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Influence of Simulated Double-crested Cormorant, *Phalacrocorax auritus*, Predation on Multiple-batch Production of Channel Catfish, *Ictalurus punctatus*

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Abstract

The double-crested cormorant, *Phalacrocorax auritus*, is considered the primary depredating bird species on commercially produced channel catfish, *Ictalurus punctatus*, in the southeastern USA. We simulated different levels of cormorant predation on losses at harvest and economic effects on channel catfish production in a multiple-batch cropping system. We observed significant ($P < 0.05$) declines in catfish production at increasing levels of cormorant predation in this study. This decline was mitigated by increased individual growth of catfish at higher predation rates (i.e., lower catfish densities). This mitigating effect produced a non-linear relationship with total kg of catfish harvested per pond resulting in a non-linear incremental increase in breakeven price related to predation. Costs of production ($/kg) increased with increasing predation levels up to very high levels of predation with a cumulative maximum increase in breakeven price of $0.143/kg. These results indicate that losses at harvest due to cormorant predation occur immediately but are mitigated in part by compensatory growth of individual catfish. Losses due to cormorant predation in multi-batch systems can be considerable, but there is not a 1:1 relationship between losses and kg of catfish harvested due to compensatory factors.

Channel catfish, *Ictalurus punctatus*, (catfish) aquaculture is one of the largest dollar value finfish aquaculture industries in the USA (USDA NASS 2014). The majority of this production occurs in the southeastern USA and the delta region of Mississippi in particular (USDA NASS 2014). The double-crested cormorant (*Phalacrocorax auritus*, cormorant) is abundant in the region and is considered the primary depredating bird species on commercially produced channel catfish (Glahn et al. 2000; Dorr et al. 2012a). These factors have resulted in significant concern over the potential economic losses to the catfish aquaculture industry attributable to cormorant. Consequently, there has been considerable effort to understand and manage cormorant depredation issues.

Most of the research effort to date on cormorant impacts to catfish aquaculture has focused on bioenergetics modeling, delta-wide population surveys, and extrapolation of these data to the industry in estimating potential losses (Stickley et al. 1992; Glahn and Brugger 1995; Glahn and Stickley 1995; Glahn et al. 1996; Dorr et al. 2012b). However, little information exists regarding impacts at the pond or farm level. Glahn and Dorr (2002) addressed this issue for single-batch production scenario (Tucker et al. 2004) with alternative prey being present. Although this study provided insights on the effects of cormorant predation and alternative prey, it does not reflect current practices in the aquaculture industry. Glahn et al. (2002) evaluated the effects of cormorant predation at different levels by adapting research pond production data and modeling observed mortalities for multiple-batch cropping systems (see

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Tucker et al. 2004 for a description). However, they acknowledged several shortcomings to this approach for evaluating effects of cormorant predation. Chief among these issues is that other mortality sources (e.g., disease) do not impact catfish and production in the same way as cormorant depredation. Few studies have directly evaluated the potential loss at harvest due to cormorant predation at the individual pond level in a multiple-batch production system. Multiple-batch production of catfish is the primary commercial production method for channel catfish in the USA (Hanson and Steeby 2003).

We used research ponds in a multiple-batch cropping system to evaluate the effects of cormorant depredation on catfish aquaculture that more realistically represents current production practices and characteristics of cormorant foraging on catfish aquaculture (Dorr et al. 2012a). This study can help to better define the economic impact of cormorants on commercial catfish ponds, address some of the issues stated by Glahn et al. (2002), and inform management strategies to alleviate depredation impact. Specifically, our objectives were to (1) determine the effect of simulating different levels of cormorant predation on number and biomass at harvest and compensatory growth and mortality of channel catfish in a multiple-batch cropping system, (2) develop models for describing changes in number and biomass at harvest for varying levels of cormorant predation, and (3) evaluate these production losses in term of pond level economics.

Materials and Methods

Stocking, Maintenance, and Harvest of Catfish

Forty approximately 0.05-ha catfish ponds were stocked in April 22–23, 2003, using standard multiple-batch practices (Tucker and Robinson 1990) at rates observed in the catfish aquaculture industry 24,710 head/ha (10,000/acre; USDA/APHIS 1997; Tucker et al. 2004). We compressed the time line of this study from the typical 18-mo cycle by stocking ponds to mimic ponds at ≥ 18 mo into the production cycle and immediately following a foodfish harvest cycle. We simulated this point in the harvest cycle by stocking approximately 50% of the total number of catfish as 13–18 cm or stocker size fingerlings for grow-out with the remainder simulating graded and unharvested catfish averaging less than 0.34 kg (Tucker and Robinson 1990). The unharvested catfish represents catfish from the previous stocking that had not grown large enough for sale. This procedure simulated a situation in which a multiple-batch cropping system has recently been harvested of approximately 50% of the total head count for foodfish processing and then restocked with a similar percentage of stocker size fingerlings, to replace the foodfish removed (Tucker et al. 2004).

To simulate cormorant predation, the initial stocking rate of catfish was adjusted based on a given percentage level of predation. Because cormorants primarily consume 15–18 cm fingerlings (Glahn et al. 1995), the initial stocking rate of fingerlings was adjusted based on the level of cormorant predation to be simulated. Cormorant predation on understocked fingerlings in foodfish ponds also occurs primarily in winter, so impacts are often not realized until the subsequent growing season. In total, eight predation levels were evaluated: 0, 15, 30, 45, 60, 75, 90, and 100%. Five ponds were stocked at each of the five associated levels of predation (i.e., 40 ponds total). The control (0% predation) ponds were stocked 50:50 stocker-sized fingerlings and < 0.34 kg catfish, as described in the preceding paragraph. All other pond stocking rates were adjusted based on their associated predation levels. For example, the 15% predation stocking rate was $((0.50 \times 24{,}710/\text{ha})) \times (1-0.15) = 10{,}502/\text{ha}$ of stocker size fingerlings. The 100% predation level received only < 0.34 kg catfish. Average weight of individual catfish per pond at stocking was determined by dividing total weight stocked by total number stocked per pond.

Weights and counts for each category of catfish stocked (i.e., <0.34 kg and fingerling catfish) were recorded to account for the distribution of initial catfish sizes stocked in each pond.

Catfish were fed a satiation diet of 32% protein feed daily (Robinson et al. 2004). Feeding rate was initiated at a level not to exceed 3% of total catfish biomass in the pond. Subsequent feeding was adjusted based on the amount of feed consumed in an approximately 15-min period. If all the feed was consumed in less than 15 min, then the amount of feed was increased; if not, it was reduced. Other factors that may affect feeding are water temperature and health status of catfish. Temperatures lower than about 18 C can reduce the amount or period of feeding (Robinson et al. 2004). Some disease treatments require the reduction or elimination of feeding (Robinson et al. 2004). Daily records of feeding for each pond were maintained for the duration of the study.

After a grow-out period of approximately 7 mo, catfish were harvested and counted from each pond and removed to holding ponds. Harvested catfish were separated into two categories: catfish < 0.34 kg and catfish ≥ 0.34 kg. This was done to track cohort-specific characteristics regarding growth, survival, and production of the two size classes of fish in each pond (i.e., larger but not harvestable size fish and stocker size fingerlings) present at the beginning of the production cycle. Harvesting involved using seine nets and 1–3 seine hauls per pond and hand counting 50 fish at a time into baskets and weighing each basket to the nearest 0.01 kg. Following seining, ponds were drained and all fish missed by seining were hand counted from the drained ponds. Total counts provided information on estimates of total mortality, and compensatory versus additive mortality effects. Average weight of individual catfish per pond at stocking and harvest was determined by dividing total weight stocked or harvested by total number stocked or harvested. Weight data provided estimates of individual compensatory growth and additive or compensatory effects on total weight of catfish harvested for each predation scenario.

Statistical and Economic Analyses

Linear polynomial (first to third order) regression analysis SAS (version 9.2) PROC REG (SAS Institute Inc., 2008) was used to model total weight of catfish harvested from ponds (response variable) at each predation level (explanatory variable) and total weight for each size category harvested (i.e., <0.34 kg and foodfish). The same regression analysis was used to model overall average individual weight of catfish from ponds (response variable) at each predation level and for each size category at harvest. Lastly, we standardized total kg of catfish harvested/pond by survival of remaining fish to isolate the effects of cormorant predation relative to other mortality sources (e.g., disease). We then modeled trends in this standardized harvest estimates using regression analyses as described previously. Higher order polynomials were included for modeling trends in harvest and individual growth if the partial F statistic was $P < 0.15$ and the R^2 was maximized (Draper and Smith 1981). An alpha of 0.05 was used for all other significance tests.

We used the overall weight of catfish standardized for pond specific survival to calculate the kg yield of catfish for each predation level. We then converted these estimates to kg/ha by dividing by the mean pond size in this study. We modified an existing catfish enterprise budget (Engle 2012) for a 104-ha farm which is a common size for a commercial catfish foodfish farm (Engle 2007), and adjusted the stocking rate to 12,355 fingerlings per ha. The feed quantity used in the budget was based on the observed feed conversion ratio (FCR) in this study, and the average size of catfish fingerlings at stocking. This base budget was used for each predation level with the corresponding yields at each predation level used for budget determination. The breakeven price above total cost, which also is the per-kg cost of production, was used for comparison across predation levels.

Results

A total of 35 of the 40 ponds initially stocked were used for analyses (Table 1). Five ponds were not used as they were inadvertently stocked at rates greater than 24,710/ha. The ponds removed included one at the 60% predation rate, two at the 75% predation rate, and two at the 90% predation rate (Table 1). A total of 23,500 ≤ 0.34 kg catfish were stocked at a mean individual weight (total weight/total stocked per pond) of 257 g ($N = 35$, SD = 9.6 g; Table 1). A total of 12,320 fingerlings were stocked at a mean weight of 28 g ($N = 30$, SD = 2.9 g; Table 1).

Catfish were harvested November 3–5, after a grow-out period of 195–198 days. A total of 19,502 foodfish were harvested at a mean individual weight (total weight/total number harvested per pond) of 662 g ($N = 35$, SD = 104.7 g; Table 2). A total of 9118 ≤ 0.34 kg catfish were harvested at a mean individual weight of 236 g ($N = 33$, SD = 64.7 g; Table 2). Trend in overall weight of catfish harvested was significant ($F_{2,32} = 17.48$, $P < 0.001$) and non-linear ($R^2 = 0.52$, Fig. 1A). Trend in total weight of <0.34 kg catfish harvested was significant ($F_{1,33} = 157.36$, $P < 0.001$) and linear ($R^2 = 0.83$, Fig. 1B). Trend in total weight of foodfish harvested was significant ($F_{2,32} = 11.42$, $P < 0.001$) and non-linear ($R^2 = 0.42$, Fig. 2A). Trend in overall weight of catfish harvested and standardized for pond specific survival was significant ($F_{2,32} = 34.05$, $P < 0.001$) and non-linear ($R^2 = 0.68$, Fig. 2B). Trend in mean individual weight of all catfish harvested was significant ($F_{2,32} = 27.79$, $P < 0.001$) and non-linear ($R^2 = 0.64$, Fig. 3A). Trend in mean individual weight of foodfish harvested was non-significant. Trend in mean individual weight of <0.34 kg catfish harvested was significant ($F_{2,28} = 23.80$, $P < 0.001$) and non-linear ($R^2 = 0.63$, Fig. 3B). Mean survival of all catfish in all ponds was 78.8% (min = 44.2, max = 93.7). There was no significant trend in survival across predation levels.

Trend in overall weight of catfish harvested and standardized for pond-specific survival (Fig. 2B) was used to generate harvest estimates used in the catfish production enterprise budget. The incremental increase in breakeven price ($/kg) at each predation level ranged from −$0.003 to $0.031 (mean = 0.013, SD = 0.013, $n = 7$). The cumulative maximum breakeven price was $0.143/kg. Costs of production ($/kg) increased with increasing predation levels up to very high levels of predation (Fig. 4). However, the incremental rate of increase declined as predation level increased due to lower total costs of production caused by lower feeding rates and increased individual catfish growth (Fig. 4).

Discussion

We observed significant declines in catfish production at increasing levels of cormorant predation simulated in this study. However, this decline was mitigated in part by increased individual growth of catfish at lower catfish densities. The mitigating effect of increased individual catfish growth (Fig. 3) produced a non-linear relationship with total kg of catfish harvested per pond (Fig. 1A), even when only considering losses attributable to cormorant predation (Fig. 2B). The effects of compensatory growth resulted in a non-linear incremental increase in price per kg necessary to break even with respect to production costs (Fig. 4). Increased predation levels resulted in lower total costs of production due to lower feeding rates. However, the lower yields that resulted from increased predation resulted in per-kg costs of production that increased as predation rates increased up to very high (90%) rates of predation. Clearly, profitability, for any given farm price of catfish, will decrease as per-unit cost of production increases (Fig. 4).

As in this study, Glahn et al. (2002) found that cormorant predation had a non-linear relationship with the simulated number of catfish consumed by cormorants foraging on individual ponds. However, the maximum mortality modeled by Glahn et al. (2002) was about 60 and 40% at the 18,500 catfish/ha and 25,000 catfish/ha stocking rates, respectively. Thus, Glahn et al. (2002) had no samples at higher mortality rates from which to draw conclusions regarding the relationship between cormorant predation and effects on harvest. While USDA (2010) reported catfish farmers' estimates of losses from single depredation events, there are no data from commercial catfish farms that measure actual, cumulative losses due to predation. Glahn et al. (2002) also used production data from experimental ponds that had varying sources of mortality to estimate cormorant impacts. The losses modeled by Glahn et al. (2002) and used to simulate cormorant predation

TABLE 1. *Number of ponds (N) at each predation level, mean pond size (standard deviation), mean number and weight (kg) of < 0.34 kg channel catfish,* Ictalurus punctatus*, and stocker size fingerlings stocked per pond, respectively, and total number and weight (kg) stocked in ponds using multiple-batch production at different simulated double-crested cormorant,* Phalacrocorax auritus*, predation levels in April 2003.*

N	Mean pond ha	Simulated predation level	Mean number ≤ 0.34 kg	Mean number fingerlings	Total number	Mean weight ≤ 0.34 kg	Mean weight fingerlings	Total weight Stocked
5	0.06 (0.004)	0.00	730 (45)	730 (45)	1460 (89)	193.1 (8.9)	19.2 (1.5)	212.4 (10.2)
5	0.06 (0.003)	0.15	690 (42)	587 (36)	1277 (77)	177.4 (16.0)	16.4 (1.0)	193.8 (16.6)
5	0.05 (0.007)	0.30	660 (82)	462 (58)	1122 (140)	172.6 (20.1)	12.8 (3.4)	185.3 (23.2)
5	0.05 (<0.000)	0.45	600 (0)	330 (0)	930 (0)	152.0 (4.7)	9.0 (0.7)	160.9 (5.3)
4	0.05 (0.005)	0.60	675 (65)	270 (25.8)	945 (90)	172.6 (15.7)	8.1 (1.2)	180.7 (16.9)
3	0.05 (<0.000)	0.75	650 (0)	163 (0)	813 (0)	163.3 (9.1)	5.1 (0.5)	168.4 (8.6)
3	0.06 (0.004)	0.90	700 (50)	70 (5)	770 (55)	178.4 (13.4)	1.9 (0.2)	180.3 (13.3)
5	0.05 (0.002)	1.00	670 (27)	0 (0)	670 (27)	167.9 (6.1)	0.0 (0.0)	167.9 (6.1)

TABLE 2. *Number of ponds (N) at each predation level, mean pond size (standard deviation), mean number and weight (kg) of foodfish and < 0.34 kg channel catfish,* Ictalurus punctatus*, harvested per pond, respectively, and total number and weight (kg) harvested from ponds using multiple-batch production at different simulated double-crested cormorant,* Phalacrocorax auritus*, predation levels in November, 2003.*

N	Pond ha	Predation level	Mean number foodfish	Mean weight foodfish	Mean number ≤0.34 kg	Mean weight ≤ 0.34 kg	Total number	Total weight
5	0.06 (0.004)	0.00	684 (26)	587.7 (33.6)	517 (47)	100.4 (9.4)	1200 (69)	688.1 (40.6)
5	0.06 (0.003)	0.15	623 (68)	533.3 (56.5)	438 (76)	83.0 (12.3)	1060 (133)	616.4 (67.5)
5	0.05 (0.007)	0.30	547 (123)	468.6 (95.3)	320 (90)	66.1 (18.4)	867 (187)	535.0 (105.7)
5	0.05 (<0.000)	0.45	427 (87)	368.6 (78.4)	193 (88)	40.0 (9.2)	620 (150)	408.6 (80.1)
4	0.05 (0.005)	0.60	572 (70)	467.4 (51.6)	233 (63)	51.4 (11.4)	805 (130)	518.8 (59.4)
3	0.05 (<0.000)	0.75	441 (170)	353.2 (131.6)	186 (33)	49.3 (4.9)	627 (193)	402.5 (132.6)
3	0.06 (0.004)	0.90	558 (67)	487.3 (40.5)	84 (2)	22.7 (3.3)	642 (65)	510.0 (37.5)
5	0.05 (0.002)	1.00	567 (41)	487.6 (71.5)	5 (10)	1.6 (3.5)	571 (45)	489.1 (72.0)

effects on catfish harvest were caused primarily by disease, which differed from our study. Disease may affect various size and age classes differently and therefore effects on final harvest. Disease also occurs throughout the production cycle, whereas cormorant predation on catfish in the southeastern USA occurs primarily during the winter months. In addition, disease may inhibit growth of remaining catfish if they have symptoms but recovered or if the disease was chronic.

Conversely, cormorants are relatively specific in the mortality they cause on catfish in that they primarily consume 15–18 cm fingerlings during the winter (Glahn et al. 1995). So losses of stocker size fingerling generally occur either before or after the growing seasons for stocked catfish. The mortality on specific size classes of catfish modeled in this study differs from that of Glahn et al. (2002), and better simulates the effects of cormorant predation in the industry. In addition, Glahn et al. (2002) used data from catfish cultured in single-batch ponds not multiple-batch ponds as in this study. The effects of the presence of larger fish competing with smaller fish for the same food resource may influence compensatory growth effects at varying catfish densities. These differences may account for the mitigating effect of compensatory growth observed in this study.

Glahn et al. (2002) found that higher catfish stocking densities (25,000 vs. 18,500 catfish/ha) may mitigate the effects of cormorant predation on catfish. Glahn et al. (2002) attributed this finding to compensatory mortality and growth of surviving fish. They also found that simulated predation did not appear to affect production in single-batch systems until it exceeded

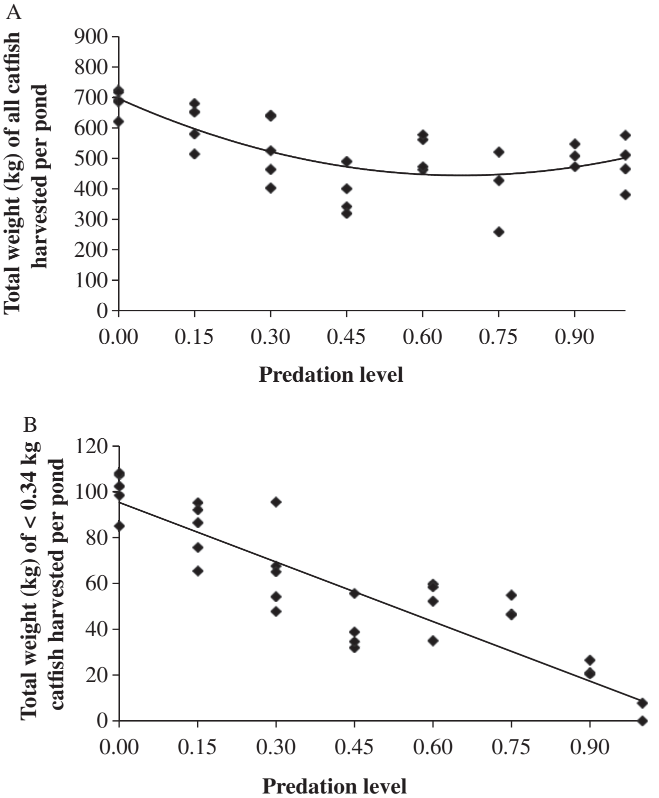

FIGURE 1. *(A) Non-linear trend (*$R^2 = 0.52$*) in total weight of all channel catfish,* Ictalurus punctatus*, harvested November 3–5, 2003 from 35 ponds stocked April 2–3, 2003, in Mississippi to simulate various levels of double-crested cormorant,* Phalacrocorax auritus*, predation. (B) Linear trend (*$R^2 = 0.83$*) in weight of* < 0.34 *kg catfish harvested.*

about 15% mortality relative to total stocked in single-batch systems. We did not find a difference in survival of remaining catfish across the various predation levels due to factors other than predation (e.g., disease) in our study. Therefore, compensatory factors mitigating losses in our study appeared to be driven by compensatory growth of surviving catfish rather than other mortality sources. In our multiple-batch system, we described an immediate non-linear drop in production (Fig. 1A) at a declining rate up to about 60% predation level. Beyond 60% predation compensatory growth mitigated losses in the multiple-batch system but never fully regained the production at lower predation levels. For data standardized for survival of remaining catfish (to isolate cormorant predation effects), the threshold for mitigating losses occurred at about the 75% predation level of stocker size fingerlings (Fig. 2B). This differs from the findings of Glahn et al. (2002).

We did observe a linear trend in losses of 0.34 kg size catfish harvested (Fig. 1B). These fish likely represent smaller fingerlings stocked or catfish that exhibited slower growth than their cohorts or some combination of these factors. This effect of uneven growth of individual fish is well documented in almost all finfish aquaculture and certainly in catfish aquaculture (Tucker et al. 2004). In addition, growth rate tends to slow as fish get larger. This effect was observed in our study as there was no trend in mean weight of food-size catfish harvested relative to predation level. However, there was a significant non-linear trend in the individual growth rates of <0.34 kg catfish harvested. Thus, some fingerlings stocked grew faster, particularly at higher predation levels. As food should

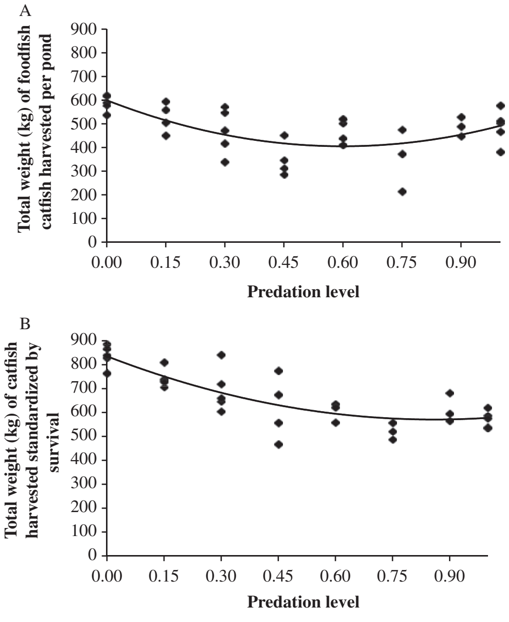

FIGURE 2. *(A) Non-linear trend (*$R^2 = 0.42$*) in weight of food size channel catfish,* Ictalurus punctatus*, harvested November 3–5, 2003, from ponds stocked in April 2–3, 2003, in Mississippi to simulate various levels of double-crested cormorant,* Phalacrocorax auritus*, predation. (B) Non-linear trend (*$R^2 = 0.68$*) in overall weight of catfish harvested standardized for pond specific survival.*

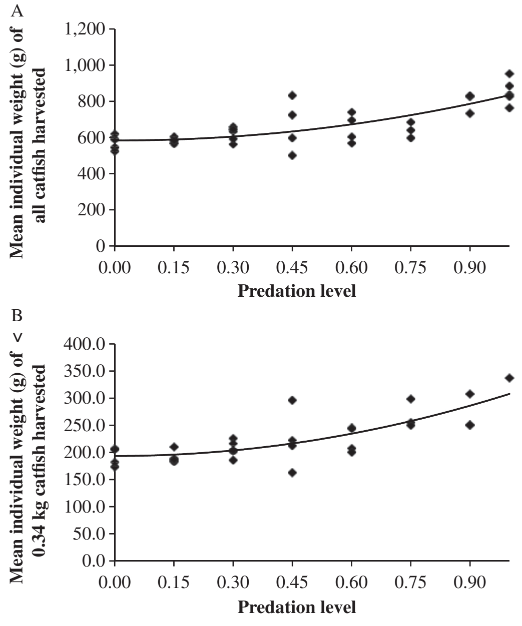

FIGURE 3. *(A) Non-linear trend in (*$R^2 = 0.64$*) in mean individual weight of all channel catfish,* Ictalurus punctatus*, harvested November 3–5, 2003, from ponds stocked in April 2–3, 2003, in Mississippi to simulate various levels of double-crested cormorant,* Phalacrocorax auritus*, predation. (B) Non-linear trend in (*$R^2 = 0.63$*) in mean individual weight of < 0.34 kg catfish harvested.*

not be limiting (fish were fed to satiation), the individual compensatory growth response may be due to a density-dependent response caused by a reduction in competition or overcrowding at higher predation levels. This increased growth associated with the lower total numbers likely produced the mitigating effects on losses observed in this study at higher predation rates.

To our knowledge, this is the first effort to model the impacts of cormorant predation on harvest in a simulated multiple-batch production system (Tucker and Robinson 1990; Tucker et al. 2004). Our findings indicate that losses at harvest due to cormorant predation occur immediately in a multiple-batch system but are mitigated to some degree primarily by compensatory growth of individual catfish at higher predation levels. Glahn and Dorr (2002) found similar compensatory effects on cormorant predation in simulated single-batch catfish culture systems. They attributed this to several factors including compensatory growth, mortality, and the presence of a buffer prey. Regardless of whether cormorant predation occurs in single-batch or multiple-batch systems, losses due to cormorant predation can be considerable, but there is not a one-to-one relationship between losses and kg harvested due to compensatory factors.

This study evaluated effects of a range of cormorant predation levels in a simulated multiple-batch catfish culture system based on an initial stocking density of 25,000 channel catfish/ha. However, this range of predation levels may have different outcomes if initial stocking levels are much lower (e.g., 12,500 catfish/ha). In addition, this study represents effects after only one production cycle. If cormorant depredation on fish stocks occurs over multiple years, the producer may realize a cumulative decline in numbers of fish in the pond and harvested. Lastly, hybrid catfish grow faster which may reduce vulnerability to predation

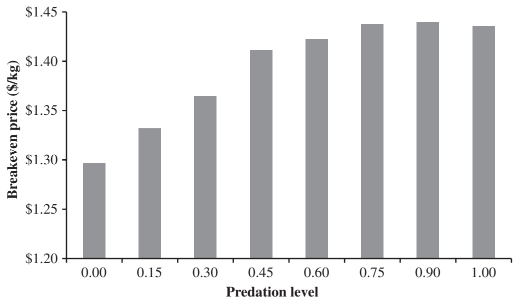

FIGURE 4. *Estimated breakeven price of channel catfish,* Ictalurus punctatus*, harvest ($U.S./kg) above total production cost specific to losses associated with varying levels of simulated double-crested cormorant,* Phalacrocorax auritus*, predation.*

(Wolters and Tiersch 2004). Further research could provide valuable insights on the use of hybrids and how production at varying stocking densities and multiple production cycles in a multiple-batch culture system is affected by cormorant predation.

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Literature Cited

Dorr, B. S., L. W. Burger, S. C. Barras, and K. C. Godwin. 2012a. Double-crested cormorant distribution and abundance on catfish aquaculture in the Yazoo River Basin of Mississippi. Wildlife Society Bulletin 36:70–77.

Dorr, B. S., L. W. Burger, S. C. Barras, and K. Godwin. 2012b. Economic impact of double-crested cormorant (*Phalacrocorax auritus*) depredation on channel catfish (*Ictalurus punctatus*) aquaculture in Mississippi, USA. Journal of World Aquaculture 43:502–513.

Draper, N. R. and H. Smith. 1981. Applied regression analysis, 2nd edition. John Wiley and Sons, Inc., New York, New York, USA.

Engle, C. R. 2007. Arkansas catfish production budgets. MP466, Arkansas Cooperative Extension Program, University of Arkansas at Pine Bluff, Pine Bluff, Arkansas. Accessed March 25, 2015 at http://www.extension.org/mediawiki/files/b/ba/Arkansas_Catfish_Production_Budgets.pdf.

Engle, C. R. 2012. Catfish Enterprise budgets. University of Arkansas at Pine Bluff, Pine Bluff, Arkansas. Accessed March 30, 2015 at: http://aqfi.uaex.edu/extension/aquaculture/economics/.

Glahn, J. F. and K. E. Brugger. 1995. The impact of double-crested cormorants on the Mississippi Delta catfish industry: a bioenergetics model. Colonial Waterbirds 18 (Special Publication 1):168–175.

Glahn, J. F. and B. Dorr. 2002. Captive double-crested cormorant predation on channel catfish (*Ictalurus punctatus*) fingerlings and its influence on single batch cropping production. Journal of the World Aquaculture Society 33:85–93.

Glahn, J. F. and A. R. Stickley Jr. 1995. Wintering double-crested cormorants in the delta region of Mississippi: population levels and their impact on the catfish industry. Colonial Waterbirds 18 (Special Publication 1):137–142.

Glahn, J. F., P. J. Dixson, G. A. Littauer, and R. B. Mccoy. 1995. Food habits of double-crested cormorants wintering in the delta region of Mississippi. Colonial Waterbirds 18:158–167.

Glahn, J. F., A. May, K. Bruce, and D. S. Reinhold. 1996. Censussing double-crested cormorants (*Phalacrocorax auritus*) at their winter roosts in the delta region of Mississippi. Colonial Waterbirds 19:73–81.

Glahn, J. F., D. S. Reinhold, and C. A. Sloan. 2000. Recent population trends of double-crested cormorants wintering in the delta region of Mississippi: responses to roost dispersal and removal under a recent depredation order. Waterbirds 23:38–44.

Glahn, J. F., S. J. Werner, T. Hanson, C. R. Engle. 2002. Cormorant predation losses and their prevention at catfish farms: Economic considerations. Pages 138-146 *in* L. Clark, editor. Human conflicts with wildlife: economic considerations. United States Department of Agriculture, Wildlife Services, National Wildlife Research Center. Proceedings of the 3rd NWRC Special Symposium, Fort Collins, Colorado, August 2000.

Hanson, T. R. and J. A. Steeby. 2003. Comparison of multiple-batch and "modular" catfish production systems. NWAC News, The Thad Cochran National Warmwater Aquaculture Center, Stoneville, Mississippi, USA.

Robinson, E. H. B., B. Manning, and M. H. Li. 2004. Feeds and feeding practices. Pages 324–328 *in* C. S. Tucker and J. A. Hargreaves, editors. Biology and culture of channel catfish. Elsevier B.V., San Diego, California, USA.

SAS Institute Inc. 2008. SAS/STAT 9.2 user's guide. SAS Institute Inc., Cary, North Carolina, USA.

Stickley, A. R., G. L. Warrick, and J. F. Glahn. 1992. Impact of double-crested cormorant depredations at channel catfish farms. Journal of the World Aquaculture Society 23:192–198.

Tucker, C. S. and E. H. Robinson. 1990. Channel catfish farming handbook. Van Nostrand Reinhold, New York, New York, USA.

Tucker, C. S., J. L. Avery, and D. Heikes. 2004. Culture methods. Pages 166–195 *in* C. S. Tucker and J. A. Hargreaves, editors. Biology and culture of channel catfish. Elsevier B.V, San Diego, California, USA.

US Department of Agriculture, Animal Plant Health Inspection Service. 1997. Catfish NAHMS '97, Part II: reference of 1996 U.S. catfish management practices. USDA/APHIS Centers for Epidemiology and Animal Health, Fort Collins, Colorado, USA.

US Department of Agriculture, Animal Plant Health Inspection Service. 2010. Catfish 2010 Part III: changes in catfish health and production practices in the United States 2002–2009. USDA-APHIS-VS-CEAH-NAHMS, Fort Collins, Colorado, USA.

US Department of Agriculture, National Agriculture Statistics Service. 2014. The 2012 Census of Agriculture. Accessed July 23, 2014 at http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/st99_1_032_033.pdf.

Wolters, W. R. and T. R. Tiersch. 2004. Genetics and breeding. Pages 95–128 *in* C. S. Tucker and J. A. Hargreaves, editors. Biology and culture of channel catfish. Elsevier B.V, San Diego, California, USA.