

Table 7 showed the effect of input price changes on breakeven prices. The response of breakeven price was consistently less than input price

TABLE 7 Sensitivity of Economic and Management Parameters to Changes in Survival Rates and Prices

	Parameter % change	Breakeven Price % change	Hard Shells Procured % change	Output % change
DSR[a]	−1	7.37	29.3	−3.07
	−5[c]	N/A	N/A	N/A
	−10[c]	N/A	N/A	N/A
DSRCT[a]	−1	0.36	2.81	0.00
	−5	2.34	15.81	0.00
	−10	5.58	37.68	0.00
Stocking density	5	−4.68	5.00	5.00
	10	−6.83	10.00	10.00
	26[d]	−15.47	26.00	26.00
W_{HS}[b]	1	0.18	0	0
	5	0.72	0	0
	10	1.44	0	0
W_{Gas}[b]	1	0	0	0
	5	0.36	0	0
	10	0.54	0	0
$W_{Propane}$[b]	1	0	0	0
	5	0.18	0	0
	10	0.18	0	0
W_{Wage}[b]	1	0.54	0	0
	5	2.88	0	0
	10	5.58	0	0

[a]DSR stands for the daily survival rate of crayfish in culture and molting trays located in the greenhouse. DSRCT stands for the daily survival rate of hard shell crayfish in holding trays located in the cold room.

[b]P stands for price of soft shell crayfish ($/dozen), W_{HS} stands for the price of hard shell crayfish ($/kg), W_{Gas} stands for gasoline price ($/lt), $W_{Propane}$ stands for propane price ($/lt), and W_{Wage} stands for wage rate ($/hour).

[c]Production drops from 28 culture trays to zero.

[d]Culley and Duobinis-Gray (1987) indicate that molting rates and mortality of soft shell crayfish did not significantly differ up to a 26% increase in stocking density.

A small-scale scenario with 28 culture trays forms the base model for this table.

changes. Predictably, this response was greatest for changes in the wage rate. Notably, energy price variations had a very modest effect on breakeven prices, and thereby profits.

Soft shell crayfish operations are dependent on reliable supplies of immature hard shell crayfish. Although such crayfish are normally available in May, their supply might be hampered in later months (Culley and Duobinis-Gray 1990). We investigated the sensitivity of production and economic parameters towards the limited availability of immature hard-shell crayfish. If immature hard-shell crayfish were only available in May, producers would be constrained to keep a larger inventory in the cold room, which would add to their costs. The corresponding results show that if soft shell crayfish were sold as bait, it would require a minimum 51 culture tray system for the operation to be profitable. At this level of production, 2,821 kg of hard-shell crayfish were purchased and 8,470 dozens of soft shell crayfish were produced.

DISCUSSION AND CONCLUSIONS

This study evaluated the economics, optimal size, financing issues, and sensitivity to variations in resources, prices, and management parameters of a soft shell crayfish operation. Production data were obtained from Louisiana for indoor recirculating soft shell crayfish systems, but price and marketing data were obtained from Kentucky where producers are interested in this enterprise.

The main results were that soft shell crayfish enterprise is very heavy on fixed investments with building construction costs taking the majority share (56%). Hence, producers with existing greenhouses and other buildings that could be adapted for soft shell crayfish operations would have a strong advantage. Variable costs were mostly defined by labor and management expenses that accounted for more than 60% of the former. Due to the importance of labor, producers depend family and friends more than hired part-time workers because part-time workers might not return in future years, requiring extensive training of new workers, and family labor allows more cash-flow flexibility in paying wages, which is important because very little product is available for sale in the first month of operations.

Soft shell crayfish are in demand as fish bait in Kentucky. Average prices of soft shell crayfish, reported in Bussen and Dasgupta (2010) indicated that a facility with a minimum of 25–30 culture trays was essential for profitability. A 28-culture tray facility was considered to be the minimum size of a production unit designed to sell soft shell crayfish only to bait shops. Such a facility required two full-time workers for a 5-month period, well within the capabilities of many farm families to supply. Such a system produced sufficient crayfish to supply more than 10 bait shops, indicating that soft shell crayfish operations must be located in close proximity to large sport fisheries in Kentucky, such as Lake Cumberland, Land Between the Lakes, etc.

Although this article focused on selling soft shell crayfish to bait shops, upcoming research is investigating the product's potential as a food item in local restaurants and specialty retailers (Probst & Dasgupta, 2010). Initial results show these outlets are willing to pay significantly more than the breakeven prices illustrated in Figure 3. This warrants further marketing research, in conjunction with economics feasibility research of having small-scale operations located near large metropolitan areas supplying restaurants with fresh and/or frozen product.

ACKNOWLEDGMENTS

The authors are grateful to Kentucky soft shell crayfish producers for providing data for this study and the USDA CSREES Evans-Allen Program (Project No.: KYX-80-06-16A) for funding this study.

REFERENCES

Aquatic Eco-Systems, Inc. (2010) Master Catalog. 2395, Apopka Blvd., Apopka, Florida, USA.

Bussen, N. & Dasgupta, S. (2010) Marketing soft shell crayfish as fishing bait in Kentucky. Kentucky
Q3 Aquatic Farming, in press.

Brown, P.B. (1993) Soft shell crayfish: A new crop for the midwest. In: *New Crops* (eds., J. Janick & J.E. Simon), pp. 654–656. Wiley, New York, New York, USA.

Caffey, R.H. (1988) An economic analysis of alternative forty tray soft shell crayfish production facilities. Department of Agricultural Economics and Agribusiness. Louisiana State University, Baton Rouge, Louisiana, USA.

Culley, D.D. & Duobinis-Gray, L.F. (1987) Molting, mortality, and the effects of density in a soft shell crayfish culture system. *Journal of the World Aquaculture Society*, **18**(4), 242–246.

Culley, D.D. & Duobinis-Gray, L.F. (1990) Culture of Louisiana soft crayfish: a production manual. Louisiana Sea Grant College Program, Center for Wetland Resources, Louisiana State University, Baton Rouge, Louisiana, USA.

Dasgupta, S. (2005) Economics of freshwater prawn farming in the United States. Southern Region Aquaculture Center Publication No. 4830. https://srac.tamu.edu/index.cfm/event/getFactSheet/whichfactsheet/185/

Dey, M.M., Prien, M., Mahfuzul Haque, A.B.M., Sultana, P., Dan, N.C., & Hao, N.V. (2005) Economic feasibility of community-based fish culture in seasonally flooded rice fields in Bangladesh and Vietnam. *Aquaculture Economics and Management*, **9**, 65–88.

Engle, C.R. (2010) Personal communication. Aquaculture/Fisheries Center, University of Arkansas at Pine Bluff, Pine Bluff, Arkansas, USA.

Engle, C.R. & Stone, N. (2002) Costs of small-scale catfish production. Southern Region Aquaculture Center Publication No. 1800. https://srac.tamu.edu/index.cfm/event/getFactSheet/whichfactsheet/150/

Fong, Q.S.W., Ellis, S., & Haws, M. (2005) Economic feasibility of small-scale black-lipped pearl oyster (*Pinctada margaretifera*) pearl farming in the central pacific. *Aquaculture Economics and Management*, **9**, 347–368.

GAMS. (2006) GAMS Development Corporation. 1217 Potomac Street, NW, Washington, DC.

Huner, J. (1999) The fate of the Louisiana soft shell crayfish. *Aquaculture Magazine*, **May/June**, 46–51.

Kay, R. & Edwards, W. (1999) *Farm Management*. McGraw-Hill Company, New York, New York, USA.

Ogunsanya, T. & Dasgupta, S. (2009) Characteristics of baitfish retailers in Kentucky: Evidence of a market to support a regional industry. *Journal of Applied Aquaculture*, **21**, 120–127.

Philips, H., Hanson, T. R., Dasgupta, S. & Ohs, C. (2010) Marketing and preparation for consumption. In: *Freshwater Prawns Biology and Farming* (eds. M.B. New, W.C. Valenti, J.H. Tidwell, L.R. D'Abramo,
Q4 & Kutty, M.N.), pp. Wiley-Blackwell, West Sussex, UK.

Probst, K.R. & Dasgupta, S. (2010) Characterizing restaurant and demand for soft shell crayfish in
Q5 Kentucky: A Preliminary Analysis. *Kentucky Aquatic Farming*, in press.

Rao, G.S. & Kumar, R.N. (2008) Economic analysis of land-based production of cultured marine pearls in India. *Aquaculture Economics and Management*, **12**, 130–144.

Ross, D.S. (1992) *Greenhouse heating, circulation, and ventilation systems*. Bulletin 351. University of Maryland, Cooperative Extension Service, College Park, Maryland, USA.

USDA: NASS (National Agricultural Statistics Service). (2010) Catfish processing. www.NASS.USDA.GOV

APPENDIX

This section provides details of the linear programming (LP) model for a soft shell crayfish operation including selected operating and fixed cost calculations and constraints placed upon values of the decision variables. A single operating season for a soft shell crayfish operation in Kentucky and neighboring states is typically 17 weeks, starting in May.

Decision variables used in the model were: 1) TrayNum, representing the number of culture trays (i.e., specifying facility size), 2) HS(τ) representing the amount of hard shell crayfish procured during week "τ" ($1 \leq \tau \leq 12$), 3) N(t) representing the amount of replacement hard shell crayfish stocked in culture trays on day "t" ($1 \leq t \leq 119$, or 17 weeks), and (4) THS(t) representing the total number of hard-shell crayfish available in culture and molting trays on day "t".

Revenue

Q2 Revenue is the product of output ($\sum_t$THS(t) × MRate(t)/12 dozens) and price of soft shell crayfish, where MRate(t) is an exogenously-specified molting rate (Figure 2). Hence, Revenue = P × $\sum_t$THS(t) × MRate(t)/12, where P represents the price per dozen of soft shell crayfish. Profit is the difference between revenue and the sum of operating costs and fixed costs.

Operating Costs

Operating costs included the costs of stocking and feeding crayfish, energy costs, labor and management costs, packaging and marketing costs, utilities and legal fees, and maintenance costs. Also included were the opportunity costs associated with forgone interest from the money invested in operating the soft shell crayfish facility, charged at a rate of 8% per annum for a 5-month period.

Stocking costs were derived by multiplying the total amount of hard-shell crayfish used and the price of hard shell crayfish (W_{HS}). An average weight of crayfish (AveWt) was necessary to convert number of crayfish into a weight measure:

$$\text{Stocking cost} = W_{HS} \times \text{AveWt} \times \sum_{\tau} \text{HS}(\tau) \tag{A1}$$

Feeding costs were derived using a feeding rate of 1% of body weight per day (Culley & Duobinis-Gray, 1987):

$$\text{Feeding costs} = W_{Feed} \times 1\% \times \text{AveWt} \times \sum_{t} \text{THS}(t) \tag{A2}$$

Electricity was used to operate water pumps, an air blower, ultraviolet (UV) sterilization systems, an air conditioner, and lights. Two water pumps were used to circulate water in the greenhouse and the cold storage room, respectively. The electrical load of water pump and UV sterilization system depended upon maintaining an appropriate water flow rate, which increased with the number of culture and molting trays.

The flow rate varied from 30 l/min (8 gpm) for small systems to 378 l/min (100 gpm) for a 70-culture tray system, and correspondingly, the pump size varied from 1/8 hp to 1/3 hp, and the UV system varied from 65-watt power to 150-watt power. The pump, air blower, and UV-system in the greenhouse was operated for the entire 17-week period, but the pump and UV-system in the cold room was operated for only 12 weeks, because hard shell crayfish in the cold room was not held beyond 12 weeks. Hence, the electricity cost was:

$$\begin{aligned}\text{Electricity cost} = W_{\text{Elec}} \times \{ & (\text{Pump}_G \text{ hp} \times 0.74 \text{ KW/hp} \\ & + \text{UV}_G\text{system kilo-wattage} + 1.1 \times \text{TrayNum} \times 0.2 \text{ KW} \\ & \times 8/24) \times 24 \text{ hr} \times 17 \text{ weeks} + (\text{Pump}_{CR} \text{ hp} \\ & \times 0.74 \text{ KW/hp} + \text{UV}_{CR} \text{ system kilo-wattage} \\ & + \text{Air conditioner kilo-wattage} \times 12/24) 24\, hr \times 12 \text{ weeks}\},\end{aligned} \tag{A3}$$

where the subscripts "G" and "CR" refer to "greenhouse" and "cold room," respectively. Equation (A3) shows inclusion of two 100-watt lamps per tray to provide lighting for 8 hours a day. The air conditioner was operated for approximately 12 hours/day.

Propane was used to heat the greenhouse for approximately ten hours per day during May when outside air temperature in Kentucky is usually too low to encourage feeding and molting of crayfish. Propane use depended upon the area of the greenhouse, which was assumed to be twice the area of the culture and molting trays; this area indicated the total area of the four walls and roof of the greenhouse (TotArea). Using Ross (1992), propane cost was calculated to be:

$$\begin{aligned}\text{Propane cost} = W_{\text{Propane}}\ & 10 \text{ hrs/day} \times 30 \text{ days} \times \text{TotArea} \\ & \times \text{Temp Difference} \times \text{Heat loss factor}(5.045 \text{ kJ/m}^2/\text{C} \\ & \text{temperature difference/hour})/(90\% \times 25,872 \text{ kJ/liter}),\end{aligned} \tag{A4}$$

where "Temp Difference" is the difference between outside and inside air temperature, "90%" refers to the efficiency of the propane heater, and "25,872 kJ/liter" refers to the heating capacity of propane.

Labor hours were calculated by assuming that the operator spent 0.5/day/tray feeding crayfish, checking for pre molts, and freezing molted crayfish. In addition, 5.5 hours/week was devoted to tasks such as cleaning, maintenance, purchasing feed and supplies, and transporting soft shell crayfish to local buyers.

$$\begin{aligned}\text{Labor and management cost} = {} & \text{Wage rate} \times (0.5\ \text{hr/tray/day} \\ & \times 1.1 \times \text{TrayNum} \times 119\ \text{days} \\ & + 5.5\ \text{hr/week} \times 17\ \text{weeks}).\end{aligned} \quad \text{(A5)}$$

Fixed Costs

Fixed costs included depreciation and forgone interest associated with land, buildings, and equipment. In addition, rent for a propane tank, property taxes, and miscellaneous fixed cost were also included. Table 2 lists fixed costs for a hypothetical 28-culture-tray soft shell crayfish operation. Straight-line depreciation and interest calculations were used using methods outlined in Kay and Edwards (1999).

Two buildings were required for a soft shell crayfish operation: a greenhouse with culture and molting trays and a cold room (Figure 1). The greenhouse floor area was twice the total tray area, i.e., greenhouse area $= 2 \times \text{TrayNum} \times 1.1 \times \text{Tray Area}$ (total number of trays = 110% of the number of culture trays or TrayNum). The construction cost for the greenhouse, including a gravel floor and electricity connections, was computed at \$107.60/m^2 (\$10/sqft). Using information in Table 2, the annual depreciation and interest associated with the greenhouse is given by:

$$\begin{aligned}\text{Depreciation} &= 0.05112 \times \text{TrayNum} \times \text{Tray Area Interest} \\ &= 0.1227 \times \text{TrayNum} \times \text{Tray Area}.\end{aligned} \quad \text{(A6)}$$

The cold room was a small, insulated, air-conditioned room that is designed to hold hard shell crayfish in quiescence for future stocking in culture trays. The air conditioner unit kept the indoor temperature to approximately 10°C (50°F). The room contained multiple stacks of trays, with each stack containing four trays, shelved one on top of other, as shown in Figure 1. Each stack was plumbed in a recirculating system, which consisted of a small biofilter, water pump, and UV-sterilization unit that were also inside the room. Aeration for the biofilter was provided by an air blower that also aerated the greenhouse biofilter.

As explained earlier, the cold room was designed to have a maximum holding capacity of 69% of the total volume of hard shell crayfish that kept in the culture trays. Hence, the number of stacks in the cold room was (69% × TrayNum/4). The cold room floor area was twice the floor area of the stacks, i.e., cold room area = (69% × TrayNum × Tray Area/2). The construction cost for the cold room was estimated to be \$107.60/m^2 (\$10/sqft). The depreciation and interest associated with the cold room is given next:

$$\begin{aligned} \text{Depreciation} &= 0.00804 \times \text{TrayNum} \times \text{Tray Area Interest} \\ &= 0.01928 \times \text{TrayNum} \times \text{Tray Area}. \end{aligned} \tag{A7}$$

Trays and stacks (in cold rooms) were constructed using heavy-duty pressure-treated lumber, pressure-treated plywood, pond liner material, and supported by concrete blocks. The construction cost of each tray was estimated to be \$100 and each cold room stack was \$500, which included the plumbing associated with each stack. The depreciation and cost of trays and 4-tray stacks are given next:

$$\begin{aligned} \text{Depreciation} = 11 \times \text{TrayNum(trays)} &+ 8.645 \\ &\times \text{TrayNum}(4 - \text{tray stacks})\text{Interest} \\ &= 4.4 \times \text{TrayNum(trays)} + 3.458 \\ &\times \text{TrayNum}(4 - \text{tray stacks}). \end{aligned} \tag{A8}$$

Plumbing for trays in the greenhouse was dependent upon the number of trays. Using cost data for PVC pipes and fittings for additional trays, plumbing cost was estimated to be (157 + 47.3 × TrayNum) dollars, resulting in the following depreciation and interest:

$$\begin{aligned} \text{Depreciation} &= 15.7 + 47.3 \times \text{TrayNum Interest} \\ &= 6.28 + 1.892 \times \text{TrayNum}. \end{aligned} \tag{A9}$$

Other fixed cost items are listed in Table 2. The fixed costs for the air blower, air conditioner, generator, pickup truck, and propane heater were consistent for different facility sizes, from 1 to 70 culture trays. However, fixed costs for water pumps, greenhouse biofilter, and UV sterilization systems varied with TrayNum. Appropriate values of this equipment were derived for various number of culture trays by matching the necessary water flow rates with the flow rates and nutrient load supported by different sizes of water pumps, bio filter and UV sterilization systems available through Aquatic Eco-Systems 2010 Master Catalog (Aquatic Eco-Systems, 2010).

Constraints

Various constraints in the LP model restricted values of decision variables due to resource limitations or production sequencing activities. The number of hard-shell crayfish initially stocked (N(t = 1)) depended upon on the number of culture trays, size of culture trays, and the stocking density, as shown here:

$$N(t = 1) \leq \text{TrayNum} \times \text{Tray Area} \times \text{Stocking Density}. \qquad \text{(A10)}$$

Subsequently, the hard-shell crayfish were stocked ($N(t>1)$) to replace crayfish that have either died or entered the pre-molt stage the day before, as shown here:

$$N(t > 1) \leq THS(t - 1) \times (1 - DSR + MRate(t - 1)), \qquad \text{(A11)}$$

where, DSR denotes daily survival rate in the greenhouse and MRate(t-1) is the molting rate, or the percentage of hard shell crayfish that are expected to molt of day "t"(Figure 2). Hence, "THS(t-1) × (1-DSR)" captured the number of crayfish that have died during the previous day, and "THS(t-1) × MRate(t-1)" captured the number of crayfish that have entered the pre-molt stage.

Hard-shell crayfish were procured once a week for the first 12 weeks. The amount of hard shell crayfish bought per week ($HS(\tau)$) was directly related to the amount of crayfish initially stocked in trays and replaced during the production season ($N(t)$). However, hard-shell crayfish were obtained infrequently, necessitating an inventory of such crayfish in the cold room, which had an associated mortality rate. The following constraint shows that the amount of hard shell crayfish procured weekly, discounted by an appropriate survival rate in the holding facility, must be at least the amount of crayfish needed for replacements:

$$\sum_{t=1}^{7\times\tau}\left(N(t)\Big/ DSRCT^{t-7\times(\tau-1)}DSRCT^{t-7\times(\tau-1)}\right) \leq \frac{HS(1)}{DSRCT^{1-7\times\tau}} + \frac{HS(2)}{DSRCT^{7-7\times\tau}} + \cdots + \frac{HS(\tau)}{DSRCT^{7\times\tau-7\times\tau}} \qquad \text{(A12)}$$

where the left-hand side of the constraint accounts for all the replacement hard shell crayfish stocked in trays from week 1 to week "τ", and the right-hand side accounts for all the hard shell crayfish procured from week 1 to week "τ", both sides being appropriately discounted by survival rate in the cold room (DSRCT).

By compiling the annual profit and various constraints outlined here, the LP model could be optimized to discover the best management choices for soft shell crayfish growers.