JOURNAL OF THE
WORLD AQUACULTURE SOCIETY

Vol. 31, No. 4
December, 2000

Economic Interactions Between Feeding Rates and Stocking Densities in Intensive Catfish *Ictalurus punctatus* Production

WILLARD LOSINGER

Centers for Epidemiology and Animal Health, USDA-APHIS Veterinary Services, 555 S. Howes St., Fort Collins, Colorado 80521 USA

SIDDHARTHA DASGUPTA AND CAROLE ENGLE[1]

Aquaculture/Fisheries Center, P.O. Box 4912, University of Arkansas at Pine Bluff, 1200 N. University Dr., Pine Bluff, Arkansas 71611 USA

BRUCE WAGNER

Centers for Epidemiology and Animal Health, USDA-APHIS Veterinary Services, 555 S. Howes St., Fort Collins, Colorado 80521 USA

Abstract

Feed represents the largest cost input in intensive catfish *Ictalurus punctatus* production. Daily feed rations are generally related to stocking densities, up to a point at which high feeding rates begin to affect water quality. There has been no prior research to analyze the economic interactions between feeding and stocking rates. Econometric techniques were used to estimate a Just-Pope catfish production function, which was used to compute marginal products of inputs, and to identify stocking and feeding rates associated with the boundaries between Stages I, II, and III of the production function. Survey data collected by USDA National Animal Health Monitoring System were used for this analysis. Maximum yield, when accounting for both stocking and feeding rates, occurred at about 30,000 fingerlings/ha. However, profit-maximizing stocking densities ranged between 16,942 and 21,312 fingerlings/ha, depending upon expected catfish and feed prices. Farmers stocking at higher rates could be attempting to maximize yield instead of profit.

Feed, fingerlings, and labor are the three largest cost inputs (45%, 8%, and 9% of total costs, respectively) in intensive catfish *Ictalurus punctatus* production (Engle and Kouka 1996). Daily feed rations are generally related to the stocking density and size of catfish in a pond. Feed rations typically increase with increased stocking density nntil high feed rates begin to result in deterioration of water quality. High stocking densities with limited feed may result in reduced growth of individual fish and reduced average yield.

Economic theory indicates that output of a product (in this case catfish) increases as input levels increase until a point of maximum yield is reached. If inputs are increased beyond this point, yield will decrease (Kay and Edwards 1994). This production function relationship can be estimated econometrically using farm-level data and is characterized by three distinct srages. Stage II zones are uniquely associated with the profit maximization objective in perfectly competitive input and output markets (Beattie and Taylor 1985). Profit maximizing input levels within Stage II can be derived from the production function, conditional on input and output prices and other factors.

Earlier economic analyses of catfish production determined that feed, length of growing season, level of capital intensity, and stocking density significantly affected average yield (Lacewell et al. 1973; Panayotou et al. 1982; Nerrie et al. 1990). However, these production function analyses were based on datasets with limited ob-

[1] Corresponding author.

TABLE 1. *Summary statistics of continuous variables included in the analysis. (Total usable observations from the USDA National Animal Health Monitoring System's Catfish '97 survey were 181).*

Name and definition	Mean ± SD	Minimum	Maximum
Yield (kg/ha per yr)	3,354 ± 1,810	22	7,980
Stocking density (fingerlings/ha)	15,826 ± 5,012	1,235	24,700
Feeding rate (kg feed/ha per yr)	9,037 ± 4,413	197	24,760
Farm size (ha)	92 ± 133	2	974

servations of the high stocking densities and feeding rates that are now common in intensive catfish production. Other mathematical programming models evaluated effects of varying stocking densities on farm income, but did not include alternative feeding rates (Hansen et al. 1984; Hatch and Atwood 1988; Engle and Pounds 1994; Engle et al. 1995). The goal of this paper is to analyze explicitly the economic interactions between feeding rates and stocking densities. Our objectives are to investigate individual and joint impacts of the two inputs on catfish yield and to evaluate the profit maximizing input application levels. This information would be useful for farmers in decisions related to feeding strategies for different stocking densities and for varying feed and catfish prices.

Materials and Methods

Data for this study were obtained from catfish producer surveys that were conducted by the USDA: National Agricultural Statistical Service (NASS) in support of USDA's National Animal Health Monitoring System's (NAHMS) Catfish '97 study. The study covered four states (Alabama, Arkansas, Louisiana, and Mississippi) that represented 96% of the total catfish sales in the United States during 1996 (USDA 1997a). The survey was conducted in two stages. The first stage (during January 1997) involved telephone interviews of 571 producers regarding catfish health and production practices (USDA 1997a). In the second stage (during April 1997), more detailed information was obtained about catfish management practices from 301 first-stage respondents (USDA 1997b). Data from 181 respondents were found usable in the current analysis. The remaining 120 observations were rejected for providing incomplete information.

Survey data related to 1996 catfish production included the quantity of food-size catfish sold during 1996, normal stocking density, annual quantity of feed fed to food-fish, feed conversion ratio, and the water surface area used in production during the first 6 mo of 1997 (data for the 1996 levels were unavailable). To estimate a production function from the 1996 yield and input data, we assumed that the inventory per farm had not appreciably changed between 1996 and 1997. From this dataset, several variables were developed with the potential for explaining the yield probability distribution. Table 1 consists of definitions and summary statistics of those variables having a significant explanatory power in the empirical model. Sample means (± 1 standard deviation) from the survey data were 3,354 (± 1,810) kg/ha of catfish produced with 15,820 (± 4,998) fingerlings/ha and 9,037 (± 5,197) kg/ha of feed. These survey data indicate that most farms were operating close to recommended levels of stocking (approximately, 15,000 fingerlings/ha) and feeding (catfish yield verification trials indicated a varying annual feeding rate from 5,987 kg/ha per yr to 8,274 kg/ha per yr) (Heikes 1996). The sample average farm size was 92 (± 133) ha. Variables related to pond aeration were available but were found nonsignificant in the empirical estimations. Labor application data were unavailable for the empirical analysis.

We assumed the existence of an underlying technology function, common to the population of farms targeted by the survey, that links annual catfish yield with input levels and farm-management factors. Econometric techniques were used to estimate the underlying technology by evaluating the input effects on mean catfish yield and yield variance. This was accomplished with a Just-Pope production function model that parameterizes the expected value and variance of yield in terms of inputs and other factors (Just and Pope 1978). The advantage of using the Just-Pope method is that it completely characterizes the catfish yield probability distribution function (PDF), provided that yield is normally distributed. Hence, the Just-Pope estimation results show the changes in the yield PDF due to changes in input levels and other factors.

Just-Pope production function:

$$y = F(\mathbf{X}; \boldsymbol{\alpha}) + u \text{ ('mean' equation)} \quad (1)$$

such that $u = G(\mathbf{X}; \boldsymbol{\beta}) \times v$ ('variance' equation), where y is yield, $\mathbf{X}$ is a vector of inputs, and v is a standard normal error term that is independently and identically distributed across the sample. This implies that the variance of $\mathbf{u} = G(\mathbf{X}; \boldsymbol{\beta})^2$. Here, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are conformable parameter vectors.

The Just-Pope method is superior to conventional production function estimations that often impose ad hoc restrictions on the stochastic technology by parameterizing yield in terms of input levels and append either an additive or multiplicative random error term in order to capture the effects of unobservable, random inputs on output, as shown in (2) (de Janvry 1972; Bredahl and Peterson 1976).

$$y = f(\mathbf{X}; \boldsymbol{\delta}) + \mathbf{u}$$

Additive Error Model

$$y = g(\mathbf{X}; \boldsymbol{\gamma})e^{\epsilon}$$

Multiplicative Error Model (2)

Here, $\boldsymbol{\delta}$ and $\boldsymbol{\gamma}$ are conformable parameter vectors, f and g are functions that express average yield, y, in terms of inputs, $\mathbf{X}$, and

TABLE 2. *Akaike's Information Criterion (AIC) values for the generalized power production function, quadratic and square root functional form representing the mean equation in the empirical model of a Just-Pope production function.*

Functional form	AIC
Generalized power production function	−0.59
Quadratic	1.15
Square root	1.22

u and ϵ are random error terms such that the mean of u and e^{ϵ} are zero and one, respectively. Implicit technological restrictions in such models include: 1) yield variance is either a constant (for the additive error term) or a multiple of the square of average output (for the multiplicative error term); and 2) all higher moments of yield are either independent of input levels (for the additive error term) or are functions of average output (for the multiplicative error term) (Antle 1983; McCarl and Rettig 1983). Examples of studies using the Just-Pope model to investigate production technologies exist in McCarl and Rettig (1983) and Lambert (1990).

The Just-Pope model is estimated in three steps: 1) the parameter vector $\boldsymbol{\alpha}$ is estimated by regressing $y = F(\mathbf{X}; \boldsymbol{\alpha}) + \mathbf{u}$ using ordinary least squares (OLS); 2) using the absolute value of the residuals ($\hat{\mathbf{u}}$) from the previous regression as the dependent variable, $\boldsymbol{\beta}$ is estimated by OLS regression of the following equation: $\ln|\hat{\mathbf{u}}| = \ln[G(\mathbf{X}; \boldsymbol{\beta})] + v$; and 3) heteroskedasticity is corrected by re-estimating $\boldsymbol{\alpha}$ using a weighted least squares procedure with the fitted values from the variance equation as weights, i.e., $y/[G(\mathbf{X}; \hat{\boldsymbol{\beta}})] = \{[F(\mathbf{X}; \boldsymbol{\alpha})]/[G(\mathbf{X}; \hat{\boldsymbol{\beta}})]\} + v$. Just and Pope (1978) proved that the third stage estimates of $\boldsymbol{\alpha}$ are asymptotically efficient and the second stage estimates of $\boldsymbol{\beta}$ are consistent. The mean equation is of interest in this paper: the variance equation is used as a heteroskedasticity correction tool in order to get efficient mean equation coefficient estimates.

The empirical model specifies explicit

functional forms for F and G. The generalized power functional form (GPPF) is used to represent F and the Cobb-Douglas functional form is used to represent G, as shown in (3) and (4).

$$\begin{aligned}\ln[y] &= \ln[F(\mathbf{X})] \\ &= \boldsymbol{\alpha}_0 + \sum_{i=1}^{N} \boldsymbol{\alpha}_i \ln x_i \\ &\quad + 0.5 \sum_{i=1}^{N} \sum_{j=1}^{N} \boldsymbol{\alpha} 1_{ij} \ln x_i \ln x_j \\ &\quad + \sum_{i=1}^{N} \sum_{j=1}^{N} \boldsymbol{\alpha} 2_{ij} x_i \ln x_j \qquad (3)\end{aligned}$$

$$\ln[G(\mathbf{X})] = \boldsymbol{\beta}_0 + \sum_{i=1}^{N} \boldsymbol{\beta}_i \ln x_i \qquad (4)$$

The GPPF was chosen in the 'mean' equation because of its flexibility (de Janvry 1972). For example, the GPPF can describe all three stages of production by allowing the marginal product of an input to be either positive, zero or negative. This functional form does not restrict the technical dependence of inputs, i.e., the same inputs are allowed to be technically complementary or competitive depending upon their level of use. The GPPF functional form was compared with two other popular functional forms: the quadratic and square root forms. Table 2 presents the Akaike's Information Criterion (AIC) values for the Just-Pope mean equation estimates for the three functional forms. Given that the GPPF has the smallest AIC, it demonstrates a superior fit over the quadratic and square root functional forms (Greene 1990).

Dependent and independent variables, developed from the data, are described in the following section. The regressor selection process used here was based on minimizing the estimated model's AIC. In this method, selected regressors typically have a higher significance level than the corresponding critical value in the Theil's adjusted R^2 criterion (Maddala 1992).

The estimated production function (the Just-Pope mean equation only) was used to investigate optimal variable input application. An input's marginal product represents the additional amount of catfish production that can be obtained from increasing input levels by one unit. The average product of an input is the average catfish yield per unit of the input. Micro-economic theory indicates that economic input use occurs at levels at which the input's marginal product is positive and less than the corresponding average product (i.e., Stage II production zone). The paper analyzes the marginal product of stocking density and feeding rate by identifying the economic and noneconomic regions of production and characterizing the impact of increased input application on the marginal product of the other input. This analysis is subsequently extended to a derivation of optimal stocking and feeding rates (conditional on input and output prices) by simultaneously solving profit-maximizing necessary conditions.

Results and Discussion

Normal distribution of yield is sufficient for the Just-Pope method to characterize catfish yield's probability distribution function (Just and Pope 1978; Antle 1983). D'Agostino and Pearson's test (1973) of normality resulted in a test statistic value of 4.118 (P-value for the Chi-squared test statistic with two degrees of freedom = 0.128) for the catfish yield survey data. Hence, the null hypothesis of a normally distributed yield was not rejected.

Estimated coefficients from the Just-Pope mean equation are provided in Table 3. The adjusted R^2 for the six regressors is 0.52 (R^2 = 0.54). This R^2 value is acceptable for cross-sectional data for which R^2 values tend to be lower than for time-series data (Nakamura and Nakamura 1998). Stocking density (fingerlings/ha), feeding rate (kg feed/ha per yr) and farm size exerted significant influence on the annual expected yield.

Profit-maximizing producers always operate in Stage II of production by using inputs to an extent that additional application

TABLE 3. *Coefficient estimates from the Just-Pope production function model. Dependent variable = Ln(catfish yield). A * indicates that the coefficient estimate is significant at a 95% confidence interval. A Ramsey Test following the Weighted Least Squares regression in Step 3 of the Just-Pope procedure indicated no significant heteroskedasticity present. Adjusted R^2 for the above model = 0.52 (R^2 = 0.54).*

Regressor	Coefficient estimate	t-ratio
Intercept	−1.805	−0.231
Ln(farm size)	0.153	2.777*
Ln(stocking density)	3.872	2.313*
Ln(feeding rate)	−3.265	−3.728*
[Ln(stocking density)]²	−0.185	−1.985*
[Ln(feeding rate)]²	0.229	3.852*
Feeding rate × Ln(farm size)	−0.00001	−1.062

of the inputs results in a less than proportionate increase in output (Beattie and Taylor 1985). This implies that in Stage II, the marginal product of an input is positive and less than the average product (i.e., the input's partial production elasticity range between one, the Stage II lower bound, and zero, the Stage II upper bound) (Beattie and Taylor 1985). Assuming that farm size is a quasi-fixed input, partial production elasticities of the two variable inputs, stocking density ('StockDen') and feeding rate ('FeedRate'), are given by: $\epsilon_{StockDen} = \{\partial \ln[E(y)]\}/\{\partial \ln[StockDen]\} = 3.872 - 0.37 \times \ln[StockDen]$ and $\epsilon_{FeedRate} = \{\partial \ln[E(y)]\}/\{\partial \ln[FeedRate]\} = -3.265 + 0.458 \times \ln[FeedRate] - 0.00001 \times FeedRate \times \ln[Farm\ Size]$, respectively. Hence, for catfish production, Stage II is characterized by stocking densities between 2,349 and 35,061 fingerlings/ha per yr and feeding rates less than 33,254 kg/ha per yr, holding farm size constant at its sample average (92 ha). Although there is no lower bound for feeding rate in Stage II, commercial producers must feed at a minimum level to maintain fish stocks and/or promote growth. In a 1992 survey of catfish production in Arkansas, Engle and Brown (1997) reported a minimum average annual feeding rate of 20.4 kg/ha per d (or 4,899 kg/ha per yr). Hence, 4,899 kg/ha per yr is adopted as the minimum feeding rate in this study.

Producers who seek to maximize profits should increase feeding rates and stocking densities if they are operating in Stage I (characterized by increasing marginal products) and decrease feeding rates and stocking densities if operating in Stage III (characterized by negative, decreasing marginal products) (Beattie and Taylor 1985). Fig. 1 illustrates the boundaries of the production stages for stocking density and feeding rate for a 92-ha farm. The shaded area in Fig. 1 represents input combinations for which the farm is operating in production Stage II for both inputs. This area represents the economic region of production and demarcates the minimum and maximum input intensities that a profit-maximizing producer should apply.

Since the partial production elasticity of feeding rate varies with farm size, individual feeding rate and farm size data were used to evaluate the percentages of surveyed producers who were operating in Stages I, II and III. This evaluation is conditional on the assumption that the empirical production function estimates an underlying technology that is common to the population of catfish farms targeted by the survey. Based on results of the NAHMS survey, most producers were operating in Stage II (99% and 100% with respect to stocking and feeding rates, respectively). A few producers (1%) were operating in Stage I with respect to stocking (stocking less than 2,349 fingerlings/ha), and no producers were operating in Stage III with respect to both stocking and feeding inputs.

Marginal Product of Stocking Density

Marginal products were calculated for both stocking densities and feeding rates. Holding all continuous variables at their sample means, increasing stocking densities decreased the marginal product (MP) of stocking, for all sampled stocking densities (up to a maximum of 24,700 fingerlings/

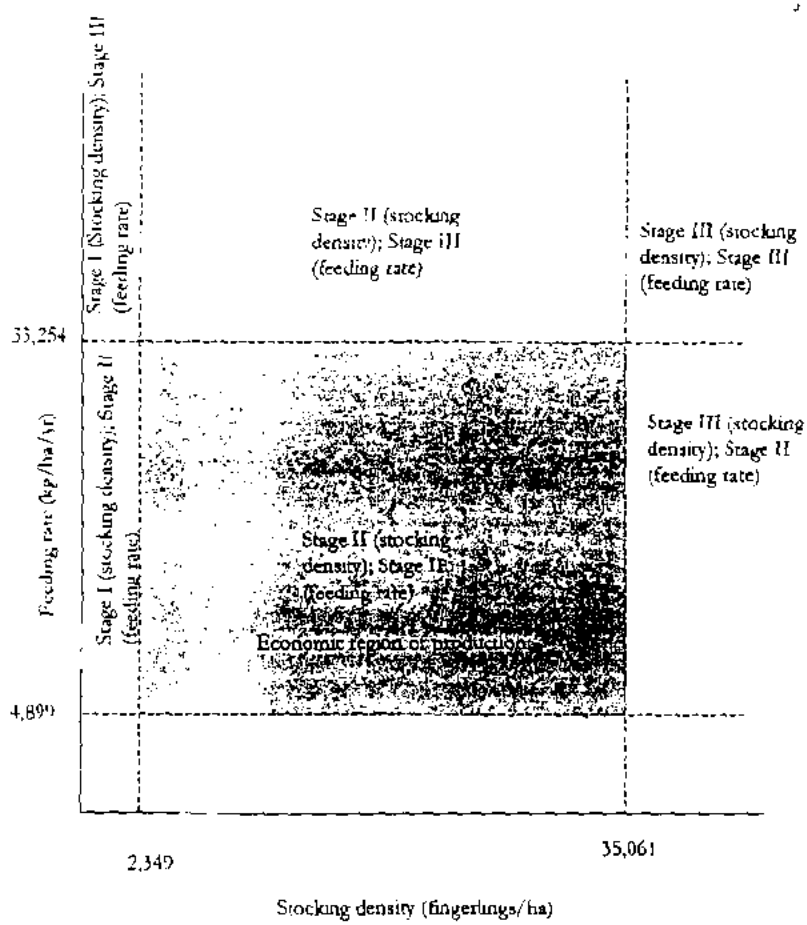

FIGURE 1. *The economic region of production with respect to stocking density and feeding rate for a 92-ha catfish farm.*

ha). Projecting the MP of stocking to higher stocking densities resulted in continued decrease of the MP of stocking to nearly zero at, approximately, 35,061 fingerlings/ha (Fig. 2). Maximum output corresponds to a marginal product of zero because additional input use does not generate an increase in catfish output (Kay and Edwards 1994). Thus, at a feeding rate of 9,037 kg/ha per yr (Table 1), the estimated production function projected maximum output to occur at 35,061 fingerlings/ha; further increases in stocking density would begin to result in decreased catfish production. The profit-maximizing level of production, however, will always be less than the point of maximum yield. This is because the profit maximizing input application occurs at the point where their MP is positive and equal to the ratio of their marginal factor cost and the output price.

Interactions between stocking and feeding can be shown by the effects of simultaneously varying the two inputs on the MP of stocking density, while holding farm size constant at the sample average (Fig. 3). Fig. 3 shows that the MP of stocking increases for higher feeding rates up to 20,000 kg/ha per yr. More intensive feeding does not appreciably increase the MP of stocking density. For feeding rates higher than 40,000 kg/ha per yr, the MP of stocking begins to decrease. Hence, stocking density and feeding rate are technologically complementary

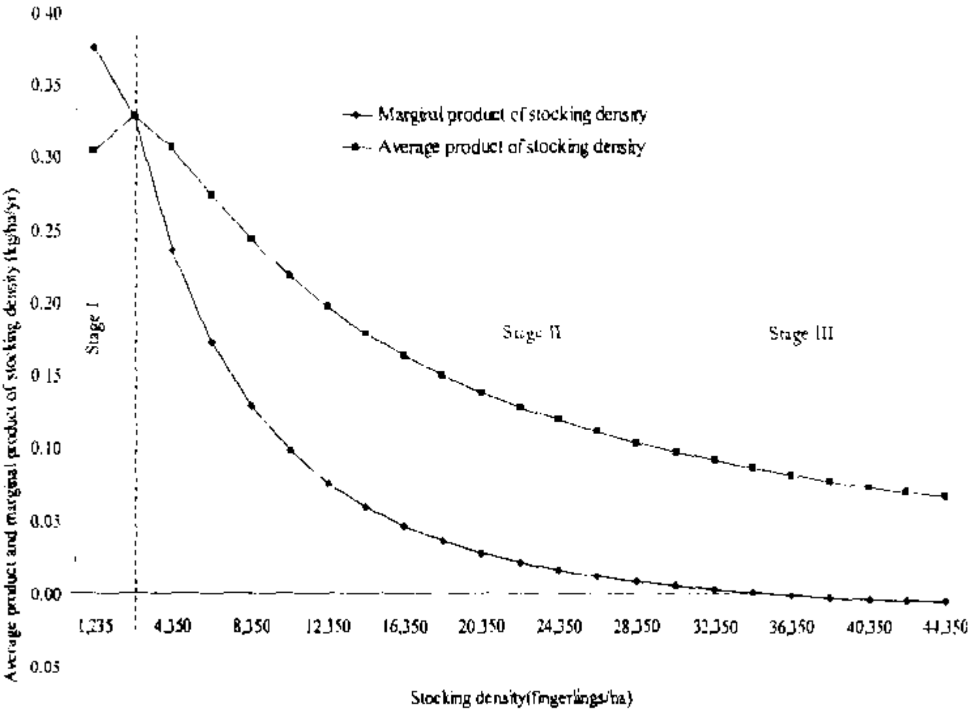

FIGURE 2. *Marginal product of stocking density with respect to varying levels of stocking. Calculated by holding other continuous variables at the sample mean.*

for feeding rates below 40,000 kg/ha per yr; at higher feeding rates, the two inputs become technologically competitive (Beattie and Taylor 1985). The MP of stocking approaches zero for stocking densities above 30,000 fingerlings/ha irrespective of feeding rate. This indicates that, when accounting for both feeding and stocking rates, maximum yield occurs at about 30,000 fingerlings/ha. At these stocking densities, farmers should not expect to increase average yield by increasing feeding rates.

Marginal Product of Feeding Rate

The survey data provided a wide range of feeding rates, as shown in Table 1. Less than 10% of the sample consisted of farms with a feeding rate less than 1,200 kg/ha per yr. If there are approximately 240 feeding days per production year, 1,200 kg/ha per yr translates to a feeding rate of 5 kg/ha per d. Typically, such low feeding rates are indicative of hobby farms and not commercial, intensive catfish operations (Heikes, University of Arkansas at Pine Bluff, personal communication). We adopt the Engle and Brown (1997) minimum-feeding rate (4,899 kg/ha per yr) in documenting the subsequent results.

The MP of feeding rate increased for feeding rates between 1,200 kg/ha per yr and 4,899 kg/ha per yr. Holding all other variables at their sample means, for feeding rates above 4,899 kg/ha per yr, the MP of feeding decreases for all higher sampled feeding rates (Fig. 4). The MP of feeding rate is projected for feeding rates higher than the sampled maximum (24,760 kg/ha per yr), for which it continues to decrease and is approximately zero at 33,254 kg/ha per yr. Fig. 4 also illustrates that the average product of feeding rate is higher than the corresponding marginal product, for feeding rates less than 33,254 kg/ha per yr. Hence, producers feeding between 4,899 kg/ha per yr and 24,760 kg/ha per yr were

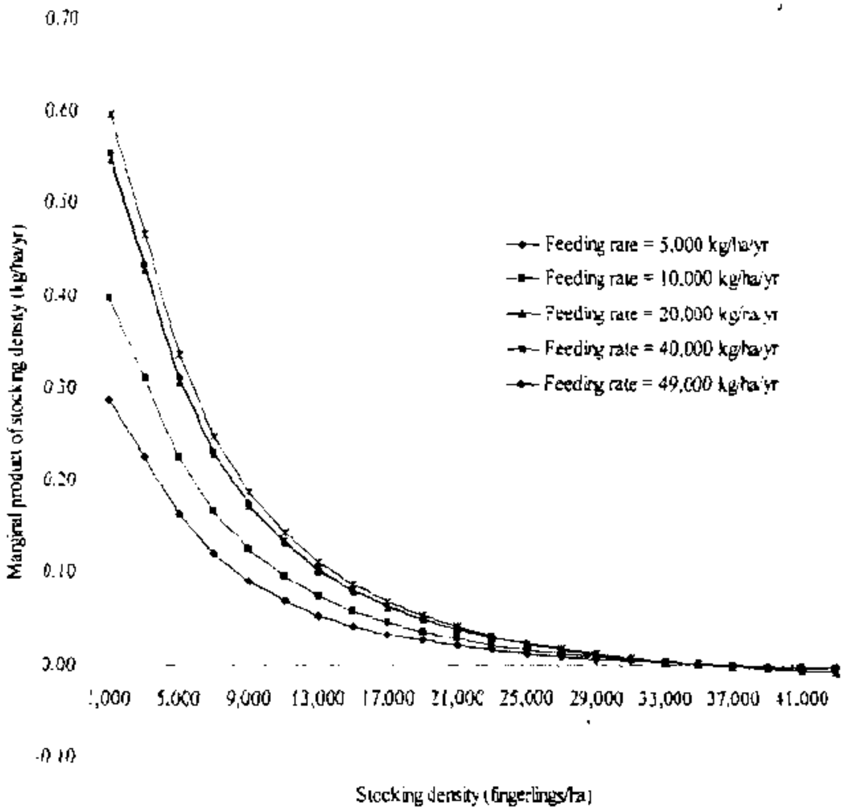

FIGURE 3. *Marginal product of stocking density with respect to stocking for different feeding rates. Calculated by holding other continuous variables at the sample mean.*

operating in production Stage II. The production function projects that feeding in excess of 33,254 kg/ha per yr will make producers operate in production Stage III of feeding, i.e., the high feeding rates will decrease catfish yield.

Fig. 5 plots the MP of feeding rate for progressively higher stocking densities (from 2,500 fingerlings/ha to 30,000 fingerlings/ha), in a 92-ha farm. As stocking density increases, the MP of feeding rate rapidly increases, for feeding rates between 4,899 kg/ha per yr and 24,760 kg/ha per yr. However, stocking more intensively than 25,000 fingerlings/ha does not appreciably increase the MP of feeding rate. Hence, for stocking densities between 2,500 fingerlings/ha and 30,000 fingerlings/ha, feeding rate is technologically complementary to stocking density (Beattie and Taylor 1985).

Profit-Maximizing Levels of Stocking and Feeding

Assuming price-taking behavior of profit maximizing producers in both input and output markets, the profit-maximizing necessary conditions indicate that inputs should be applied until the expected output price × input-marginal product (also known as the expected value of the input's marginal product or VMP) is equal to the input's expected marginal factor cost (Kay and Edwards 1994). This is illustrated in the following two equations (profit-maximizing necessary conditions) derived from the estimated production function. The profit-maximizing necessary conditions presume that producers make optimal input allocations based on their price expectations. Catfish producers often contract with feed mills

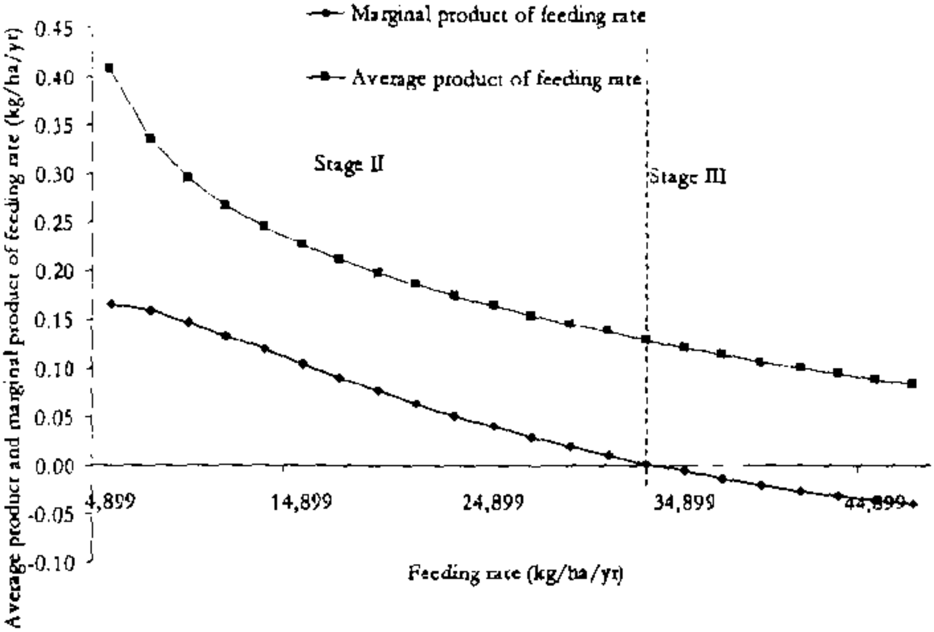

FIGURE 4. *Marginal product of feeding rate with respect to varying feeding levels. Calculated by holding other continuous variables at the sample mean.*

at a pre-determined price (Heikes, personal communication). They also have access to catfish price projections that are based on historical price data. Using the expected (or projected) prices, profit-maximizing optimal input levels could be derived by solving (5) and (6).

$$\begin{aligned}
&\text{VMP(stocking density)}\\
&\quad = P \times \frac{y}{\text{StockDen}}\\
&\qquad \times \{3.872 - 0.37 \ln(\text{StockDen})\}\\
&\quad = \text{expected price/fingerling} \qquad (5)
\end{aligned}$$

$$\begin{aligned}
&\text{VMP(feeding rate)}\\
&\quad = P \times \frac{y}{\text{FeedRate}}\\
&\qquad \times [-3.265 + 0.458 \ln(\text{FeedRate})\\
&\qquad\quad - 0.00001\text{FeedRate} \ln(\text{FarmSize})]\\
&\quad = \text{expected feed price/kg,} \qquad (6)
\end{aligned}$$

where

$$\begin{aligned}
&\text{output } y\\
&\quad = \exp\{[-1.805 + 0.153 \ln(\text{FarmSize})\\
&\qquad + 3.872 \ln(\text{StockDen})\\
&\qquad - 3.265 \ln(\text{FeedRate})\\
&\qquad - 0.185\{\ln(\text{StockDen})\\
&\qquad\qquad \times \ln(\text{StockDen})\}\\
&\qquad + 0.229\{\ln(\text{FeedRate})\\
&\qquad\qquad \times \ln(\text{FeedRate})\}\\
&\qquad - 0.00001 \text{ FeedRate}\\
&\qquad \times \ln(\text{FarmSize})]\} \quad \text{and}
\end{aligned}$$

P = expected output price

Equations (5) and (6) were solved simultaneously for different input and output prices, keeping farm size fixed at the sample average. A range of output prices and feed prices were chosen to illustrate the price sensitivity of optimal stocking and feeding rate, profit-maximizing expected yield, and expected revenue over variable costs. The catfish price range (\$1.54/kg to

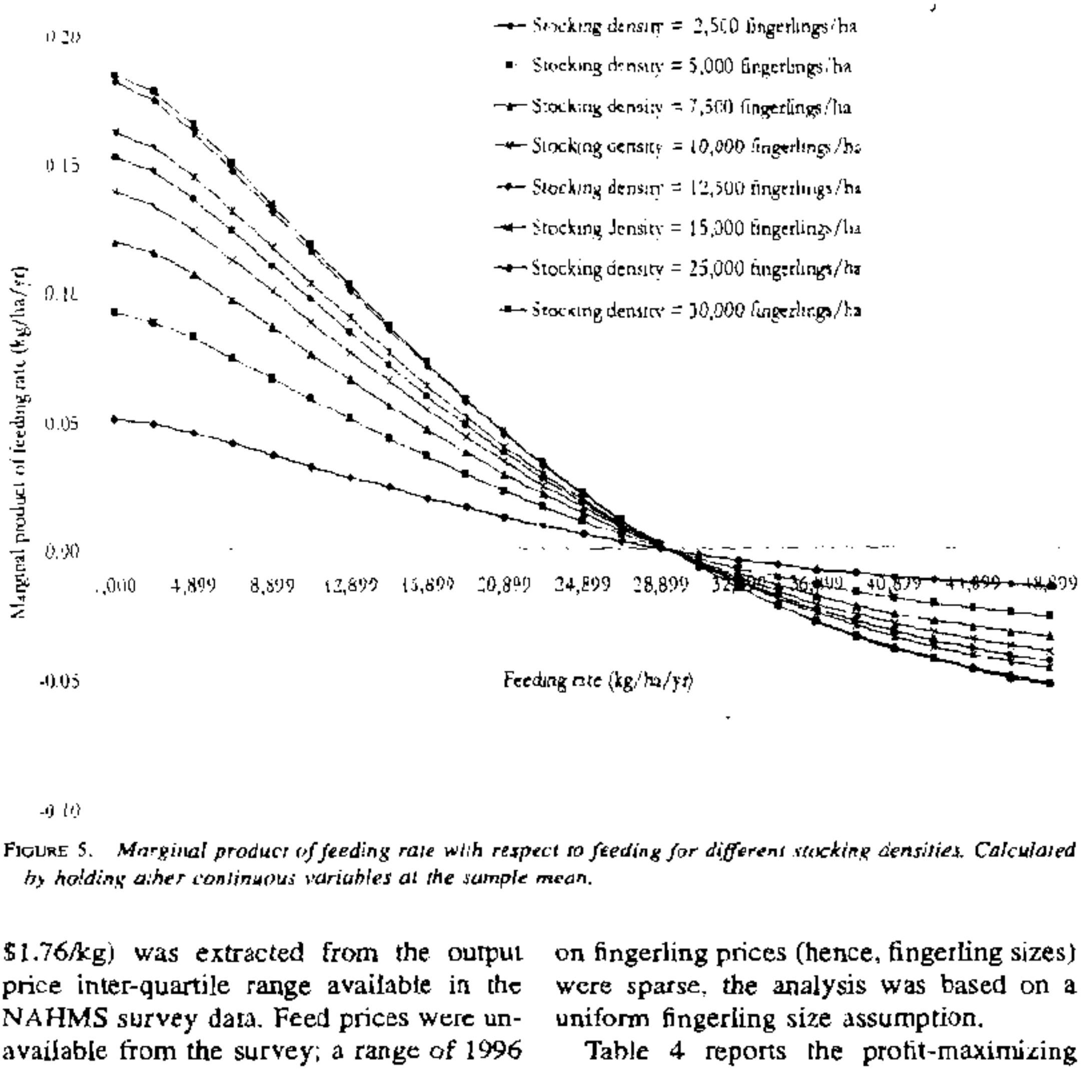

FIGURE 5. *Marginal product of feeding rate with respect to feeding for different stocking densities. Calculated by holding other continuous variables at the sample mean.*

\$1.76/kg) was extracted from the output price inter-quartile range available in the NAHMS survey data. Feed prices were unavailable from the survey; a range of 1996 catfish feed prices (\$0.22/kg to \$0.27/kg) was provided by the ARKAT feed mill (ARKAT Feed Mill 1996). Fingerling price was kept fixed at the sample average (\$0.055); typically, fingerling prices have been relatively stable since 1982 (prices have increased by only 0.4% per year since 1982) (Engle and Kouka 1996). Price variations are primarily due to different fingerling sizes: 5-cm fish are approximately \$0.02 each and 20-cm fish are \$0.08 each. Fingerling size could potentially affect the production function. For example, an operation based on stocking 5-cm fingerlings could experience different feeding requirements and mortality rates than one based on stocking 20-cm fingerlings. Since the data on fingerling prices (hence, fingerling sizes) were sparse, the analysis was based on a uniform fingerling size assumption.

Table 4 reports the profit-maximizing stocking density, feeding rate, expected yield and expected revenue over variable costs for a 92-ha catfish farm. The results show that the profit-maximizing stocking and feeding rates are within the economic region of production, highlighted in Fig. 1. Application rates for both variable inputs increase if output price increases and/or feed price decreases. Similarly, the optimal expected yield and expected revenue over variable costs increase if output price increases and/or feed price decreases. For example, as catfish price increases from \$1.54/kg to \$1.76/kg, the profit-maximizing stocking density increases from 17,968 fingerlings/ha to 20,655 fingerlings/ha (assuming feed price is \$0.25/kg). Similarly, the

TABLE 4. *Profit maximizing stocking and feeding rates, expected yield and expected revenue over variable costs for a 92-ha catfish farm for varying catfish and feed prices. Fingerling price is fixed at the sample mean of $0.055.*

Catfish price ($/kg)	Feed price ($/kg)	Stocking density (fingerlings/ha per yr)	Feeding rate (kg/ha per yr)	Optimal expected yield (kg/ha per yr)	Expected revenue over variable costs ($/ha)
1.54	0.23	18,910	9,426	2,832	1,153.97
1.65	0.23	20,216	11,529	3,178	1,480.50
1.76	0.23	21,312	13,379	3,454	1,829.83
1.54	0.25	17,968	7,171	2,447	987.21
1.65	0.25	19,416	9,232	2,820	1,276.77
1.76	0.25	20,655	11,211	3,148	1,601.22
1.54	0.27	16,942	5,222	2,096	885.90
1.65	0.27	18,500	7,047	2,452	1,126.37
1.76	0.27	19,857	8,917	2,794	1,418.09

corresponding profit-maximizing feeding rate increases from 7,171 kg/ha per yr to 11,211 kg/ha per yr. As feed price increases from $0.25/kg to $0.27/kg, for a catfish price of $1.54/kg, the profit-maximizing stocking density decreases from 17,968 fingerlings/ha to 16,942 fingerlings/ha. The profit-maximizing feeding rate decreases from 7,171 kg/ha per yr to 5,222 kg/ha per yr. Since the optimal stocking density decreases with increase of feed price, the stocking input is an economic complement of feeding rate (Beattie and Taylor 1985).

Conclusions

This study showed that most of the surveyed catfish farms were operating in Stage II (profit-maximizing stage) of production; only 1% were operating in Stage I with respect to stocking. Farms operating in Stage I would be better off stocking more intensively and receive a more than proportionate increase in yield. If these farms operate in Stage II, i.e., stock at least 2,349 fingerlings/ha, they should experience higher net returns.

When accounting for both feeding and stocking rates, maximum yield was determined to occur at approximately 30,000 fingerlings/ha. Furthermore, highly intensive application rates of stocking and feeding inputs were found to be only modestly technologically complementary: increasing feeding rates at these high stocking densities will not substantially increase yields.

Profit-maximizing stocking densities ranging from 16,942 to 21,312 fingerlings/ha increased with catfish prices and decreased with higher feed prices (for an output price range from $1.54 to $1.76/kg and a feed price range from $0.23 to $0.27/kg). Stocking densities associated with maximum yield (25,000–30,000 fingerlings/ha) were in a range that has been reported on catfish farms. Thus, this study indicates that farmers stocking at these high rates are probably maximizing yields and not profits.

Lack of survey data related to fingerling sizes precluded analysis of optimal stocking size of fingerlings. Additional research is needed to examine the potential economic tradeoffs associated with stocking varying sizes of fingerlings.

Acknowledgments

The authors acknowledge the USDA-APHIS National Animal Health Monitoring System for providing data from the 1997 national survey. They further thank the catfish farmers who participated in the survey. Rajan Sampath, Nathan Stone, David Heikes, Don Freeman, H. Steven Killian, Ari Mwachōfi, Thomas Knight, H. Alan Love, Stephen Ott and John Green provided useful suggestions and comments. This paper is published with the approval of the Direc-

tor of the Arkansas Agricultural Experiment Station, Manuscript #99077.

Literature Cited

Antle, J. M. 1983. Testing the stochastic structure of production: a flexible moment-based approach. Journal of Business and Economic Statistics 1: 192–201.

ARKAT Feed Mill. 1996. Annual records. Dumas, Arkansas, USA.

Beattie, B. R. and C. R. Taylor. 1985. The economics of production. Robert E. Kreiger Publishing Company, Malabar, Florida, USA.

Bredahl, M. and W. Peterson. 1976. The productivity and allocation of research: U.S. agricultural experiment stations. American Journal of Agricultural Economics 58:684–692.

D'Agostino, R. B. and E. S. Pearson. 1973. Tests of departure from normality. Empirical results for the distribution of b_2 and $\sqrt{B_1}$. Biometrika 60:613–622.

de Janvry, A. 1972. The generalized power production function. American Journal of Agricultural Economics 54:234–237.

Engle, C. R. and D. W. Brown. 1997. Catfish production characteristics in Arkansas: survey results. Cooperative Extension Program. ETB253. University of Arkansas at Pine Bluff, Pine Bluff, Arkansas, USA.

Engle, C. R. and P. J. Kouka. 1996. Effects of inflation on the cost of producing catfish. Report submitted to the Catfish Bargaining Association. Arkansas Cooperative Extension Program, University of Arkansas at Pine Bluff, Pine Bluff, Arkansas, USA.

Engle, C. R. and G. L. Pounds. 1994. Trade-offs between single- and multiple-batch production of channel catfish, *Ictalurus punctatus*: an economics perspective. Journal of Applied Aquaculture 3(3/4):311–332.

Engle, C. R., G. L. Pounds, and M. Van der Ploeg. 1995. The cost of off-flavor. Journal of the World Aquaculture Society 26(3):297–306.

Greene, W. H. 1990. Econometric analysis. Macmillian Publishing Company, New York, USA.

Hansen, G., N. R. Martin, Jr., and J. B. Flynn. 1984. Production, price and risk factors in channel catfish farming. Southern Journal of Agricultural Economics 16(1):173–182.

Hatch, U. and J. Atwood. 1988. A risk programming model for farm-raised catfish. Aquaculture 70: 219–230.

Heikes, D. 1996. Catfish yield verification trials. Final report. May 1993–December 1996. Arkansas Cooperative Extension Program. University of Arkansas at Pine Bluff, Pine Bluff, Arkansas, USA.

Just, R. E. and R. D. Pope. 1978. Stochastic specification of production functions and economic implications. Journal of Econometrics 7:67–86.

Kay, R. D. and W. M. Edwards. 1994. Farm management, 3rd edition. McGraw-Hill, Inc., New York, USA.

Lacewell, R. D., J. P. Nichols, and T. H. Jambers, Jr. 1973. An analysis of pond raised catfish production in Texas. Southern Journal of Agricultural Economics 5:141–145.

Lambert, D. K. 1990. Risk considerations in the reduction of nitrogen fertilizer use in agricultural production. Western Journal of Agricultural Economics 15(2):234–244.

Maddala, G. S. 1992. Introduction to econometrics. Prentice Hall, Inc., Englewood Cliffs, New Jersey, USA.

McCarl, B. A. and R. B. Rettig. 1983. Influence of hatchery smolt releases on adult salmon production and its variability. Canadian Journal of Aquatic Sciences 40:1880–1886.

Nakamura, A. and M. Nakamura. 1998. Model specification and endogeneity. Journal of Econometrics 83:213–237.

Nerrie, B. L., L. U. Hatch, C. R. Engle, and R. O. Smitherman. 1990. The economics of intensifying catfish production: a production function analysis. Journal of the World Aquaculture Society 21(3):216–224.

Panayotou, T., S. Wattanutchariya, S. Isvilanondo, and R. Tokrisna. 1982. The economics of catfish farming in central Thailand. Technical report 4. International Center for Living Aquatic Resources Management, Manila, The Philippines.

United States Department of Agriculture. 1997a. Part I: Reference of 1996 U.S. catfish health and production practices. N235.597. United States Department of Agriculture: Animal and Plant Health Inspection Service: Veterinary Services, Center for Epidemiology and Animal Health, Fort Collins, Colorado, USA.

United States Department of Agriculture. 1997b. Part II: Reference of 1996 U.S. catfish health and production practices. N246.897. United States Department of Agriculture: Animal and Plant Health Inspection Service: Veterinary Services, Center for Epidemiology and Animal Health, Fort Collins, Colorado, USA.