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# Economic Impact of Double-Crested Cormorant, *Phalacrocorax auritus*, Depredation on Channel Catfish, *Ictalurus punctatus*, Aquaculture in Mississippi, USA

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## Abstract

**The Yazoo River Basin of Mississippi, USA, supports the largest concentration of hectares devoted to channel catfish, *Ictalurus punctatus*, aquaculture production in North America. The Yazoo Basin also supports large numbers of resident, wintering and migrating fish-eating birds, with the Double-crested Cormorant, *Phalacrocorax auritus*, implicated as the most serious depredating species. We used data from aerial surveys of numbers and distribution of cormorants in the Yazoo Basin and on commercial catfish ponds during winters (November–April) 2000–2001 and 2003–2004 to refine estimates of regional economic losses due to cormorant depredation. In both periods, the greatest monthly estimates of cormorant foraging occurred from 1 January to 31 March. Losses in terms of biomass, number, and dollar value were greater for foodfish ponds than fingerling ponds. Monthly weighted estimates of catfish consumed were 1775.3 and 1346.6 m.t. over winters 2000–2001 and 2003–2004, respectively. Total estimated losses for foodfish and fingerling ponds in 2000–2001 were $11.56 and $0.48 million, respectively, and in 2003–2004 were $5.22 and $0.40 million, respectively. Maximum dollar loss occurred during March in 2000–2001 and during February in 2003–2004. In this study, the volatility in variable production costs and nominal sales price, and distribution of cormorants on pond types and regionally were key factors in resulting economic loss estimates.**

Commercial production of channel catfish (catfish) is the largest aquaculture industry in the United States with catfish being the sixth most frequently consumed finfish in the United States as of 2008 (National Fisheries Institute 2009). The farm-gate value of the catfish crop was estimated at $373 million in 2009 (USDA NASS 2009), and sales of fresh and frozen processed product grossed $613 million in 2008 (Hanson and Sites 2009). More than half of the total hectares in production and associated value of catfish produced occur in the Yazoo River Basin (Yazoo Basin) of Mississippi (Hargreaves and Tucker 2004). Geologic and socioeconomic factors, such as the ready availability of large quantities of groundwater, existing agriculture infrastructure, flat topography, and clay soils with low infiltration

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rates, have made the Yazoo Basin conducive to catfish aquaculture (Hargreaves and Tucker 2004). These characteristics have allowed for large-scale catfish production methods in the Yazoo Basin suited to "embankment" type production ponds (Boyd 1985, 2004). Embankment ponds are typically large (3–8 ha), shallow (1.2–1.8 m), open rectangular ponds (Boyd 2004) with the average farm in the Yazoo Basin comprised of 25 ponds totaling 117 ha of water surface area (USDA 2003). These embankment type production ponds provide a readily available food resource for many species of fish-eating birds.

Many of the characteristics that make the Yazoo Basin conducive to large-scale catfish aquaculture also make it an important area for resident, migratory and wintering waterbirds. Included among these waterbirds are numerous piscivorous species that come into conflict with aquaculture producers. A survey of catfish producers in 1996 indicated that the two primary sources of catfish losses in commercial operations were disease (45%) and wildlife (37%) (USDA 1997). Of wildlife species at catfish farms, species or species groups of piscivorous birds have been identified as the primary depredators. These birds include Double-crested Cormorants (cormorant), wading birds and the American White Pelican *Pelecanus erythrorhynchos* (Wywialowski 1999). Cormorants were implicated by catfish producers as the most serious depredating species with respect to direct predation losses (Wywialowski 1999). The fact that cormorants are perceived as the primary depredating species is likely due to the fact that cormorant populations have increased by an order of magnitude since the 1970s (Hatch 1995; Tyson et al. 1999). The importance of catfish aquaculture production and the number of cormorants wintering in the Yazoo Basin and utilizing aquaculture have resulted in increasing concern with the economic impacts of depredation.

Economic loss associated with cormorant depredation has been estimated by various methods and at various scales. At the industry scale, Wywialowski (1999) used producer surveys to estimate a $12 million annual loss due to wildlife. However, this estimate included all depredating wildlife species and did not partition the component attributable to cormorants.

Glahn and Brugger (1995) used a bioenergetics modeling approach to estimate regional loss in the Yazoo Basin specific to cormorants. Spatial distribution of cormorants in the Yazoo Basin was a significant factor in Glahn and Brugger's (1995) loss estimates because there are significant differences in diet based on where cormorants forage in the Yazoo Basin. Glahn and Dorr (2002) estimated losses at harvest for foodfish grow-out ponds at a given stocking rate and levels of cormorant predation (500 cormorant/d/ha/yr) observed by Stickley et al. (1992) and in the presence of a "buffer" prey species, golden shiner, *Notemigonus chrysoleucas*. Glahn and Dorr (2002) found that loss at harvest in this scenario was 22% of biomass, resulting in a 111% loss in profit per pond. Glahn et al. (2002) and Glahn and Dorr (2002) estimated that losses at harvest may be as much as five times greater than replacement cost to producers (i.e., fingerling sale price) if losses occur on foodfish ponds compared with fingerling ponds. Because data on the distribution of cormorants on production pond types were unavailable to Glahn and Brugger (1995), their estimated losses of $5 million were determined at simple replacement cost of $0.10 per fingerling. The result of the aforementioned research has been that losses to cormorant depredation on catfish aquaculture in the Yazoo Basin have been estimated at between $5 million and $25 million annually, dependent on whether the loss is occurring on fingerling or foodfish ponds (Glahn et al. 2002). The estimated difference in loss is largely attributable to the distribution of cormorants both geographically within the Yazoo Basin and their distribution on pond types (i.e., foodfish or fingerling).

Our objective was to use aerial survey information on population estimates and distributions of cormorants on commercial catfish ponds obtained over a 2-yr period in the Yazoo Basin and incorporate this information with existing food-habits and bioenergetics information specific to cormorants wintering in the

Yazoo Basin. These data were then used to refine estimates of economic losses due to cormorant depredation on catfish aquaculture in the Yazoo Basin.

## Materials and Methods

We used Glahn and Brugger's (1995) approach to estimating regional economic loss due to cormorant depredation which was based on modeling energy flow between predator and prey. Glahn and Brugger (1995) built a three-component model to estimate (1) individual energy demand of cormorants wintering in the Yazoo Basin, (2) extrapolate individual energy demands to population energy demands, and (3) estimate catfish crop losses per month and total for the wintering season, given as November–April.

Glahn and Brugger (1995) developed estimates of basal metabolic rate (BMR) partitioned into active (day) and inactive (night) phases, adjusted for mean monthly temperature, average monthly day and night length in hours and mean monthly biomass of cormorants collected for food habits in the Yazoo Basin during winters 1989–1990 and 1990–1991. The BMR estimate was adjusted upward for the additional energy required beyond BMR for thermoregulation based on time budgets for five activities (flying, diving, swimming, daytime loafing, and night roosting) observed for VHF-marked cormorants (King et al. 1995) in the Yazoo Basin. The resulting daily energy budget was then adjusted for the average metabolic efficiency of cormorants fed diets of catfish, gizzard shad, *Dorosoma cepedianum*, and bluegill, *Lepomis macrochirus* (Brugger 1992, 1993), which comprise most of the diet of cormorants wintering in the Yazoo Basin (Glahn et al. 1995).

From this bioenergetics information, Glahn and Brugger (1995) developed the average monthly fish consumption in g/bird/d for cormorants wintering in the Yazoo Basin. For the first and second model components, we used the average of the 2-yr individual fish consumption in g/bird/d specific to each month developed from estimates derived by Glahn and Brugger (1995). We then extrapolated these individual average monthly fish consumption estimates to population estimates derived from aerial night roost surveys in the Yazoo Basin.

Aerial survey counts of cormorants in all known night roosts in the Yazoo Basin were scheduled biweekly from October–April in winters 2000–2001 and 2003–2004, and conducted by personnel with the United States Department of Agriculture, Wildlife Services, Mississippi (WS-MS). Aerial surveys were conducted in a Cessna 172 at 150–215 m above ground level, at a flight speed of about 175 kph. Surveys were conducted from sunrise to 3 h after sunrise and 3 h prior to sunset to sunset following procedures described by Glahn et al. (1996).

Aerial survey counts were used to develop estimates of the number of cormorant foraging days per month derived from polynomial trend equations that best described the relationship between the trend and biweekly night roost counts as measured by the associated $R^2$ value. Because diet varies between river and interior roost locations (Glahn et al. 1995), we developed separate polynomial equations for aerial counts of cormorants night roosting within each region (Fig. 1). Cormorant counts at the beginning (i.e., 1 October) and end (i.e., 30 April) of the wintering period were assumed to be zero. The presence of resident birds and associated depredation was considered to be negligible. By integrating the area under the curve of the trend equation, we determined the total number of cormorant days of predation per month and region. Although aerial surveys were conducted to determine numbers of cormorants in the Yazoo Basin in October, we did not use these numbers in loss estimates because information on proportion of catfish in the diet is lacking (Glahn et al. 1995). Also, bioenergetics specific to characteristics of cormorant physiology and activity in October have not been developed as it has for other months.

Glahn et al. (1995) determined that the average proportion of catfish biomass in diets of cormorants roosting in the river region (Fig. 1) was 14.3 and 74.5% for the interior region (Fig. 1) in the Yazoo Basin ($n = 461$ stomachs). The average biomass of catfish consumed

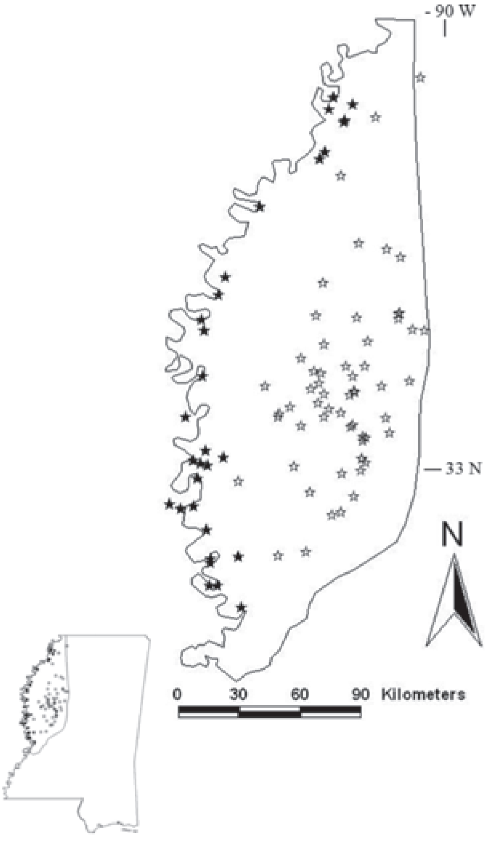


FIGURE 1. *The Yazoo River Basin of Mississippi. Locations (stars) of known Double-crested Cormorant night roosts aerially surveyed by United States Department of Agriculture, Wildlife Services, Mississippi, during the winters (October–April) 2000–2001 and 2003–2004. Roosts were surveyed in daylight in the early AM and late PM before cormorants depart the night roost and after they return, respectively. Open stars represent known interior night roost locations and solid black stars represent known night roost locations along the Mississippi River.*

over the wintering period for each region was used in consumption estimates. The number of cormorants counted within each region weighted overall consumption proportionally within regions. Average total biomass of catfish consumed by cormorants was determined by multiplying total number of foraging days within each month and region by the weighted % biomass of catfish in the diet by the fish consumption in g/bird/d. Because Dorr et al. (2011) determined during winters 2000–2001 and 2003–2004 that cormorant foraging on pond types was functionally proportional to pond distribution, average total biomass of catfish consumed within pond types was determined by multiplying biomass consumed by % availability of each pond type in Mississippi (Hanson and Sites 2005). The biomass consumed was then converted to total number of fingerlings based on observed diets of cormorants wintering in the Yazoo Basin (Glahn et al. 1995) and the estimated number of fingerlings per m.t. based on size and mass distribution in the diet as reported by Glahn and Brugger (1995).

The value of catfish lost to cormorants from fingerling ponds was determined at the average sale value (i.e., replacement cost) for stocker sized fingerlings during 2000–2001 and 2003–2004 (Hanson and Sites 2005), multiplied by the total number of fingerlings consumed from fingerling ponds. Because most of the size classes of fingerlings consumed by cormorants (Glahn et al. 1995) would have already survived to a harvestable size, no adjustment for compensatory mortality to harvest due to other mortality sources such as disease was made (i.e., they have already reached a saleable size). Because losses to cormorants on foodfish ponds are not realized until harvest, estimation of losses from foodfish ponds were determined as the net revenue lost at harvest or the "opportunity cost" of cormorant depredation specific to catfish aquaculture production in the Yazoo Basin.

Opportunity cost is defined as the measure of the cost of choosing to use one resource over an alternative (Hyman 1997). The opportunity cost in the context of cormorant depredation is the net revenue that could have been earned in the absence of depredation. We computed this value as the value of the average size foodfish sold, less total variable costs to produce a given foodfish for each period in this study (i.e., 2000–2001 and 2003–2004). The resulting value was the estimated value lost due to cormorant depredation. This opportunity cost was then multiplied by the estimated number of fingerlings removed from foodfish ponds to estimate the total opportunity cost due to removal of fingerlings.

TABLE 1. *Estimate of opportunity cost of catfish fingerlings removed from foodfish production ponds due to Double-crested Cormorant depredation. Based on Mississippi industry averages for study periods 2000–2001 and 2003–2004.*

| Variable (2003–2004) | Value or cost 2000–2001 | Value or cost 2003–2004 |
|---|---|---|
| Average weight (g) of foodfish harvested[a] | 676.10 | 823.85 |
| Average weight (g) of fingerling consumed[b] | 38.10 | 38.10 |
| Expected growth (g) to average harvested size | 638.00 | 785.75 |
| Feed conversion ratio[c] | 2.28 | 2.28 |
| Grams of feed fed/fish | 1454.64 | 1791.51 |
| Cost of feed/kg[a] | 0.21 | 0.27 |
| Cost of feed/fish | 0.31 | 0.49 |
| Other variable costs[d] | 0.31 | 0.49 |
| Total variable cost ($)/fish | 0.62 | 0.98 |
| $ At harvest for average size foodfish[a] | 1.05 | 1.24 |
| Less total variable cost/fish ($) | 0.62 | 0.98 |
| Net revenue "lost" (opportunity cost $)/food fish | 0.43 | 0.26 |

[a]Average weight at harvest, $/kg at harvest, and cost of feed for 2000–2001 and 2003–2004 from Hanson and Sites (2005).
[b]From Glahn et al. (1995) and Steeby (1995).
[c]From Li and Lovell (1992) and Hatch et al. (1998).
[d]Assumes other variable production costs are 50% of total variable costs (Hanson et al. 2004).

TABLE 2. *Survey date and counts of Double-crested Cormorants from United States Department of Agriculture, Wildlife Services, Mississippi, aerial census of all known night roosts (* n = 80*) in the Yazoo River Basin of Mississippi, winters 2000–2001 and 2003–2004.*

| 2000–2001 Survey date | 2000–2001 Count | 2003–2004 Survey date | 2003–2004 Count |
|---|---|---|---|
| 25 October | 28,815 | 27 October | 9273 |
| 20 November | 18,600 | 10 November | 8330 |
| 5 December | 10,225 | 8 December | 8375 |
| 8 January | 28,650 | 11 January | 35,900 |
| 26 January | 62,270 | 20 January | 25,285 |
| 5 February | 58,515 | 3 February | 81,873 |
| 20 February | 43,460 | 9 March | 60,058 |
| 12 March | 57,525 | 23 March | 25,837 |
| 19 March | 67,190 | 6 April | 18,960 |
| 5 April | 27,095 | 20 April | 1248 |

Unlike the situation with fingerling ponds, catfish consumed by cormorants from foodfish ponds would be removed at the beginning of the production cycle based on the sizes consumed. Due to depredation occurring at the beginning of the production cycle, mortality of fish removed must be considered in estimating loss at harvest. We used a 1.5% monthly mortality rate for a 12-mo production period (total = 18%) from stocking to harvest (SRAC 2004). This monthly mortality rate treats 18% of cormorant depredation as compensatory to other sources of loss that would have occurred in the absence of depredation with the

TABLE 3. *Trends in Double-crested Cormorant abundance in the Yazoo River Basin of Mississippi, winters 2000–2001 and 2003–2004, as described by polynomial trend equations of order 1–6.*[a]

| Equation order | 2000–2001 $R^2$ interior | 2000–2001 $R^2$ river | 2003–2004 $R^2$ interior | 2003–2004 $R^2$ river |
|---|---|---|---|---|
| 1 | 0.05 | 0.38 | 0.15 | 0.11 |
| 2 | 0.19 | 0.52 | 0.33 | 0.32 |
| 3 | 0.47 | 0.53 | 0.54 | 0.53 |
| 4 | 0.77 | 0.77 | 0.55 | 0.55 |
| 5 | 0.82 | 0.82 | 0.68 | 0.72 |
| 6 | 0.82 | 0.88 | 0.68 | 0.74 |

[a]Trend lines were based on United States Department of Agriculture, Wildlife Services, Mississippi, aerial census ($n$ = 10 in each period) of all known night roosts ($n$ = 80) in the Yazoo Basin. Trend lines were developed separately for night roosts along the Mississippi River and those in the interior Yazoo Basin. Trend lines with the highest $R^2$ and lowest order within each region were used to determine monthly, and total wintering (November–April) cormorant foraging days in the Yazoo Basin.

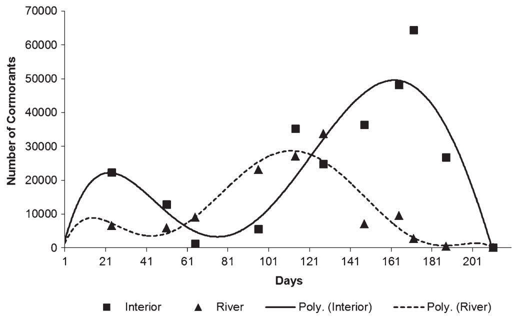


FIGURE 2. *Trend in Double-crested Cormorant numbers per day for winter (1 October–30 April) 2000–2001 based on aerial night roost counts conducted by United States Department of Agriculture, Wildlife Services, Mississippi. Roosts were surveyed in daylight in the early AM and late PM before cormorants depart the night roost and after they return, respectively. Separate polynomial equations were developed for aerial counts of cormorants roosting within interior and river regions of the Yazoo River Basin of Mississippi. Cormorant counts at the beginning (1 October = day 1) and end (30 April = day 212) of the wintering period were assumed to be zero. Equations are given as interior* $y = 0.0000063x^5 - 0.0041241x^4 + 0.9067710x^3 - 77.8874663x^2 + 2325.5706228x$ *and river* $y = -0.0000001x^6 + 0.0000631x^5 - 0.0156995x^4 + 1.7482579x^3 - 83.9686757x^2 + 1506.9946947x$.

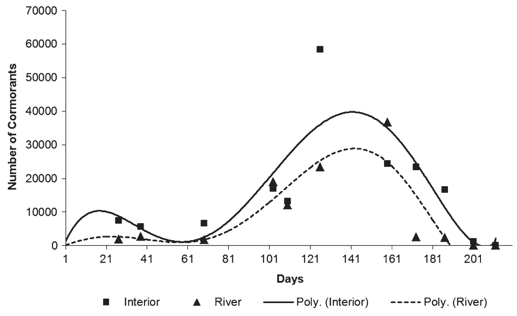


FIGURE 3. *Trend in Double-crested Cormorant numbers per day for winter (1 October–30 April) 2003–2004 based on aerial night roost counts conducted by United States Department of Agriculture, Wildlife Services, Mississippi. Roosts were surveyed in daylight in the early AM and late PM before cormorants depart the night roost and after they return, respectively. Separate polynomial equations were developed for aerial counts of cormorants night roosting within interior and river regions of the Yazoo River Basin of Mississippi. Cormorant counts at the beginning (1 October = day 1) and end (30 April = day 213 {leap year}) of the wintering period were assumed to be zero. Equations are given as interior* $y = 0.0000094x^5 - 0.0049845x^4 + 0.8882470x^3 - 60.4470552x^2 + 1402.9805484x$ *and river* $y = 0.0000001x^6 - 0.0000248x^5 + 0.0038401x^4 - 0.1805454x^3 - 1.4202059x^2 + 204.7374579x$.

remaining 82% assumed to be additive. The estimated value of catfish lost from foodfish ponds was adjusted downward by the % of fish that would have been lost due to other sources of mortality (18%) to determine net loss attributable to cormorant depredation.

## Results

The average sale price for fingerlings was \$0.09 in each study period. The estimated opportunity cost of removal of a fingerling catfish from foodfish ponds due to cormorant depredation was \$0.43 during 2000–2001 and \$0.26 in 2003–2004 (Table 1). Twenty total aerial night roost surveys were flown by WS-MS, 10 in each year. Total counts of cormorants from night roost surveys conducted by WS-MS over both years for the Yazoo Basin ranged from 1248 to 81,873 ($n = 20$, mean = 33,874, SE = 5230; Table 2). Fifth- and sixth-order polynomial equations best described trends in cormorant numbers in the Yazoo Basin based on associated $R^2$ values (Table 3). Peak cormorant counts based on trend lines in winter 2000–2001 for interior and river regions occurred on 12 March and 20 January, respectively (Fig. 2). Peak cormorant counts based on trend lines in winter 2003–2004 for both interior and river regions occurred on 19 February (Fig. 3). Total cormorant foraging days based on trend lines for 2000–2001 and 2003–2004 were 6.5 and 5.2 million, respectively. In 2000–2001, maximum estimates of number of cormorant days of foraging per month for the interior and river regions occurred during March and January, respectively (Table 4). However, maximum total numbers of cormorant foraging days occurred during February (Table 4). In 2003–2004, maximum estimates of number of cormorant days of foraging per month for the interior and river regions and total numbers occurred during February (Table 5). In both periods, the three greatest monthly estimates of cormorant foraging days occurred over the

TABLE 4. *Projected catfish losses due to Double-crested Cormorant depredation in the Yazoo River Basin (YRB) of Mississippi during winter 2000–2001.*[a]

| Month | BFD-I | BFD-R | WDC | BCFIP (m.t.) | BCFOP (m.t.) | NFIC (millions) | NFOC (millions) | LFIP ($10^3$) | LFOP ($10^3$) | TL ($10^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| November | 391,952 | 138,395 | 0.59 | 19.5 | 120.8 | 0.42 | 2.59 | $38.0 | $913.5 | $951.5 |
| December | 135,619 | 489,548 | 0.27 | 12.5 | 77.3 | 0.27 | 1.66 | $24.3 | $584.6 | $609.0 |
| January | 522,823 | 851,385 | 0.37 | 36.1 | 223.1 | 0.77 | 4.79 | $70.2 | $1687.6 | $1757.9 |
| February | 1,095,119 | 582,594 | 0.54 | 64.7 | 400.2 | 1.39 | 8.58 | $126.0 | $3026.7 | $3152.6 |
| March | 1,474,314 | 171,583 | 0.68 | 78.8 | 487.2 | 1.69 | 10.45 | $153.3 | $3684.7 | $3838.1 |
| April | 651,407 | 24,566 | 0.72 | 35.5 | 219.6 | 0.76 | 4.71 | $69.1 | $1661.3 | $1730.4 |
| Total | 4,271,233 | 2,258,071 | | 247.1 | 1528.2 | 5.30 | 32.78 | $481.0 | $11,558.5 | $12,039.5 |

[a]Bird foraging days (BFD) was estimated from numbers of cormorants for the interior (I) and river regions (R) for each month. Weighted % diet in catfish (WDC) is based on cormorant diet in river and interior regions (Glahn et al. 1995) weighted by cormorant numbers in those regions. Biomass consumed from fingerling (BCFIP) and foodfish ponds (BCFOP) is the g/bird/day consumed each month (Glahn et al. 1995) × BFD × % biomass of catfish in the diet × proportion of each pond type in YRB (Hanson and Sites 2005). The number of fingerling (NFIC) and foodfish consumed (NFOC) is based on catfish length distribution and biomass in the cormorant diet (Glahn et al. 1995). Loss on fingerling ponds (LFIP) is the average sale price for the period (Hanson and Sites 2005). Loss on foodfish ponds (LFOP) is the opportunity cost to produce a harvestable size fish (Table 1) lost due to predation, reduced by the estimated mortality rate (18%) of fingerlings prior to harvest (SRAC 2004). Total loss (TL) = LFIP + LFOP.

period 1 January–31 March. Maximum dollar loss occurred in March in 2000–2001 and in February in 2003–2004 (Tables 4 and 5).

In all months, losses of biomass, number, and dollar value were greater for foodfish ponds than fingerling ponds. Based on monthly weighted % biomass consumed, a total of 1775.3 m.t. of catfish was estimated to be consumed over winters 2000–2001 and 1346.6 m.t. in 2003–2004 (Tables 4 and 5). In winter 2000–2001, 247.1 m.t. from fingerling ponds and 1528.2 m.t. from foodfish ponds were estimated to have been consumed (Table 4). In winter 2003–2004, 205.1 m.t. from fingerling ponds and 1141.5 m.t. from foodfish ponds were estimated consumed (Table 5). Based on weight of size classes consumed and estimated number of catfish per m.t., this

TABLE 5. *Projected catfish losses due to Double-crested Cormorant depredation in the Yazoo River Basin (YRB) of Mississippi during winter 2003–2004.*[a]

| Month | BFD-I | BFD-R | WDC | BCFIP (m.t.) | BCFOP (m.t.) | NFIC (millions) | NFOC (millions) | LFIP ($10^3$) | LFOP ($10^3$) | TL ($10^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Nov | 95,243 | 45,157 | 0.55 | 5.3 | 29.4 | 0.11 | 0.63 | $10.4 | $134.6 | $145.0 |
| Dec | 191,855 | 120,519 | 0.51 | 12.8 | 71.0 | 0.27 | 1.52 | $25.2 | $324.9 | $350.1 |
| Jan | 779,461 | 513,225 | 0.51 | 50.3 | 280.2 | 1.08 | 6.01 | $99.3 | $1281.2 | $1380.6 |
| Feb | 1,116,699 | 792,294 | 0.50 | 74.2 | 412.8 | 1.59 | 8.86 | $141.4 | $1823.8 | $1965.2 |
| Mar | 865,111 | 523,579 | 0.52 | 55.0 | 306.3 | 1.18 | 6.57 | $111.7 | $1440.5 | $1552.2 |
| Apr | 125,832 | 6184 | 0.72 | 7.5 | 41.7 | 0.16 | 0.90 | $16.6 | $214.7 | $231.3 |
| Total | 3,174,202 | 2,000,958 | | 205.1 | 1141.5 | 4.40 | 24.49 | $404.7 | $5219.7 | $5624.4 |

[a]Bird foraging days (BFD) was estimated from numbers of cormorants for the interior (I) and river regions (R) for each month. Weighted % diet in catfish (WDC) is based on cormorant diet in river and interior regions (Glahn et al. 1995) weighted by cormorant numbers in those regions. Biomass consumed from fingerling (BCFIP) and foodfish ponds (BCFOP) is the g/bird/day consumed each month (Glahn et al. 1995) × BFD × % biomass of catfish in the diet × proportion of each pond type in YRB (Hanson and Sites 2005). The number of fingerling (NFIC) and foodfish consumed (NFOC) is based on catfish length distribution and biomass in the cormorant diet (Glahn et al. 1995). Loss on fingerling ponds (LFIP) is the average sale price for the period (Hanson and Sites 2005). Loss on foodfish ponds (LFOP) is the opportunity cost to produce a harvestable size fish (Table 1) lost due to predation, reduced by the estimated mortality rate (18%) of fingerlings prior to harvest (SRAC 2004). Total loss (TL) = LFIP + LFOP.

equates to 38.1 million catfish consumed in winter 2000–2001 and 28.9 million catfish consumed in winter 2003–2004 (Tables 4 and 5). Based on estimated numbers of catfish consumed from foodfish and fingerling ponds, total estimated dollar losses in 2000–2001 were $11.56 and $0.48 million, respectively (Table 4). Total estimated losses for foodfish and fingerling ponds in 2003–2004 were $5.22 and $0.40 million, respectively (Table 5). Total losses were $12.0 million in 2000–2001 and $5.6 million in 2003–2004 (Tables 4 and 5).

## Discussion

Economics of catfish production are largely a function of the biomass of harvestable fish produced (Glahn et al. 2002). Consequently, the most important effect of losses due to any source on foodfish production ponds is the reduction in yield at harvest (Engle and Hanson 2004). Based on pond-level loss estimates, Glahn and Dorr (2002) estimated losses at harvest on foodfish ponds due to cormorant depredation could be as much as five times more than simple replacement costs (i.e., sale price of fingerlings). Given this difference, Glahn et al. (2002) estimated losses to the catfish aquaculture industry in the Yazoo Basin due to cormorant depredation could be approximately $5 million to $25 million, dependent on whether those losses were determined at replacement value or loss at harvest. Essentially, this difference lies in whether the depredation occurs on foodfish or fingerling ponds. Our estimates of $12.0 million in 2000–2001 and $5.6 million in 2003–2004 were within this range. Similar to estimates by Glahn and Brugger (1995), these values represent approximately 4.6% in 2000–2001 and 2.3% in 2003–2004 of total catfish sales for the state of Mississippi. We found that for a given level of cormorant depredation, three factors play an important role in resulting economic loss estimates: (1) volatility in variable production costs and nominal sale price for catfish, (2) distribution of depredation on pond types, and (3) distribution of cormorants within interior or river regions.

Volatility in variable costs of production and nominal sales price of catfish greatly affected the estimated opportunity cost. The single largest input to variable costs is feed costs which varied from $214/m.t. to $274/m.t. over the study period (Hanson and Sites 2005). The nominal sales price to producers for foodsize catfish varied from $1.25/kg to $1.70/kg over the study period (Hanson and Sites 2005). During 2000–2001 average feed costs were lower and nominal sales prices were higher, resulting in a greater opportunity cost estimate than in 2003–2004, when the opposite was the case (Table 1). The lower opportunity cost in 2003–2004 contributed to a lower depredation loss estimate overall. This lower opportunity cost estimate essentially reflects a lower profit margin for producers. This suggests that even though losses due to depredation were a smaller percentage of gross sales in 2003–2004, the impact to producer profits may be as severe because profit margins were narrower.

Because the estimate of opportunity cost of cormorant depredation on foodfish ponds was three to five times the value for depredation on fingerling ponds, distribution of consequent depredation has a large effect on loss estimates. At a regional scale, the distribution of cormorants on production pond types is functionally proportional to their availability (Dorr et al. 2012). This distribution is unlikely to change as the proportion of pond types is based on industry characteristics and market factors affecting production devoted to broodfish, fingerling, and foodfish pond types in the Yazoo Basin. The large difference in % of catfish in cormorant diet reported by Glahn et al. (1995) for cormorants roosting near the Mississippi River (14.3%) compared with those in the interior Yazoo Basin (74.5%) accounts for large differences in dollar loss estimates. Hypothetically, if 100% of the cormorants roosted and foraged on river roosts in 2000–2001, total economic loss would be approximately $3.2 million. Conversely, if the opposite occurred and 100% of cormorant depredation was incurred from interior roosts, economic loss estimates would be approximately $16.7 million, or a difference of $13.5 million. In 2003–2004 this same scenario would produces losses of $1.6 million or $8.2 million, respectively, a difference of $6.6 million.

Most of the number, biomass, and dollar loss of catfish occurred from foodfish ponds. Although this result seems intuitive, previous research indirectly concluded that fingerling ponds were more vulnerable to cormorant depredation (Glahn et al. 2000b; 2002). This view was considered true because fingerling ponds are stocked at greater densities and most catfish in fingerling ponds are of a consumable size. Based on the aforementioned factors, fingerling ponds presumably would be preferred by cormorants. Clearly, focusing management efforts to reduce cormorant depredation on fingerling ponds will not provide the same dollar return as a similar effort and reduction in depredation on foodfish ponds. Although this does not suggest that cormorants should not be deterred from foraging in fingerling ponds, it should not be done at the expense of efforts on foodfish ponds.

We found a pronounced seasonal component to cormorant depredation on catfish aquaculture. Peak cormorant numbers from aerial roost counts and from estimated foraging days occurred in February–March, which agrees with Glahn et al. (2000a). The period January–March in 2000–2001 and 2003–2004 accounted for most (72 and 89%, respectively) of total estimated cormorant foraging days in the Yazoo Basin. Similarly, the same monthly period in 2000–2001 and 2003–2004 accounted for most (73 and 87%, respectively) of total estimated dollar losses due to cormorant depredation in the Yazoo Basin. One exception to this trend was in March 2001, when foraging days for the month represented 25% of the total foraging days but dollar loss for the month was 32% of the total dollar loss. This difference was because more cormorants (90%) were counted from the interior portion of the Yazoo Basin, where a greater % of the diet is comprised of commercially raised catfish. Conversely, December 2000, while accounting for 9.7% of the total number of foraging days, only accounted for 5.1% of the total dollar loss because most (78%) cormorants were counted from river roosts. Over both years, more birds were estimated to be foraging in the interior (66%) compared with river regions (34%).

To date, the most effective means of reducing cormorant impacts within the Yazoo Basin has been a coordinated region-wide night roost-harassment program (Mott et al. 1998; Reinhold and Sloan 1999; Glahn et al. 2000a). The effects of the program are twofold. Mott et al. (1998) demonstrated that harassment of night roosts reduces the number of cormorants observed at nearby aquaculture ponds. Consequently, producers reported less depredation management costs associated with the roost harassment (Mott et al. 1998). The second aspect of the program is to push cormorants to river roosts where commercially raised catfish are a much smaller % of the diet. Presumably this difference in diet is due to the greater available natural foraging habitat along the Mississippi River and associated oxbow lakes. Glahn et al. (2000a) documented a larger % of cormorants shifted to river roosts following the implementation of the region-wide roost-dispersal program in 1994, relative to roosting patterns prior to the program's initiation. Based on the 2000–2001 counts, our data suggest that an annual 10% shift in cormorant numbers from interior to river roosts would result in an estimated $0.9 million reduction in depredation losses to the industry in the Yazoo Basin, all else being equal. The same shift in 2003–2004 would result in an estimated $0.4 million reduction in depredation losses.

Although the roost-harassment program has demonstrated benefits to both individual producers and the industry in the Yazoo Basin, its effectiveness may be limited (Reinhold and Sloan 1999; Glahn et al. 2000a,b). This lack of effectiveness is due to several factors including increased numbers of cormorants, proliferation of roost sites, and conflicts with other resource activities such as duck hunting (Reinhold and Sloan 1999; Glahn et al. 2000a,b). The number of cormorant roosts has increased from 12 in 1990 to 80 in 2004 (Dorr et al. 2008). The roost proliferation alone has greatly increased the complexity and difficulty of implementing the program (Glahn et al. 2000b). Consequently, efforts to implement lethal control or implement flyway-level management have been suggested as an alternative or supplement to farm- and regional-level management efforts (Glahn et al. 2000b). The objective of flyway management would be to alleviate depredation issues by reducing the population of cormorants (Van Eerden et al. 1995; Glahn et al. 2000b). All else being equal, a 10% reduction in number of cormorants in the Yazoo Basin would have resulted in an estimated \$1.2 and \$0.6 million decrease in losses to the catfish aquaculture industry in the Yazoo Basin in 2000–2001 and 2003–2004, respectively.

Managing cormorants either by shifting them regionally, reducing flyway numbers, or a combination of these factors can reduce cormorant depredation in the Yazoo Basin. However, alternatives to these methods can be used concomitantly to supplement or enhance depredation management. Recent research on modifications to catfish cultural practices from current multi-batch systems to "modular" production systems (Hanson and Steeby 2003) may improve producers' ability to protect vulnerable stocks, quantify loss due to depredation, and reduce losses of higher-value stocks. Although pond-level management techniques have been investigated extensively, new technologies such as lasers, automated dispersal systems, and acoustic technologies may provide new and cost-effective opportunities for pond-level management (Barras and Godwin 2005). The acreage devoted to catfish aquaculture has declined substantially since 2004. This change in the industry may affect how cormorants are distributed on catfish ponds or the intensity of use and consequently methods used to mitigate losses and their effectiveness.

The use of information on the distribution of cormorant depredation on catfish aquaculture in the Yazoo Basin and the opportunity cost associated with depredation of foodfish ponds have allowed for refinement of loss estimates in the Yazoo Basin. However, several limitations exist that could increase or decrease economic loss estimates. Our projections assume that bioenergetics and food-habit parameters are the same as described previously by Brugger (1992, 1993), Glahn and Brugger (1995), and Glahn et al. (1995). Although it is unlikely that cormorant bioenergetics have changed, additional research using improved bioenergetics methods such as doubly-labeled water (Speakman 1997) could provide further insights and refine estimates of energetic requirements for cormorants. Additionally, the increase in number of identified roost sites used and possibly changes in aquaculture practices suggest further study of cormorant food habits on aquaculture in the Yazoo Basin. The need for research is particularly true for October, as relatively large numbers of cormorants were observed in the Yazoo Basin in this month (Figs. 2, 3). Glahn et al. (2000a) also suggested that aerial surveys of night roosts might underestimate cormorant numbers by as much as 55%. Finally, determination of opportunity costs due to cormorant depredation on foodfish production ponds can be refined with evaluation of how depredation affects loss at harvest at various stocking rates and production strategies and the relationship between depredation loss, opportunity cost and profit margins. Evaluation of these factors would further refine regional loss estimates. Given these limitations, the data given in this study provide the most accurate estimate of economic loss to the catfish aquaculture industry in the Yazoo Basin to date.

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