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The Epidemiology of Bacterial Diseases in Food-Size Channel Catfish

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Abstract.—Enteric septicemia of catfish (ESC) and columnaris are the most economically important bacterial diseases affecting the channel catfish *Ictalurus punctatus* industry in the United States. Although these two diseases have been extensively researched, little is known about their prevalence and epidemiology in production systems. In 1997, a two-part survey of catfish producers in Alabama, Arkansas, Louisiana, and Mississippi was conducted to estimate the proportion of ponds and catfish operations that have these diseases and to develop information on the risk factors associated with reporting an occurrence. The response rates to the two phases of the survey were 65.6% and 75.3%, respectively. Overall, 78.1% of all operations and 42.1% of all ponds experienced problems with ESC/columnaris. Higher percentages of large operations and ponds on large operations experienced these problems. The most frequently reported average loss per outbreak of the two diseases was 200–2,000 lb (1 lb = 0.454 kg) per outbreak. Univariate analysis and multivariable regression modeling of the survey data identified three possible risk factors associated with ESC/columnaris, namely, operation size, stocking density, and feeding rate. Conversely, operations that produced their own fingerlings and those that drained ponds at intervals of 3 years or less were less likely to report losses. The associations identified in this study do not establish firm causal relationships, but they do generate hypotheses about managerial and environmental interactions that represent substantial risks to production.

Bacterial diseases are the most common cause of disease-related losses in the commercial production of channel catfish *Ictalurus punctatus*. The two bacterial species responsible for most of these losses are *Flavobacterium columnare*, commonly referred to as columnaris, and *Edwardsiella ictaluri*, the causative agent of enteric septicemia of catfish (ESC; Hawke et al. 1981). Together, these species were diagnosed in more than 60% of the cases submitted to the Fish Diagnostic Laboratory at the Thad Cochran National Warmwater Aquaculture Center in Stoneville, Mississippi, from 1996 to 2001.

Research on these two diseases has been very extensive and includes the pathology of the disease (Miyazaki and Plumb 1985; Decostere et al. 1999), fish immune response (Klesius 1992a; Ciembor et al. 1995), vaccination trials (Thune et al. 1997; Shoemaker et al. 1999; Wise and Terhune 2001), diagnostic detection tools (Hawke and Thune 1992; Klesius 1993), and treatment evaluation (Wilson and MacMillan 1989; Johnson and Smith 1993; Wise and Johnson 1998). Other work, conducted primarily in laboratory and experimental pond settings, has focused on the relationship of environmental factors and management practices to these diseases (Hanson and Grizzle 1985; Francis-Floyd et al. 1987; Moore et al. 1990; Mqolomba and Plumb 1992; Kim and Lovell 1995; Plumb and Shoemaker 1995; Altinok and Grizzle 2001). Diagnostic laboratory records have been used to investigate the temporal and geographical distribution of ESC despite their documented limitations, such as selection bias (Freund et al. 1990).

As with most bacterial diseases, prevention is a key component of management efforts to control ESC/columnaris outbreaks. For this reason, it is important for both producers and researchers to identify and understand the risk factors (i.e., the putative causes; Martin et al. 1987) associated with these diseases.

Observational studies are used widely in human and veterinary epidemiology to determine whether

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particular independent variables are statistically associated with the outcome of interest (Martin et al. 1987), but they are used infrequently in studies relating to fish health. Bebak et al. (1997) studied risk factors for bacterial gill disease (BGD) in young, hatchery-reared rainbow trout *Oncorhynchus mykiss*. Georgiadis et al. (2000) investigated risk factors for white sturgeon iridovirus and white sturgeon herpesvirus-2 on a commercial sturgeon farm. No large, field-oriented observational studies have been undertaken to explore the epidemiology of ESC and columnaris.

The objectives of this study were (1) to determine the proportion of operations and ponds used for food fish production experiencing losses due to ESC or columnaris during 1996 and (2) to quantify the association between management factors and the reported presence of ESC/columnaris on a farm. The risk factors and outcome measurements are based on survey responses of producers from the four largest catfish-producing states, Alabama, Arkansas, Louisiana, and Mississippi.

Methods

Survey.—The U.S. Department of Agriculture's (USDA) National Animal Health Monitoring System (NAHMS), which is tasked with continuous surveillance of animal health in the United States (Wineland and Dargatz 1998), developed a two-part survey to study management practices and health issues on commercial channel catfish farms that produce food-size fish. In the first part of the study, implemented during January 1997, USDA National Agricultural Statistics Service (NASS) enumerators attempted to contact all of the producers (N = 870) on their list of producers in the four target states, either by phone or in person. These four states accounted for more than 95% of the commercial production and over 93% of the water surface acres used for catfish production in the United States from January 1 through June 30, 1997 (USDA 1997a). As part of the NAHMS survey, producers were asked about disease problems in their fish in 1996 (including the number of food-size fish ponds that experienced disease losses for six specific diseases), the disease that caused the greatest economic loss during the previous three years, and the average quantity of fish lost per outbreak. ESC and columnaris often occur together in a clinical disease case, making it difficult to identify the primary causative agent for the resulting mortalities. For this reason, ESC and columnaris were combined to avoid problems with recalling disease events. Producers categorized their average loss per outbreak as light (less than 200 lb [1 lb = 0.454 kg]), moderate (200–2,000 lb), or severe (more than 2,000 lb).

During the second phase of the study, implemented in April 1997, NASS personnel attempted to survey a randomly selected subset of the respondents (n = 400) from the first part of the survey. The second part of the survey covered a broader range of topics, including pond type (watershed or levee) and general management practices such as stocking, feeding, harvesting, and health management. Both parts of the survey were conducted concurrently with NASS's standard quarterly surveys. Data from these surveys, including water surface area, inventory, and sales, were provided for use in the study.

The results from the first phase of the study were weighted to account for nonresponses. In the second phase of the study, the results were weighted to account for both the subsampling of respondents from the first phase and the nonresponses to the second-phase questionnaire. All weight adjustments were made with state and operation size categories defined prior to the study by NASS.

Statistical analysis of associations.—Associations were examined between operation-level management practices and reported problems with ESC/columnaris. Management practices (independent variables) were initially screened by developing individual logistic regression models for each independent variable against the dependent variable, the presence or absence of any reported ponds with ESC/columnaris. Odds ratios (ORs) were derived from the models, and Wald statistics were used for each independent variable to test for differences in the reporting of ESC/columnaris. Variables with P-values of 0.2 or less were entered into the multivariable logistic regression model. Initially, the multivariable logistic model was constructed using a backward stepwise procedure (SAS Institute, Inc. 1999). Once the number of potential variables was reduced, the model building was continued in a second software package called SUDAAN (Shah et al. 1997), with which appropriate measures of variance could be used to finalize the model. Linear regression analysis was used to examine the relationship between ESC/columnaris positivity and feed conversion rate (feed fed per pound of fish produced). All final statistical analyses were performed on SUDAAN software, which computes correct variances for weighted, complex survey data. A P-value of 0.1 was used in determining statistical significance.

TABLE 1.—Mean number of ponds at commercial food fish operations in Alabama, Arkansas, Louisiana, and Mississippi and the percentages of all operations and ponds experiencing losses due to enteric septicemia of catfish (ESC)/columnaris in 1996, by operation size (surface water acres).

Operation size (acres)	Mean number of ponds on operations	Operations with disease (%)	Ponds with disease (%)
1–19	3.9	47.0	21.2
20–49	4.4	69.3	47.7
50–149	8.9	86.3	47.1
150 or more	38.2	95.6	41.4
All operations	14.8	78.1	42.1

TABLE 2.—Percentage distribution of operations and ponds by average severity of ESC/columnaris outbreaks in 1996, as measured by pounds of channel catfish lost.

Severity	Operations (%)	Ponds (%)
No losses	21.9	57.9
Light (<200 lb)	24.1	12.1
Moderate (200–2,000 lb)	35.7	21.3
Severe (>2,000 lb)	18.3	8.7

Results

A total of 571 producers from the four states (129 from Alabama, 117 from Arkansas, 71 from Louisiana, and 254 from Mississippi) responded to the first survey, for an overall response rate of 65.6%. There were 301 respondents (46 from Alabama, 55 from Arkansas, 60 from Louisiana, and 140 from Mississippi) in the second phase of the study, for a response rate of 75.3%. Based on producer reports, it was estimated that 78.1% of all operations and 42.1% of all ponds in the four states experienced problems with ESC/columnaris. Higher percentages of larger operations and ponds on larger operations experienced these problems (Table 1). Outbreak severity was most frequently reported to be moderate (200–2,000 lb per outbreak), both as a percentage of operations and as a percentage of ponds (Table 2). A majority of operations (70.2 ± 2.35% [proportion ± 95% confidence interval]) reported that ESC/columnaris were the diseases that caused the greatest economic loss over the previous three years. Regression analysis indicated that operations reporting problems with ESC/columnaris had significantly higher feed conversion rates than those not reporting problems (2.09 versus 1.70; $P < 0.001$).

Univariate analysis of the survey data showed significant associations between management practices and reported problems with ESC/columnaris (Table 3). The odds ratios for reported outbreaks were higher for larger farms. The odds of a positive report were significantly ($P < 0.001$) higher for operations of 50–149 acres (1 acre = 0.405 ha) and 150 or more acres than for those of less than 20 acres. In addition, reported increases in stocking and feeding rates over the previous three years increased the likelihood of reporting ESC/columnaris losses. Although increasing stocking and feeding rates were positively associated with losses, daily feeding methods and seasonal feeding practices (fall, winter, and spring) were not shown to be significant factors. Operations that drained their ponds every three years or less had lower reported incidences of ESC/columnaris. Other variables that were associated with ESC/columnaris problems were wildlife losses, the frequency of water quality testing, the most important criteria used for selecting fingerlings, stocking size trend, and the use of chemicals (copper sulfate, sodium chloride, and potassium permanganate) for disease treatment. Management practices not univariately associated with reported ESC/columnaris losses were vaccination for ESC, on-farm production of fingerlings, and the use of formalin.

A multivariable logistic regression model identified farm size, the source of the fingerlings used to stock ponds, and the frequency of draining ponds (Table 4) as factors associated with reporting ESC/columnaris problems. Relative to operations of less than 20 acres, the ORs for reporting ESC/columnaris were significantly higher for operations of 50–149 acres (7.8) and 150 or more acres (35.8). There were no differences between operations of less than 20 acres and those of 20–49 acres. Operations that drained their ponds at intervals of more than 3 years were 2.9 times as likely to have reported problems with ESC/columnaris than those that drained their ponds more frequently. Producers who purchased at least some of their fingerlings from outside sources were more likely (OR = 2.5) to report ESC/columnaris losses than those who produced all of their fingerlings.

Discussion

A principal strength of this study is the use of a well-defined inference population that represents a substantial part of the catfish industry. Also, this study represents the largest number of catfish producers that have been surveyed concerning management and health-related issues. The survey approach can be a powerful tool in identifying relationships between management practices, environmental conditions, health status, and production by making

TABLE 3.—Univariable relationships between potential risk factors, including management practices, and the percentage of operations with reported losses due to ESC/columnaris. Odds ratios for losses (positive) are presented relative to a base level (OR = 1); CI = confidence interval.

Risk factor and level	Odds ratio	90% CI	Overall *P*-value
Operation size (surface acres)			<0.001
0–19	1.00		
20–49	2.47	1.24–4.94	
50–149	6.48	3.36–12.47	
150 or more	42.90	17.72–103.90	
Wildlife loss			<0.001
No loss	1.00		
Loss	3.82	2.02–7.21	
Water quality testing			<0.001
Never/only in response to a problem	1.00		
Regularly	3.07	1.88–4.99	
Pond draining interval			<0.001
Every 3 years or less	1.00		
Over 3 years	6.86	3.65–12.87	
Vaccination for ESC			0.126
No	1.00		
Yes	2.68	0.93–7.72	
Any fish stocked that were exposed to ESC as fingerlings			<0.001
No	1.00		
Yes	5.78	3.03–11.03	
Any fish stocked that were purchased from unknown-ESC-status source			0.001
No	1.00		
Yes	3.59	1.87–6.88	
Produce all fingerlings at operation			0.166
No	1.50	0.93–2.43	
Yes	1.00		
Most important criteria in selecting fingerlings			0.064
Price	3.25	0.75–14.13	
Growth	3.56	0.70–17.95	
Disease resistance	1.63	0.33–8.11	
Fish size	6.75	1.49–30.64	
Distance from source	1.00		
Producer's reputation	5.05	1.14–22.43	
Stocking rate trend			0.011
Same or decreasing	1.00		
Increasing	2.39	1.36–4.20	
Stocking size trend			0.084
Same or decreasing	1.74	1.03–2.95	
Increasing	1.00		
Winter feeding			0.565
No feeding	1.00		
Some feeding	1.36	0.56–3.32	
Feeding method			0.230
Feed until activity stops	1.43	0.47–4.32	
Feed until activity slows	3.11	1.05–9.19	
Feed for specific time	1.45	0.51–4.10	
Feed based on fish weight in pond	1.45	0.49–4.32	
Other method	1.00		
Spring feeding regime			0.909
Twice daily	1.25	0.50–3.13	
Once before noon	1.00		
Once after noon	1.10	0.65–1.87	
Fall feeding regime			0.346
Twice daily	1.98	0.89–4.40	
Once before noon	1.28	0.76–2.17	
Once after noon	1.00		
Feeding rate trend			0.012
Decreasing or same	1.00		
Increasing	2.57	1.39–4.75	

TABLE 3.—Continued.

Risk factor and level	Odds ratio	90% CI	Overall *P*-value
Copper used			0.024
No	1.00		
Yes	1.97	1.20–3.23	
Sodium chloride used			<0.001
No	1.00		
Yes	4.17	2.57–6.76	
Potassium permanganate used			0.032
No	1.0		
Yes	2.27	1.21–4.25	
Formalin used			
No	1.65	0.57–4.80	0.441
Yes	1.00		

available information from a large number of operations. This approach to identifying the risk factors associated with production losses has been used in other animal production industries surveyed by NAHMS, including the cow–calf (Sanderson and Dargatz 2000), feedlot (Dargatz et al. 1997), dairy (Wells et al. 1999; Wells and Wagner 2000), and equine (Traub-Dargatz et al. 2001) industries. In addition, Bebak et al. (1997) implemented a mail survey of North American private and public trout hatcheries to examine the associations between management variables and bacterial gill disease.

Martin et al. (1987) described a process called the ''sequence of causal reasoning'' for investigating causality in observational studies. Identification of associations is the first step in that process, which was the primary focus of our study. The second step is to use some criteria to assess whether the association is likely to be a causal relationship. These criteria, as defined by Martin et al. (1987), are time sequence, strength of association, dose–response relationship, biological plausibility, and the consistency and specificity of association. It is not practical to meet all of these criteria in a single study, nor could they be met through a survey conducted at a single point in time. For example, because this study employed a cross-sectional survey, it was not possible to examine the temporal relationships between putative risk factors and disease outcomes. Also, the factors that were examined in this study did not lend themselves to exploration of a dose–response relationship. However, it was possible to examine the strength of association (odds ratio), biological plausibility, and consistency with other studies as a foundation for exploring causality.

TABLE 4.—Multivariable risk factor odds ratios for reported losses due to ESC/columnaris. Table includes variables that were shown to have a significant association ($P < 0.1$) in the final model.

Risk factor and level	Odds ratio	90% CI
Operation size (surface acres)		
0–19	1.0	
20–49	1.6	0.6–4.1
50–149	7.8	3.2–18.9
150 or more	35.8	12.6–101.5
Pond draining interval		
Every 3 years or less	1.0	
Over 3 years	2.9	1.4–5.8
Produce all fingerlings at operation		
No	2.5	1.3–4.9
Yes	1.0	

A potential limitation of this study was that few operations record disease outbreaks and most, if not all, of the survey responses were based on recall of disease events the previous year, which could lead to response bias. Also, many diseases are diagnosed on the pond bank and are based on behavioral and gross clinical signs of disease. Among the producers that reported problems with ESC/columnaris, 59.4% routinely have fish samples tested for disease by a public laboratory or a service provider, 24.5% do their own testing, and 16.1% do not have any testing done for these diseases (USDA 1997a). Although there was a likelihood of a misdiagnosis, these bacterial diseases are of primary importance to producers, are common in the catfish industry, and are easily recognized. The lesions from which a presumptive diagnosis is made are often pathognomonic and can be recognized without bacterial cultures and microscopic examination. Similar approaches have been used to evaluate risk factors for BGD in rainbow trout (Bebak et al. 1997). Bebak et al. (1997) were also limited by the potential for recall bias and dependence on presumptive farmer diagnoses, but it demonstrated the utility of using

univariate and multivariable analyses in defining the risk factors for poorly understood diseases such as BGD. In our study, ESC and columnaris were combined on the questionnaire to avoid problems with recall bias since both diseases often, but not always, occur together. Consequently, it was not possible to separate the two diseases during the analysis.

This survey did not obtain overall figures on the cost of ESC/columnaris to production; however, the large economic effect of these diseases is emphasized by the fact that the majority of producers reported them as the diseases causing the greatest economic impact over the previous three years (1994–1996). ESC/columnaris represented over 49% of the mortality (weighted by operation sales) experienced by catfish operations in 1996 (USDA 1997a). In addition to increasing mortality, these diseases can raise production costs through higher treatment costs and feed consumption, poor feed efficiency, and harvest delays. The higher feed conversion rates for operations with disease problems most likely reflect increased mortality. Feed conversion rates on commercial operations are typically expressed as pounds of feed fed divided by pounds of fish harvested. The production (net weight gain) of fish that die during a disease outbreak is usually not accounted for in feed conversion rates due to the complexity of estimating the number of dead fish and their total weight.

Univariate analysis of the survey data was used to screen for possible risk factors associated with ESC/columnaris infections. A multivariable logistic model was constructed to simultaneously examine the strength of association of multiple independent variables with reported problems with ESC/columnaris. Of all the variables initially included in the multivariable logistic regression, only farm size, source of fingerlings, and pond draining interval were statistically significant and remained in the final model. However, many of the variables shown to have a positive association only in the univariate model are closely related to farm size or have biological plausibility and warrant further discussion. Other variables have less direct associations or no reasonable causal relationship to ESC/columnaris problems. For example, pond treatments are probably not contributing substantially to disease problems. The association with pond treatments, specifically copper sulfate, sodium chloride, and potassium permanganate, may be to due to the preventive or therapeutic use of these chemicals. Although the use of chemotherapeutants, especially waterborne ones, may predispose fish to bacterial diseases, potassium permanganate and copper sulfate are routinely used to reduce bacterial loads on the external surfaces of fish (Schwedler et al. 1985; Plumb 1999). The univariate relationship between water quality testing and ESC/columnaris has no biological relationship and is likely related to indirect associations (such as the possibility that operations that routinely test water are more aware of the health status of their fish).

The univariate association between ESC/columnaris losses and wildlife losses may be due to wildlife's feeding on moribund fish or playing an actual role in disease transmission. Piscivorous birds are attracted to ponds where small fish are dying (Hodges 1989). Similarly, Glahn et al. (1999) noted that the consumption of live catfish by wading birds occurs primarily in the spring and fall (the seasons in which ESC is most prevalent) and suggested that many of the catfish consumed by great egrets *Ardea alba* and great blue herons *Ardea herodias* would otherwise have been lost due to disease. Glahn et al. (2002) corroborated these findings by documenting that great blue herons foraged approximately 40 times more on diseased ponds than on nondiseased ponds. Although Taylor (1992) established that it may be possible for aquatic avian species to serve as disease vectors, recent work by Waterstrat et al. (1999) suggests that birds cannot act as reservoirs for *E. ictaluri*. However, as both this survey and the available scientific literature suggest that piscivorous birds are primarily attracted to sick fish, it is clear that they can function as a mechanical disease vector by transferring infected fish from one pond to another.

With respect to the selection of fingerlings, more than 60% of the producers surveyed considered the fingerling producer's reputation and fish size to be the most important criteria (USDA 1997b). These two criteria were associated with an increased risk for disease in the univariate analysis, while none of the other criteria were associated with decreased risk. Consequently, it does not appear that the producers' most important criteria for selecting fingerlings are substantially reducing the risk of disease. The practice of stocking any fish from sources where the fingerlings were exposed to ESC or the ESC status was unknown increased the likelihood of reporting ESC/columnaris problems. However, this relationship was not significant in the multivariable analysis, and it is questionable whether the health status of fish is known to the farmer because there are no mechanisms in

place to verify past history and exposure to pathogens. Stocking any fish that were vaccinated against ESC or that originated from an ESC-free source did not appear to provide any benefit over not stocking any fish of these types. At the time of this study, however, the only vaccines available were killed bacterins of questionable efficacy (Newman 1993; Thune et al. 1993).

Operation size was shown to be associated with the likelihood of reporting ESC/columnaris in both the univariate and multivariable analyses, while stocking density and feeding rate were only univariately associated with the likelihood of reporting these diseases. The reduced reporting of problems at smaller operations may be related to less-intensive culture practices, such as stocking and feeding rates. The average fingerling stocking rate (weighted according to operation size) for smaller operations (1–19 acres) was reported to be 4,145 fish/acre (SE = 321) versus 7,716 fish/acre (SE = 372) for operations of 150 or more acres (USDA 1997b). This increase in stocking density by operation size also corresponded to an increase in the annual average feeding rate (feed fed per acre per year) from 3.4 tons for the smallest operations to 5.0 tons for the largest operations. The consumption of feed has been shown to increase the severity of *E. ictaluri* infection, and withholding feed has become a common industry practice to decrease ESC-associated losses (Wise and Johnson 1998). Plumb et al. (1994) showed that the survival of posthatch channel catfish challenged with ESC in experimental ponds was highest for fish stocked at lower densities. Mechanistically, increased stocking rates could lead to conditions that are stressful to fish, including overcrowding and poor water quality owing to increased nutrient input (Tucker et al. 1993). In addition to lowering disease resistance, stress may also lead to slower growth that delays harvest and extends the time that fish are exposed to pathogens in the culture system. In our study, no differences in reporting ESC/columnaris losses were associated with how fish were fed (when they were fed on a daily basis) or with winter-feeding practices. These relationships are consistent with the observation by Mitchell and Goodwin (1999) that the emergence of ESC as an important pathogen coincided with the adoption of more intensive production practices.

Operations that did not produce all of their own fingerlings were shown in the multivariable analysis to be more likely to have reported problems with ESC/columnaris. The decreased likelihood of reporting problems when all fingerlings are produced on the operation may be related to several biologically plausible factors. First, the health status and history of the fingerlings would be well known, and stocking decisions would be based on that knowledge. Additionally, handling- or transportation-related stress would be reduced and there would be increased flexibility in stocking strategies, including stocking outside of the temperature ranges conducive to disease outbreaks. The reduction in disease may also come from the enhanced biosecurity obtained through essentially closing the operation to outside introductions; however, ESC is considered to be endemic in most populations of cultured catfish. Conversely, this association may be related to differences in management strategies between operations that typically buy young-of-the-year fish from fingerling producers and those that raise their own fingerlings. Most vertically integrated operations use a three-phase production system to increase the age and size of the fish that are stocked into food fish production ponds (Jim Steeby, Mississippi State University Extension Service, personal communication). In this production scenario, fingerlings that are cultured over several production seasons are subjected to multiple disease epizootics in the fall and spring of each production year before they are stocked into production ponds. Fish that survive these epizootics become resistant to subsequent infections (Vinitnantharat and Plumb 1993; Klesius 1992b); as a result, most losses occur in the first two phases of production, thus reducing the burden of ESC/columnaris losses in production ponds.

Draining ponds at intervals of 3 years or less appeared to substantially reduce the likelihood that an operation would report losses due to ESC/columnaris. Increasing the frequency at which ponds are drained could lower the risk of disease in several ways. In theory, operations that completely harvest their ponds at least every three years could reduce the source of infection by removing the asymptomatic carriers of *E. ictaluri* that tend to increase in older populations of fish (Klesius 1992b). Increasing the frequency with which ponds are drained could also reduce background levels of bacterial pathogens in the pond water. In laboratory studies, Plumb and Quinlan (1986) determined that *E. ictaluri* may be able to survive in pond sediments overlaid with water for extended periods of time. Although there is no literature describing pathogen loading rates and the survival of *E. ictaluri* or *F. columnare* in a commercial

catfish pond environment, it is biologically plausible that draining and drying the pond sediments prior to stocking reduces pathogen levels in the culture system. Frequent draining can also improve environmental quality by reducing the accumulation of sediments that can lead to a decrease in the depth of the pond. Steeby et al. (2001) showed a significant relationship between pond depth and the oxygen-carrying capacity of the culture system whereby shallower ponds required more aeration hours to maintain fish populations than deeper ponds. This indicates that fish populations that are cultured in shallower ponds may be subjected to longer periods of oxygen deprivation and stress.

Conclusion

This study was not conducted to establish firm causal relationships but to generate hypotheses about managerial and environmental interactions that represent significant risks to production. The multivariable model provides the measure of association between the management practices and the outcome variable after adjusting for all the other variables in the model. The associations with operation size, intensive production practices, frequency of draining ponds, and the source of fingerlings used to stock production ponds appear logical and are supported by the scientific literature. However, the associations identified in this study need to be verified through research and production monitoring studies to establish confident cause−effect relationships.

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