Avian Predation on Low-Salinity Shrimp Aquaculture

by

Caleb Agustus Amacker

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 5, 2023

Keywords: avian predation, commercial shrimp aquaculture,
Pacific white shrimp, wildlife damage management

Approved by

Mark D. Smith, Chair, W. Kelly Mosley Environmental Professor and Extension Specialist,
Auburn University, College of Forestry, Wildlife, and Environment
Brian S. Dorr, Research Wildlife Biologist, United States Department of Agriculture, Wildlife
Services, National Wildlife Research Center
Luke A. Roy, Associate Extension Professor, Auburn University, School of Fisheries,
Aquaculture, and Aquatic Sciences

Abstract

Pacific white shrimp (*Litopenaeus vannamei*) is the most commonly produced shrimp in the world and prominent in the seafood industry in the United States. Aquaculture producers in the United States raise >2,000 metric tons of shrimp each year using various low-salinity water (LSW) sources. Although many bird species frequent aquaculture facilities and are known or suspected of consuming shrimp, no studies have examined the impact these birds may have on final yield. Therefore, our objectives were to 1) assess the distribution and relative abundance of predatory birds on commercial shrimp farms in Alabama and Florida, 2) quantify the diet of these birds, 3) and estimate the total amount of shrimp consumed annually. During May-October (2020-2021), we conducted biweekly surveys to estimate the diversity and relative abundance of birds and then conducted collections of individuals observed actively foraging around shrimp production ponds at farms in Alabama and Florida. Collected birds were injected immediately with cold (<10° C) phosphate buffered saline to halt digestion and placed on ice. Necropsies were then performed to determine the diets of each bird. A total of 106 birds (7 species) were collected during 2020 (n = 58) and 2021 (n =4 8) with most being collected closer to the harvesting months of September and October (2020: n = 34; 2021: n = 26). Of the birds collected during this time, 21 (2020: 61.8%) and 2 (2021: 7.7%) had consumed shrimp with Pied-billed Grebes (*Podilymbus podiceps*), Great Egrets (*Ardea alba*), and Double-crested Cormorants (*Phalacrocorax auritus*) consuming the most shrimp. We found that only select avian predators consume shrimp and do so closer to harvest when shrimp are mature and pond waters are lowered suggesting that management actions to mitigate losses may be targeted to a few species and may be most effective immediately before shrimp are harvested.

Acknowledgments

First and foremost, I would like to thank Dr. Mark Smith for granting me this opportunity. Thank you for your constant support, advice, and mentorship during our many travels and conversations while completing my research. I was honored to have you as a mentor and advisor throughout my time at Auburn University. Thank you, Dr. Brian Dorr, for providing me with endless knowledge of fish-eating birds and helping analyze the findings associated with our avian predators. Thank you, Dr. Luke Roy, for helping to build my relationships with shrimp producers and researchers while answering any question associated with shrimp aquaculture and production. A special thanks to Dr. Todd Steury for teaching and discussing data analysis when statistical struggles presented themselves.

I would like to thank the research teams involved in collecting and processing our birds. This project would not be possible without the endless efforts I received from the USDA's National Wildlife Research Center in Starkville, Mississippi. Stephen Clements, Lanna Rogers, Raleigh Middleton, Paul Burr, Jason Tappa, and Maddie Redd, thank you all for spending multiple hours traveling, collecting birds, and operating in the lab during my research. A special thanks to my student technician, Luke Thrower, for sticking by my side during two years of research. Your after-hour efforts were greatly appreciated, and I was incredibly lucky to have such an efficient student technician. I look forward to seeing you excel in the professional field following graduation. Thank you to Suanne Gilbert, Kim Ward, Audrey Grindle, and Michelle Straw for ensuring my finances, academics, and travel were on track throughout my time at Auburn University. I would also like to thank our funding sources from the USDA's National Wildlife Research Center, Alabama Agriculture Experiment Station's Hatch Grant, and Auburn

University’s School of Forestry and Wildlife Sciences as well as support from our shrimp producers who allowed us to use their aquaculture facilities.

Finally, a big thank you to my family and parents, Greg and Shelly Amacker, for instilling in me a passion for the outdoors and the ability to persevere through the many trials of my life. Without your love and support, I am confident I would not be the man I am today. Thank you, Jessica Amacker, for providing me with love and support while completing my education at Auburn University. I am blessed to have you by my side as we build our lives together. Thank you to the multitude of supporters across Mississippi, Alabama, Louisiana, and Tennessee who continuously encouraged and cheered me on from a distance. The love and support from my family and friends fueled my motivation throughout my graduate career.

Hail State and War Eagle forever!

Table of Contents

List of Tables

List of Figures

Chapter 1: Assessing Distribution and Abundance of Shrimp Eating Birds on Shrimp Farms in Alabama and Florida

ABSTRACT

In recent decades, the rise in low-salinity shrimp aquaculture led to increased presence of avian predators on these aquaculture facilities. As such, producers frequently implement various harassment techniques to reduce predation, but due to the intensity of shrimp production and additional costs of management, producers are often limited in their ability to deter such predators. With increased concerns from producers regarding observed abundances of avian predators on shrimp farms, research investigating the distribution and abundance of potential avian predators is needed to help guide the development of cost-effective management strategies. During the 2020 and 2021 shrimp production seasons, we conducted bi-weekly pond surveys ($n = 64$) to estimate occupancy probability and abundance of birds on commercial shrimp farms in Alabama and Florida. Bird counts were conducted at ponds and adjacent areas (e.g., pond levees) within each farm and used to construct occupancy and abundance models to estimate changes in bird numbers throughout the shrimp production season (May-October) and to examine the influence of pond characteristics on avian presence. Species-specific detection estimates varied among avian predators with the highest detection rates portrayed by great egrets ($\bar{x} = 0.27$) in Alabama and little blue herons ($\bar{x} = 0.43$) in Florida. Avian predator occupancy was not influenced by any measured pond or farm characteristics. Abundance varied among farms and species. Great egret abundance increased during the growing season in Alabama ($p = <0.001$) and Florida ($p = <0.001$). The abundance of great egrets ($p = <0.001$) and great blue herons ($p = 0.038$) in Alabama was influenced by an Adjacent Pond Index and increased as the number of adjacent ponds increased. Great egret abundance in Alabama also increased as pond size

increased (p = <0.001). Great egrets preferred afternoon over morning (p = 0.007) time periods in Alabama and preferred afternoon over morning (p = 0.034) and mid-day (p = 0.003) periods in Florida, while little blue herons selected afternoon over mid-day (p = 0.021) periods in Florida also. These results can be incorporated into management techniques to increase the efficiency of harassment efforts based on farm specific pond characteristics.

INTRODUCTION

Due to an increased demand for fishery products and a decline in wild harvests worldwide, the global aquaculture industry currently supplies more than one-third of the world's population with aquatic species for consumption (Parker 2001). In recent years, the United States' international aquaculture industry ranked fifth in exportation of multiple aquatic and crustacean products (e.g., Pacific salmon, lobster, and multiple crab species) and first in importation of shrimp and other products (e.g., tilapia and multiple crab species; FAO 2018). In the southeastern U.S., catfish are the primary commercially produced aquaculture species where the climate allows for longer growing seasons and greater production potential. Nationally, Alabama ranks second in total catfish production and in 2016 produced 33% of all catfish in the United States (ACP 2017) mostly from catfish farms in west and central Alabama.

In recent decades, several aquaculture producers in the Southeast have shifted to inland shrimp production using low-salinity water (LSW) to culture Pacific white shrimp (*Litopenaeus vannamei*; Roy et al. 2020a). This species is a non-native crustacean introduced to the U.S. in the late 20th century for commercial aquaculture and is referred to by several common names such as Pacific white, West Coast, and whiteleg shrimp (Galitzine et al. 2009, Alday-Sanz 2010). Pacific white shrimp can occupy waters with a wide range of water salinity and is the most produced shrimp in the world (National Oceanic Atmospheric Administration Fisheries 2023).

Shrimp farmers in the southeastern U.S. have exploited LSW, made available by inland artesian saltwater wells, to raise Pacific white shrimp in earthen ponds. The salinity of these water sources is suitable for the production of this euryhaline species, but additional mineral amendments, including potassium (K) and magnesium (Mg), must be added annually for adequate shrimp production (Roy et al. 2020a). Much of the research carried out in support of the commercial shrimp industry in Alabama has focused on alternative feeds, feed management techniques, and examination of the performance of shrimp with regards to modification of the ionic profile of LSW (Roy et al. 2010). Recently, additional work has been carried out to explore mortality of shrimp late in the production season and alternative intensive pond-based production systems (Roy et al. 2018, Roy et al. 2020a, Roy et al. 2020b). These collective efforts attempted to provide solutions to production related issues and increase survival and profitability of inland low salinity shrimp farms in Alabama and Florida.

Despite these efforts, there remains one area of study in which no work has been carried out, which is to determine the impact of predatory birds on shrimp survival and production. Fish-eating birds have been shown to negatively impact catfish aquaculture (Burr et al. 2020). For example, in the Mississippi Alluvial Valley, Christie et al. (2021) found catfish to be a primary prey species in cormorant diets which was consistent with historic diet trends as predator diets may shift based on local prey availability. For example, a decline in the availability of aquaculture prey items potentially influenced predator species to increase consumption of naturally occurring prey items and vice versa as aquaculture presence increased (Christie et al. 2021). Although earlier focus has been on the impacts of fish-eating birds to the catfish industry, Clements et al. (2020) found that lesser (*Aythya affinis*) and greater scaup (*A. marila*) frequently consumed golden shiners (*Notemigonus crysoleucas*), fathead minnows (*Pimephales promelas*), and goldfish (*Carassius auratus*) at baitfish and ornamental aquaculture farms in Arkansas. A portion of these scaup were opportunistically consuming farmed fish prey during the coldest survey periods of winter sampling (Clements et al. 2020). Historically, fish-eating birds have been a concern at fish-rearing facilities because of the correlation between avian presence and economic losses (Rhoades et al. 2019, Burr et al. 2020). Many of these same predatory species are often found near shrimp aquaculture facilities where an abundance of prey is available (Beynon et al. 1981) and commercial farmers believe shrimp depredation is likely significant. Although fish-eating birds forage frequently at aquaculture facilities (Barras and Godwin 2005), the degree to which avian predation may impact shrimp aquaculture is unknown. In recent years, Alabama shrimp farmers have reported greater mortality following harvest of production ponds in the fall, which has been a significant factor in reducing overall production and yield (Roy et al. 2018). This mortality is linked to various production concerns, including disease, algal toxicity, and avian predation.

Aquaculture facilities often occur near coastal environments, overlapping with the home ranges of many avian species that typically feed on freshwater fish, saltwater fish, and crustaceans, hence creating a potential for conflicts with aquaculture (Nagarajan and Thiyagesan 2006). Rhoades et al. (2019) found that the shallow depths and high stocking rates of catfish ponds created ideal foraging environments while natural wetlands in the Mississippi Delta provided loafing, roosting and/or breeding habitats for fish-eating birds involved with aquaculture conflicts. Multiple avian species are known to feed on commercial shrimp ponds including: great blue herons (*Ardea herodias*), great egrets (*Ardea alba*), and snowy egrets (*Egretta thula*). The family Ardeidae commonly feed on both fish and shrimp and have accounted for 60-70% of shrimp mortality on mariculture ponds during nocturnal predation with prey-capture rates ranging from 50-65% (Beynon et al. 1981).

To reduce losses, aquaculture producers employ multiple methods to mitigate depredation from several species including cormorants, pelicans, herons, egrets, and other waterfowl species (Hoy et al. 1989; Gorenzel et al. 1994; Reinhold and Sloan 1997; Glahn et al. 2000; Dorr and Taylor 2003; King 2005; Richman 2013). Avian predator control techniques used at aquaculture facilities can be grouped into three primary categories: 1) exclusion, 2) nonlethal harassment (frightening), and 3) lethal control (Gorenzel et al. 1994, Reinhold and Sloan 1997). Whereas these management techniques may reduce predation rates, in most cases they do not serve as a consistently effective deterrent for avian predators. Applying exclusion methods are potentially the most effective but may be too expensive for large farms (Glahn et al. 2000). In most situations, harassment programs are the most efficient method of mitigation when combined with lethal removal of determined birds that continually return to a location (Hoy et al. 1989).

To develop effective avian predator management strategies to reduce losses, it is necessary to document the distribution and abundance of avian predators on low-salinity shrimp farms. Specifically, information is needed to better understand bird usage of ponds throughout the shrimp production cycle, and whether other farm-level land cover characteristics (e.g., pond size, distance to buildings) may affect bird usage of ponds. Understanding these characteristics associated with avian predator numbers and use of aquaculture ponds will help producers focus their management efforts to areas and times when predatory birds are most likely to impact production.

METHODS

Study Area

Our study was conducted on two shrimp aquaculture farms, one in Greene County, Alabama and one in Gulf County, Florida. The Alabama farm was in rural west central Alabama where catfish is the dominant commercial aquaculture species but is currently home to shrimp production also. The Florida farm was in northwest Florida approximately 1.6 km from the coast. Both farms were privately owned and focused primarily on commercial shrimp production. Both farms had multiple (~12–20) aquaculture ponds of approximately 0.6−1.99 ha each that were used for shrimp production. In both regions, LSW has been used for the cultivation of shrimp for decades with farmers using wells to pump ground water into earthen production ponds. The Alabama farm had a greater number of ponds used for shrimp farming in 2020 (n = 20) than 2021 (n = 15) while the Florida farm's production pond total was constant from 2020 and 2021 (n = 12). The Alabama farm also used ponds for red swamp crayfish (*Procambarus clarkii*) production during 2020 and 2021 (n = 5). All study ponds had a depth of approximately 1−1.5m. Pond size in Alabama ranged from 0.6−1.99 ha ($\bar{x}$ = 1.20 ha) while Florida's pond size ranged from 1.33−1.97 ha ($\bar{x}$ = 1.65 ha).

Avian Surveys

To determine the distribution and relative abundance of avian predators on shrimp farms, we conducted biweekly ground surveys during the shrimp production seasons (April–October) in 2020 and 2021. During each sampling period (usually about 2−3 days) we conducted three surveys: morning, midday, and afternoon, beginning at 0700, 1100, and 1800 local time, respectively. Surveys were conducted by researchers using trucks to slowly drive along the levee system of each farm and surveying each pond for at least 5 minutes. Surveyors used binoculars and spotting scopes from distances that minimized bird disturbance but allowed for an unobstructed view of the pond's surface (i.e., 50–300 m from the pond's edge; Swanson and Bartonek 1970). Multiple survey routes (Alabama: *n* = 3, Florida: *n* =2) were used at each farm and randomly assigned among surveys (morning, midday, and afternoon). Randomly selecting a survey route helped better estimate avian counts by eliminating surveyor bias. During each survey, all potential shrimp-eating bird species and their behaviors (foraging from pond, foraging from land, swimming, loafing, or flushed) were recorded along with any other anecdotal information influencing avian use such as farmers passing on levees or equipment disturbing bird presence. Because no previous research had been conducted on predatory birds at shrimp aquaculture farms in the Southeast, we developed a list of 11 birds that were likely consumers of shrimp. We used combinations of life history characteristics and foraging ecology of water birds, range maps to determine potential species present at our study sites, review of peer-refereed literature of predatory birds at aquaculture farms in the Southeast, and observations from local aquaculture producers (Beynon et al. 1981, Christie et al. 2019, Burr et al. 2020, Clements et al. 2020) to compile this list. These birds included great blue heron, little blue heron, great egret, double-crested cormorant, green heron (*Butorides virescens*), lesser scaup, greater scaup, ring-necked duck (*Aythya collaris*), pied-billed grebe (*Podilymbus podiceps*), hooded merganser (*Lophodytes cucullatus*), and belted kingfisher (*Megaceryle alcyon*).

Although most observations were of individual or small (<10 birds) groups of birds, in a few instances larger congregations (e.g., >100 birds) of birds were encountered. In these instances, we estimated the total number of birds by counting each group of a single species to the tenth bird then summing the number of groups of similar sizes to estimate total flock size. This method is described by Arbib (1972) who uses repeated counts of bird groups to determine flock size when it is difficult to count individuals. The location and species of individual birds were marked on high resolution imagery captured by the National Agriculture Imagery Program (NAIP) and obtained from the USDA Geospatial Gateway for later integration into a Geographic Information Systems (GIS) database using ArcMap. We also noted the movement of birds on these maps as we progressed through the sampling route to avoid double counting. If travel or any other activity disturbed birds on ponds, observers waited 15 minutes before beginning surveys to allow birds to resume normal activity. In Alabama, some ponds were inactive during the 2021 production season, so these ponds were not surveyed and removed from survey routes.

Detection and Occupancy Covariates

Covariates used in detection modeling were observational covariates with parameters that differed between sampling periods. Because species relative abundances are known to fluctuate across seasons (Dorr et al. 2008), we included ordinal date of each survey in our detection models beginning with the first day of the season which corresponded to when shrimp were first introduced into the pond and concluded on the date of our final survey. Ordinal date was applied up to a third order term to account for possible fluctuations within detection probabilities over a season. We did not have sufficient sample sizes to justify a comparison of detection between years, therefore years were pooled to determine detection rates of each species at each farm.

We generated several pond and site level metrics to include in occupancy models to determine their relative influence on predatory bird presence and distribution at each farm. We first digitized the landcover of both farms in ArcMap using combinations of high-resolution imagery from NAIP obtained from the USDA Geospatial Gateway. We then created polygons of each production pond to determine pond size (in ha) and computed the distance (in m) from the pond edge closest to the farm base of operations. Finally, we measured the distance from the pond edge to the nearest forest edge (in m). We also classified ponds based on product type being produced (shrimp/crayfish).

Abundance Covariates

When modeling avian predator abundance, we incorporated multiple continuous and categorical covariates. We selected covariates based on previous studies and factors we expected to influence abundance over time (Clements et al. 2021). Like detection and occupancy modeling, we used covariates at both an observational level, changing over time, and a pond or farm level which remained constant over time. Farmers acquired average weekly weight (g) measurements of shrimp throughout each season to incorporate into our modeling. We sourced precipitation (mm) quantities from the National Oceanic and Atmospheric Administration's (NOAA) historical weather database. Adjacent Pond Index (API) was adapted from Burr et al. (2020) to help determine the influence of adjacent ponds on the abundance of avian predators. Since aquaculture ponds are often structured in clusters, we based our index on the number of ponds touching a specific pond's edge.

STATISTICAL ANALYSIS

Detection and Occupancy

Our ground surveys resulted in repeated visits to each farm during shrimp production seasons for two years. Because of the inherently different geographical regions in which each farm was located (e.g., Black Belt Prairie of Alabama, Gulf Coast Lowlands of Florida), we analyzed each farm separately while investigating differences among individual ponds within each farm. We constructed species-specific occupancy models where the probability of individuals occupying a site were estimated while incorporating imperfect detection (Mackenzie et al. 2006, Burr et al. 2020). With this approach, we were also able to model detection and occupancy separately along with the integration of covariates as explanatory variables in the models. Within our models, we included both temporal and pond-level covariates during the model selection process. Occupancy modeling using unmarked survey methods required sampling units, occasions, and seasons. In our case, sampling units were individual ponds at each farm, sampling occasions were ground surveys conducted approximately every two weeks, and seasons were shrimp production periods (e.g., May-October) during 2020 and 2021. We combined counts collected during morning, mid-day, and afternoon surveys to represent each biweekly sampling occasion. If an avian predator was surveyed during these surveys, then the individual was present during the sampling period. When conducting occupancy modeling, it was assumed that each site was closed to occupancy changes between surveys within a given season. This means a pond was considered occupied (or used) throughout an entire season if a target species was observed once. Although the species may not be consistently present across the entire season, we assumed a pond with known usage was likely to be used throughout the continuation of a season (Burr et al. 2020).

We used a two-step process to model species occupancy of shrimp ponds using package *unmarked* (Fiske and Chandler 2011, Burr et al. 2020) in program R. First, detection was modeled using covariates we believed would affect detection probabilities, while holding occupancy constant. Second, occupancy was modeled using variables corresponding to *a priori* hypothesis while incorporating the best detection model (Bailey et al. 2004). Like detection, we were not able to compare year covariates due to minimal data samples across species. It was necessary to incorporate more simple models during occupancy analysis because of our complex models' inability to appropriately predict occupancy.

For our study, detecting a target species on a pond was not an issue since an entire pond could be observed during surveys. Rather, species detection was related to our survey methods. For example, ponds were surveyed every two weeks and we were present for ≥ 5 minutes. If a pond was being used by a targeted species, they were most likely observed during the survey. Similarly, if there was a greater abundance of a species, the probability of observing the species increased. Because each species' relative abundance was potentially related to ordinal date, we did not include relative abundance in our models (Burr et al. 2020).

Once we selected parameters for detection models, we created three occupancy models for surveyed species. MacKenzie and Royle (2005) recommended study designs be evaluated on a case-by-case basis, tailored to scientific goals and biology of the target species. Sufficient sample sizes needed to perform occupancy modeling varied among species and state as total counts ranged from 12−1,456 in Alabama and 12–223 in Florida. Mackenzie et al. (2006) stated that the success of occupancy analysis is dependent on the complexity of model parameters, an adequate number of survey periods throughout a season, and evenly distributed survey counts across parameters and surveys. The models were based on two hypotheses influencing pond selection: 1) pond-level variables (e.g., only the pond), and/or 2) surrounding habitat variables (e.g., a pond's physical surroundings). Therefore, we included occupancy models incorporating and pond variables, surrounding habitat variables, and a global model using both sets of variables. Unlike the Alabama farm, the Florida farm did not have varying pond-level (e.g., pond size) or surrounding habitat variables (e.g., distance to forests), so these variables were removed because of their inability to estimate occupancy due to a lack of measurement diversity. Continuous variables (pond size, distance to activity center, and distance to forests) were standardized by scaling each prior to modeling to avoid parameter estimation problems

(Schielzeth 2010). Top detection and occupancy models were selected based on the smallest AIC value using the *AICcmodavg* package in program R (Burnham and Anderson 2002, Burr et al. 2020). We performed a Pearson's correlation test between estimated detection probabilities and total avian counts throughout the season to determine the relationship. Models were removed for species when our data samples did not allow models to converge. Because there are too many poorly fitting observations of avian counts across model variables, a lack of convergence indicates the data did not fit the model well (Linacre 1987).

The relative influence of pond size, distance to activity centers, and distance to forest edge on species occupancy and detection models was determined by creating multiple linear combinations using *predict* functions within *unmarked* frameworks for program R (Fiske and Chandler 2011). This was completed by allowing the variable of interest to change over its range while all other variables were held at their mean. Because our observational counts were limited across numerous variables, we did not include product type in the models, but compared bird usage of shrimp or crayfish ponds by determining the percentage of birds surveyed on each pond type.

Abundance

We used the following methods described by Clements et al. (2021) when modeling species-specific avian abundance across production seasons. Each species' count was modeled against ordinal date. Prior to modeling abundance, we only analyzed counts greater than zero. We determined the maximum number of each species surveyed during biweekly survey periods by selecting the largest count recorded during morning, mid-day, and afternoon surveys of that period and selecting the largest count. This allowed us to conservatively select the highest number of each species in a twenty-hour period without double counting individuals.

We established generalized linear fixed effect models following a negative binomial distribution using the *MASS* package, in program R. We employed backward stepwise selection to determine the best fitting model by creating a full model and removing variables with insignificant p-values until all variables were significant (Bolker 2008, Clements et al. 2021). Models were created using variables we believed may influence avian abundance such as day of season, year, pond size (ha), pond distance to forests (m), pond distance to activity centers (m), shrimp size (g), precipitation (mm), and Adjacent Pond Index. When beginning our analysis, data sets were limited due to model robustness, but removing additional variables enabled our models' prediction power. We used the top models to further investigate, and graph trends associated with the selected variables.

To determine if avian predators favored different survey times during sampling periods, we also developed generalized linear fixed effect models following a negative binomial distribution to compare avian abundance across survey times. We modeled species counts against survey times (morning, mid-day, and afternoon) for each state and season.

RESULTS

We conducted 64 ground surveys at the Alabama farm (n = 31 in 2020; n = 33 in 2021) and 64 surveys at the Florida farm (n = 31 in 2020; n = 33 in 2021). These surveys included morning (n = 63), mid-day (n = 64), and late afternoon (n = 63) survey periods. The length of survey seasons varied across years and states (Table 1.1) while each farm provided different pond structures to employ survey techniques (Figure 1.1). From these surveys we recorded 2,083 individuals of 7 species of potential predatory birds. The most common species observed were great egrets, followed by great blue herons, and little blue herons. Other less commonly recorded potential predatory species included double-crested cormorants, pied-billed grebes, green herons, and belted kingfishers.

We discovered a correlation between survey counts of great egrets ($p = 0.005$), great blue herons ($p = < 0.001$), little blue herons ($p = 0.046$), and green herons ($p = 0.006$) and the probability of detecting these species as day of season increased at the Alabama farm. Similarly, we found there was a correlation between survey counts of pied-billed grebes ($p = 0.002$), green herons ($p = 0.025$), and belted kingfishers ($p = <0.001$) and the probability of detecting these species as day of season increased at the Florida farm (Table 1.2). Species-specific detection estimates varied among avian predators with the highest rates portrayed by great egrets ($\bar{x} = 0.27$) in Alabama and little blue herons ($\bar{x} = 0.43$) in Florida (Table 1.3).

Detection

Alabama

When we developed the full model for our detection and occupancy analyses, the year covariate created convergence issues within models for both states, so it was removed. While holding occupancy constant, parameters for top detection models for the Alabama data included $date^3$ for great egrets, great blue herons, little blue herons, and green herons, date for pied-billed grebes, and the null model for belted kingfishers (Table 1.4). The detection rate of green herons peaked in June during production seasons ($\beta = 0.782$, p = 0.034; Table 1.5). Our estimated detection probabilities were compared to total survey counts and varied among species (Figure 1.2).

Florida

Detection probabilities compared to total survey counts in Florida also varied among species (Figure 1.3). Top detection models for the Florida data included $date^3$ for great egrets and little blue herons, date^2 for pied-billed grebes, green herons, belted kingfishers (Table 1.7). Our estimated detection models for great egrets (β = 1.225, p = 0.006), pied-billed grebes (β = -11.9, p = 0.047), and belted kingfishers (β = -1.69, p = 0.005; Table 1.8) were significant at the Florida farm.

Occupancy

Alabama

Occupancy probabilities also differed among species and variables in Alabama (Figure 1.3.) At the Alabama farm, great egret and pied-billed grebe models included only pond variables, little blue heron and green heron models included only surrounding habitat variables, and great blue heron models included both pond and surrounding habitat variables (Table 1.6). Great egret (β = 0.717, p = 0.277), great blue heron (β = 1.055, p = 0.099) and pied-billed grebe (β = -0.165, p = 0.775) occupancy were not affected by pond size. Likewise, the distance from farm activity centers to ponds did not affect the occupancy of great blue herons (β = 0.496, p = 0.523), little blue herons (β = 0.404, p = 0.574), or green herons (β = 3.95, p = 0.179). The distance from forested areas to ponds also had no effect on the occupancy of great blue herons (β = -1.046, p = 0.176), little blue herons (β = -0.460, p = 0.502), and green herons (β = 3.69, p = 0.222; Table 1.5). Sufficient sample sizes were not available to determine the detection and occupancy of double-crested cormorants in Alabama.

The top avian predators occupying crayfish ponds in Alabama were pied-billed grebes (91.7%), belted kingfishers (42.9%), and little blue herons (36.1%). The proportions of great egrets, great blue herons, and green herons surveyed on crayfish ponds were ≤20%.

Florida

In Florida, the occupancy models of great egrets, great blue herons, little blue herons, pied-billed grebes, green herons, and belted kingfishers included surrounding habitat variables (Table 1.9). The occupancy of great egrets (β = -1.02, p = 0.333), little blue herons (β = -0.338, p = 0.611), pied-billed grebes (β = -1.731, p = 0.200), green herons (β = -0.184, p = 0.765), and belted kingfishers (β = -0.264, p = 0.763) were not affected by distance from activity centers to ponds in Florida (Table 1.8). Sufficient sample sizes were not available to determine the detection and occupancy of great blue herons or double-crested cormorants in Florida.

Abundance

Alabama

We employed multiple parameters when preparing abundance models (Table 1.10). We were only able to model abundance for select species due to limited sample size and applied null models to those species with insufficient sample sizes (Table 1.11 and Table 1.12). In Alabama, our top great egret model included day, pond size, and adjacent pond index (API). Great egret abundance increased through summer (β = 0.541, p = <0.001; Figure 1.4), increased with pond size (β = 0.494, p = <0.001; Figure 1.4), and increased with API (β = 0.512, p = <0.001; Figure 1.4). The top great blue heron model included API as the only variable influencing abundance. Great blue heron abundance increased with API ((β = 0.306, p = 0.038; Figure 1.5).

When analyzing avian abundance across survey times, we compared the species-specific counts observed during each survey time (AM, Mid-day, PM) throughout production seasons. Due to limited data sets, we were only able to determine survey time preference for select species. In Alabama, great egret abundance decreased during morning surveys (β = -0.929, p = 0.007; Table 1.13) in 2021. Belted kingfishers were only observed during morning surveys in

Alabama during 2020 while belted kingfishers and pied-billed grebes were only observed during afternoon surveys in Alabama during 2021.

Florida

Great egrets were the only Florida species with sufficient sample size to support abundance modeling. The top abundance model included our day variable and increased through summer ($\beta = 0.522$, $p = <0.001$; Figure 1.6). Species with insufficient sample sizes were applied to null models to determine abundance variation.

In Florida, great egret abundance decreased during morning ($\beta = -1.417$, $p = 0.034$; Table 1.14) and mid-day surveys ($\beta = -1.417$, $p = 0.003$; Table 1.15) during 2020. Double-crested cormorants were only observed during mid-day surveys in Florida during 2020. Little blue heron abundance decreased during mid-day surveys ($\beta = -0.508$, $p = 0.021$; Table 1.16) in Florida during 2021 also.

DISCUSSION

Detection and Occupancy

Our ability to understand the characteristics of shrimp ponds and their influence on use by avian predators is vital to understanding the potential impacts of these predators on low-salinity shrimp aquaculture. Collectively, our results were varied across species and farms which was likely due to significant differences in physiographic regions, landscape cover, and distance from the Gulf of Mexico. Because we only investigated shrimp consumption at two farms, we are unable to say our findings are likely typical at all shrimp farms. A small number of survey sites limited the inferential space of our study to a much smaller scale whereas ecological surveys are often expanded over a larger scale, region, or home range (Linden et al. 2017). Burr et al. (2020) employed the designation of survey sites at a finer scale, analyzing each site as individual catfish ponds. Similarly, we elected to examine shrimp ponds as separate sites. Within our detection framework, we assumed ponds being used by a species were prone to be used throughout the shrimp production season (Burr et al. 2020). Our detection probability was directly correlated with the relative abundance of target species near sampling sites, so species-specific detection varied across seasons. When a greater abundance of a certain species was present in the area, we were more likely to observe this species using a pond (Royle and Nichols 2003). Like other studies, our detection probabilities were exclusive to our survey procedures.

The covariates examined and the results from each occupancy model varied between farms. The farm structure at the Alabama site exhibited diverse pond sizes, distances to forests, and distances to activity centers. Our covariate measurements were unique to each farm which enabled us to examine avian predator occupancy across a range of differing combinations. Increased pond size did not influence the probability of great egret and great blue heron occupancy. We expected great egrets and great blue herons to favor larger ponds as they're more advantageous to these species because of their ability to exhibit wading characteristics versus smaller ponds with limited available shoreline (Sebastian-Gonzalez and Green 2014). Pied-billed grebe occupancy was also not affected by a change in pond size. Osnas (2003) found pied-billed grebe occupancy commonly increased as wetland size increased which suggests grebe occupancy may increase as pond size increases. Pied-billed grebes favor large wetland areas because of the high resource availability associated with increased wetland size (Osnas 2003). It is possible grebes did not select larger ponds based on resource availability due to occurrence of shrimp prey across various pond sizes. The Florida farm's structure displayed uniform pond sizes, so avian predator occupancy related to pond size was not determined due to a lack of pond size variation.

In Alabama, the distance from ponds to forests did not impact great blue, little blue, or green heron occupancy, although based on previous research we'd expect these species to use ponds closer to forest cover. The findings of Gibbs and Kinkel (1997) stated that great blue herons predominantly occuped forested habitats. Rodgers (1980) also found little blue herons favored habitats containing shrubs and trees. Wooded areas provide these species with loafing, perching, or nesting sites; therefore, they are comfortable near these environments (Davis and Kushlan 1994, Butler 1997). It's possible the distance from ponds to forested areas was insignificant since the entirety of the Alabama farm is relatively close to woodland habitat (e.g., ≤ 298.7 m). Suitable green heron habitat occurs near wetland areas where shrubby vegetation is present (Kaiser and Reid 1987). We observed green herons along pond edges with appropriate vegetation cover comprised of shrubs and tall grasses; however, none were surveyed near the tree lines of wooded areas. We elected not to conduct an occupancy analysis of the distance to forested areas from ponds due to little variation in these distances across all ponds at the Florida farm.

At the Alabama farm, the distance from ponds to activity centers also had little influence on great blue, little blue, and green heron occupancy. We hypothesized there was a greater probability of these species occupying sites as the distance from activity centers increased. Great blue herons are known to occupy areas with minimum human disturbance (Gibbs and Kinkel 1997). This is expected as activity centers are continuously used by farm personnel and vehicles. Our findings in Florida were like those in Alabama as our results show great egret, little blue heron, pied-billed grebe, green heron, and belted kingfisher occupancy was not affected by the distance to activity centers. Due to recent studies, we expected avian presence to decrease as ponds become closer to activity centers due to regular human presence. Burr et al. (2020)

discovered the occupancy of great egrets on aquaculture ponds increased as the distance to activity centers increased. It is possible birds may favor ponds closer to activity centers due to an associated protection from natural predators due to human presence. Traut and Hostetler (2003) revealed that wading bird foraged significantly more along developed shoreline near human activity in central Florida. Borgmann (2011) stated the impacts of human disturbance on waterbirds varies significantly among species, types of disturbance, and disturbance frequency.

Because of crayfish pond availability among shrimp ponds in Alabama, we also surveyed avian predator usage of crayfish ponds. However, our sample sizes of species on crayfish ponds were insufficient to include in detection and occupancy modeling. We found proportions of our surveyed populations of pied-billed grebes (91.7%), belted kingfishers (42.9%), and little blue herons (36.1%) present on crayfish ponds while other avian species were < 20%. This is expected as we found crayfish among diet items consumed by pied-billed grebes, belted kingfishers, and little blue herons. Pied-billed grebes have been found foraging crayfish when available (Muller and Storer 1999). Of the crayfish consumed by belted kingfishers, all were juveniles and appropriate size for kingfisher consumption. Fleury and Sherry (1995) also reported the long-term population trends of little blue herons and other waterbirds exploiting the habitat and foraging opportunities provided by crayfish aquaculture in Louisiana. Therefore, we'd expect to see little blue herons occupy waterbodies containing crayfish prey.

Abundance

As expected, the observed avian predator abundance was subjective to instinctive species-specific decision making and the environmental factors which influenced those strategies. Brandolin and Blendinger (2016) found waterbird abundance was influenced by local and landscape environmental factors, as well as the specialization of different waterbird groups.

Analyzing variables specific to shrimp ponds may help determine the factors influencing avian predator abundance and therefore efficiently focus harassment efforts toward these elements.

We found avian predator abundance varied from AM to PM across Alabama and Florida. Great egret abundance decreased during mornings when compared to afternoon surveys in Alabama during 2021. Similarly great egret abundance in Florida during 2020 was less during morning and mid-day surveys than those in the evenings. Our results were similar to Glahn et al. (1999) who found great egret densities varied daily with mid-afternoon egret densities higher than all surveys except mid-morning on catfish aquaculture ponds in Mississippi. Our results also showed little blue heron abundance in Florida during 2021 was less during mid-day than afternoon surveys. Since warmer temperatures occur between mid-morning and afternoon hours, we may speculate that these species avoid periods of prolonged warmth. Producers may maximize harassment techniques for these species by prioritizing harassment efforts toward evening hours when avian abundance is higher on shrimp ponds.

Our samples of potential avian predators surveyed and results differed among Alabama and Florida farms. At the Alabama farm, great egret abundance was influenced by day of season, pond size, and adjacent pond index while great blue herons were only affected by adjacent pond index. In Alabama, great egret numbers increased well into summer with the highest number of observations occurring at the end of the shrimp production season during fall months. Great egret populations increase in west central Alabama during April as birds migrate northward for breeding season (McCrimmon et al. 2020). Increased great egret abundance later in the production season coincides with the lowering of water levels necessary for shrimp harvest. Shrimp have reached mature size later in the production season which may entice great egrets to congregate near this food source. Great egrets use of aquaculture ponds as forage availability increases and water depth decreases is supported by Fidorra et al. (2015). At the Florida farm, great egret abundance was only influenced by day of season, increasing into summer and fall months closer to harvest. Great egrets are present in the Florida region year-round and may increase due the availability of shrimp in ponds, especially when prey items are isolated in shallow waters (Hoy 2017, McCrimmon et al. 2020). Because avian abundance increases into production seasons, producers could allocate harassment resources later in the season when avian abundance is likely higher. Ignoring birds when flock size is not problematic would lessen the chance of predators becoming acclimated to harassment techniques thus increasing harassment efficiency when flocks are larger. We observed a greater amount of shrimp in the diets of avian predators later in the production season. The increased shrimp consumption insinuates that increased avian abundance was correlated with these predators actively foraging for shrimp prey.

Great egret abundance at the Alabama farm increased as pond size increased. It is possible this is due to increased edge habitat associated with larger ponds which allow great egrets to exhibit wading and foraging behaviors (Sebastian-Gonzalez and Green 2014). Also in Alabama, great egret and great blue heron abundance increased as adjacent pond index increased, indicating these avian predators favor areas with multiple waterbodies neighboring one another. This contradicts Burr et al. (2020) who found great egret occupancy decreases as the number of adjacent ponds increase. Burr et al. (2020) surveyed an expanded region of aquaculture that provided an increased avian count. Our low amount of sampling sites may have limited our bird abundance and found an avian relationship specific to the Alabama farm. Therefore, it would favor producers to increase harassment techniques near larger ponds and within the interior of farms where the number of adjacent ponds is higher. A potential strategy to help producers mitigate avian depredation would be to stock smaller ponds. Producers could take advantage of favorable use of predators on small ponds to help reduce shrimp consumption. Converting larger shrimp into smaller ponds would likely increase a farm's adjacent pond index but would allow producers to effectively harass multiple ponds from a single levee while dispersing birds from all sides of each pond. If stocking shrimp in smaller ponds is not a feasible option, we recommend producers increase harassment of larger production ponds.

We suggest producers implement non-lethal harassment techniques such as vehicles or propane cannons with the reinforcement of lethal measures to effectively harassment birds on ponds. These methods are supported by Kumar et al. (2021) who suggests non-lethal harassment is less effective unless used in combination with lethal control methods.

REFERENCES

Alabama Catfish Producers. 2017. Fact sheet: catfish. Alabama catfish producers. A Division of Alabama Farmers Federation.

Alday-Sanz, V. 2010. The Shrimp Book. Nottingham University Press, Nottingham, UK.

Arbib, R. S. 1972. On the art of estimating numbers. American Birds 26:706–712.

Bailey, L. L., D. I. Mackenzie, and J. D. Nichols. 2014. Advances and applications of occupancy models. Methods in Ecology and Evolution 5:1269–1279.

Barras, S. C., and K. C. Godwin. 2005. Controlling bird predation at aquaculture facilities: frightening techniques. Southern Regional Aquaculture Center. <https://appliedecology.cals.ncsu.edu/wp-content/uploads/401.pdf>.

Beynon, J. L., D. L. Hutchins, A. J. Rubino, A. L. Lawrence, and B. R. Chapman. 1981. Nocturnal activity of birds on shrimp mariculture ponds. Journal of the World Mariculture Society 12:63–70.

Bolker, B.M. 2008. Ecological Models and Data in R. Princeton University Press.

Borgmann, K. L. 2011. A review of human disturbance impacts on waterbirds. Audubon California 376:1–23.

Brandolin, P. G., and P. G. Blendinger. 2016. Effect of habitat and landscape structure on waterbird abundance in wetlands of central Argentina. Wetlands Ecology and Management 24:93–105.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer-Verlag, New York, New York, USA.

Burr, P. C., J. L. Avery, G. M. Street, B. K. Strickland, and B. S. Dorr. 2020. Fine scale characteristics of catfish aquaculture ponds influencing piscivorous avian species foraging use in the Mississippi Delta. PLoS ONE 15(2): e0229402.

Butler, R. W. 1997. The great blue heron. University of British Columbia Press, Vancouver, British Columbia.

Christie, T. W., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2021. Food habits of wintering double-crested cormorants in the Mississippi Delta. Food Webs 26: e00185.

Christie, T. W. 2019. Predation risk of Double-crested Cormorants (Phalacrocorax auritus) on commercial catfish production in the Mississippi Delta. Master of Science Thesis. Mississippi State University, Starkville, Mississippi.

Clements, S. A., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2020. Diets of scaup occupying baitfish and sportfish farms in eastern Arkansas. Food Webs 23: e00141.

Clements, S. A., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2021. Distribution and abundance of scaup using baitfish and sportfish farms in eastern Arkansas. Journal of World Aquaculture Society 52:347–361.

Davis, Jr., W. E., and J. A. Kushlan. 1994. Green Heron (*Butorides virescens*). The Birds of North America. Cornell Lab of Ornithology, Ithaca, New York, USA.

Dorr, B. S., and J. D. Taylor II. 2003. Wading bird management and research on North American aquaculture facilities. Pages 52–61 *in* Proceedings of the 2003 Wildlife Damage Management Conference. The Wildlife Damage Management Working Group of The Wildlife Society, 6 April–9 April 2003, Fort Collins, Colorado, USA.

Dorr, B. S., L. W. Burger, and S. C. Barras. 2008. Evaluation of Aerial Cluster Sampling of Double-crested Cormorants on Aquaculture Ponds in Mississippi. Journal of Wildlife Management 72:1634–1640.

Fiske, I. J., and R. B. Chandler. 2011. Unmarked: An r package for fitting hierarchical models of wildlife occurrence and abundance. Journal of Statistical Software 43:1–23.

Fidorra, J. C., P. C. Frederick, D. C. Evers, and K. D. Meyer. 2015. Selection of human-influenced and natural wetlands by great egrets at multiple scales in the southeastern USA. The Condor 118:46–56.

Fleury, B. E., and T. W. Sherry. 1995. Long-term population trends of colonial wading birds in the southern United States: the impact of crayfish aquaculture on Louisiana populations. The Auk 112:613–632.

Food and Aquaculture Organization. 2018. Cultured aquatic species information program: *Penaeus vannamei*. FAO, Rome, Italy.

Galitzine, V., S. Morgan, and J. Harvey. 2009. Pacific white shrimp (*Litopenaeus vannamei*). Seafood Watch/FishWise U.S. Farmed Shrimp Report. <http://agrilife.org/fisheries2/files/2013/09/U.S.-Farmed-Shrimp.pdf>.

Gibbs, J. P., and L. K. Kinkel. 1997. Determinants of the size and location of great blue heron colonies. Colonial Waterbirds 20:1–7.

Glahn, J. F., D. S. Reinhold, and P. Smith. 1999. Wading bird depredations on channel catfish *Ictalurus punctatus* in Northwest Mississippi. Journal of the World Aquaculture Society 30:107–114.

Glahn, J. F., M. E. Tobin, and B. F. Blackwell. 2000. A science-based initiative to manage double-crested cormorant damage to southern aquaculture. USDA Animal and Plant

Health Inspection Service, Wildlife Services National Wildlife Research Center, Fort Collins, Colorado, APHIS 11-55-010. <https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1528&context=icwdm_usdanwrc>.

Gorenzel, W. P., F. S. Conte, and T. P. Salmon. 1994. Bird damage at aquaculture facilities. The Handbook: Prevention and Control of Wildlife Damage, 57. <https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1055&context=icwdmhandbook>.

Hoy, M.D. 2017. Herons and egrets. Wildlife Damage Management Technical Series. USDA-APHIS-Wildlife Services, Almyra, Arkansas, USA.

Hoy, M. D., J. W. Jones, and A. E. Bivings. 1989. Economic impact and control of wading birds at Arkansas minnow ponds. Eastern Wildlife Damage Control Conference, 23. <https://core.ac.uk/download/pdf/188055701.pdf>.

Kaiser, M. S., and F. A. Reid. 1987. A comparison of green-backed heron nesting in two freshwater ecosystems. Colonial Waterbirds 10:78–83.

King, D. T. 2005. Interactions between the American white pelican and aquaculture in the southeastern United States: an overview. Waterbirds 28:83–86.

Kumar, G., S. Hegde, D. J. Wise, C. C. Mischke, B. S. Dorr. 2021. Economic losses of catfish to avian predation: a case report. North American Journal of Aquaculture 83:127–137.

Linacre, J. M. 1987. Rasch estimation: iteration and convergence. Rasch Measurement Transactions 1:7–8.

Linden, D. W., A. K. Fuller, J. A. Royle, and M. P. Hare. 2017 Examining the occupancy-density relationship for a low-density carnivore. Journal of Applied Ecology 54:2043–2052.

MacKenzie, D. I., and J. A. Royle. 2005 Designing efficient occupancy studies: general advice and tips on allocation of survey effort. Journal of Applied Ecology 42:1105–1114.

MacKenzie, D. I., J. D. Nichols, J. A. Royle, K. H. Pollock, L. L. Bailey, and J. E. Hines. 2006. Occupancy estimation and modeling: inferring patterns and dynamics of species occurrence. Academic Press, New York, New York, USA.

McCrimmon Jr., D. A., J. C. Ogden, G. T. Bancroft, A. Martinez-Vilalta, A. Motis, G. M. Kirwan, and P. F. D. Boesman. 2020. Great egret (*Ardea alba*). Birds of the World. Cornell Lab of Ornithology, Ithaca, New York, USA.

Muller, M. J. and R. W. Storer. 1999. Pied-billed grebe (*Podilmbus podiceps*). The Birds of North America, Incorporated, Philadelphia. <https://guides.nynhp.org/pied-billed-grebe/>

National Oceanic Atmospheric Administration Fisheries. 2023. Species directory: white shrimp. <https://www.fisheries.noaa.gov/species/white-shrimp#overview>

Nagarajan, R., and K. Thiyagesan. 2006. The effects of coastal shrimp farming on birds in Indian mangrove forests and tidal flats. Acta Zoologica Sinica 52:541–548.

Osnas, E. E. 2003. The role of competition and local habitat conditions for determining occupancy patterns in grebes. Waterbirds 26:209–216.

Parker, H. S. 2001. Aquaculture research is key to the future of U.S. fish farming. Agricultural Research 49:2.

Reinhold, D. S., and C. A. Sloan. 1997. Strategies to reduce double-crested cormorant depredation at aquaculture facilities in Mississippi. Pages 99–106 *in* Proceedings of

Symposium on Double-crested Cormorants: Population Status and Management Issues in the Midwest. USDA National Wildlife Research Symposia, December 1997. <https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1009&context=nwrccormorants>.

Rhoades, C. A., P. J. Allen, and D. T. King. 2019. Using unmanned aerial vehicles for bird harassment on fishponds. Pages 13–23 *in* Proceedings of the 2019 Wildlife Damage Management Conference. The Wildlife Damage Management Working Group of The Wildlife Society. <https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=3286&context=icwdm_usdanwrc>.

Richman, S. E., E. Varennes, J. Bonadelli, and M. Guillemette. 2013. Sea duck predation in mussel farms: the best nets for excluding common eiders safely and efficiently. Aquaculture Environment Interactions 4:31–39.

Rodgers Jr., J. A. 1980. Breeding ecology of the little blue heron on the west coast of Florida. Condor 82:164–169.

Roy, L. A., D. A. Davis, I. P. Saoud, C. A. Boyd, H. J. Pine, and C. E. Boyd. 2010. Shrimp culture in inland low salinity waters. Reviews in Aquaculture 2:191–208.

Roy, L. A., D. Teichert-Coddington, S. Dahl, B. H. Beck, C. A. Shoemaker, G. N. Whitis, and J. James. 2020a. On-farm evaluation of three different hatchery sources of Pacific white shrimp (*Litopenaeus vannamei*) cultured in on-levee tanks in low-salinity waters of west Alabama. Journal of Applied Aquaculture 32:193–204.

Roy, L. A., D. Teichert-Coddington, B. H. Beck, S. Dahl, J. James, J. Guo, and D. A. Davis. 2020b. Evaluation of stocking density and fish meal inclusion level for intensive tank production of Pacific white shrimp (*Litopenaeus vannamei*) in low salinity water. North American Journal of Aquaculture 82:345–353.

Roy, L. A., D. Teichert-Coddington, S. Laramore, S. Dahl, J. James, G. N. Whitis, B. H. Beck, and C. A. Shoemaker. 2018. Commercial evaluation of a probiotic mixture to enhance Pacific white shrimp production in inland ponds of Alabama and Florida. World Aquaculture 49:42–49.

Royle, J. A., and J. D. Nichols. 2003 Estimating abundance from repeated presence-absence data or point counts. Ecology 84:777–790.

Schielzeth, H. 2010. Simple means to improve the interpretability of regression coefficients. methods in ecology and evolution 1:103–113.

Sebastian-Gonzalez, E., and A. J. Green. 2014. Habitat use by waterbirds in relation to pond size, water depth, and isolation: lessons from a restoration in southern Spain. Restoration Ecology 22:311–318.

Swanson, G. A., and J. C. Bartonek. 1970. Bias associated with food analysis in gizzards of Blue-winged Teal. The Journal of Wildlife Management 34:739–746.

Traut, A. H., and M. E. Hostetler. 2003. Urban lakes and waterbirds: effects of development on avian behavior. Waterbirds 26:290–302.

Table 1.1. Duration (in days) of shrimp production seasons at farms in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

State	Year	First Day	Last Day	Total Days
Alabama	2020	May 14	October 19	160
	2021	May 24	October 12	143
Florida	2020	May 26	October 19	148
	2021	May 24	October 12	143

Table 1.2 Results from Pearson' R correlation tests between detection probabilities and survey counts of avian predators on commercial shrimp farms in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Alabama			Florida		
Species	T-score	r	*p*	T-score	r	*p*
Great Egret	3.15	0.59	0.005	1.02	0.23	0.319
Great Blue Heron	7.09	0.85	<0.001			
Little Blue Heron	2.14	0.44	0.046	1.83	0.39	0.083
Pied-billed Grebe	0.36	0.08	0.721	3.62	0.64	0.002
Green Heron	3.07	0.58	0.006	2.44	0.49	0.025
Belted Kingfisher[a]				3.96	0.67	<0.001

[a]Correlation tests were not conducted for Belted Kingfishers in Alabama or Great Blue Herons in Florida.

Table 1.3 Detection probabilities of avian predators on commercial shrimp farms in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Alabama		Florida	
Species	Mean	Range	Mean	Range
Great Egret	0.27	(0.01–0.61)	0.17	(0.00–0.33)
Great Blue Heron	0.17	(0.00–0.75)		
Little Blue Heron	0.11	(0.01–0.24)	0.43	(0.08–0.56)
Pied-billed Grebe	0.07	(0.00–0.27)	0.07	(0.00–0.40)
Green Heron	0.05	(0.01–0.14)	0.09	(0.00–0.37)
Belted Kingfisher[a]			0.13	(0.00–0.30)

[a]Detection probabilities were not found for Belted Kingfishers in Alabama or Great Blue Herons in Florida.

Table 1.4 Detection models (*p*) constructed for avian predators on commercial shrimp ponds at the Greene County, Alabama, USA, study site, 2020–2021.

Model	K	AIC	ΔAIC	*w*
Great Egret				
Ψ(.) *p*(date^3)	5	411.7	0.0	0.47
Ψ(.) *p*(date^2)	4	412.0	0.3	0.40
Ψ(.) *p*(date)	3	414.1	2.4	0.14
Ψ(.) *p*(.)	2	472.2	60.5	0.0
Great Blue Heron				
Ψ(.) *p*(date^3)	5	175.0	0.0	0.54
Ψ(.) *p*(date)	3	176.0	1.0	0.33
Ψ(.) *p*(date^2)	4	177.9	2.9	0.13
Ψ(.) *p*(.)	2	210.9	35.9	0.0
Little Blue Heron				
Ψ(.) *p*(date^3)	5	156.7	0.0	0.59
Ψ(.) *p*(date^2)	4	158.9	2.2	0.20
Ψ(.) *p*(date)	3	160.1	3.3	0.12
Ψ(.) *p*(.)	2	160.5	3.7	0.09
Pied-billed Grebe				
Ψ(.) *p*(date)	3	62.9	0.0	0.89
Ψ(.) *p*(.)	2	67.0	4.2	0.11

Table 1.4 Continued

Model	K	AIC	ΔAIC	*w*
Green Heron				
Ψ(.) *p*($date^3$)	5	153.8	0.0	0.65
Ψ(.) *p*($date^2$)	4	155.8	2.0	0.24
Ψ(.) *p*(date)	3	157.5	3.7	0.1
Ψ(.) *p*(.)	2	162.0	8.2	0.01
Belted Kingfisher				
Ψ(.) *p*(.)	2	126.2	0.0	0.5
Ψ(.) *p*($date^2$)	4	127.8	1.5	0.23
Ψ(.) *p*(date)	3	128.2	2.0	0.18
Ψ(.) *p*($date^3$)	5	129.8	3.5	0.09

Table 1.5 Parameter estimates for occupancy and detection variables from occupancy analysis of avian predators on commercial shrimp ponds at the Greene County, Alabama, USA, study site, 2020–2021.

	Great Egret			Great Blue Heron			Little Blue Heron		
Model Variable	β	SE	*p*	β	SE	*p*	β	SE	*p*
Detection									
Intercept	-0.936			-1.541			-1.699		
Date	0.802	0.320	<0.001	0.857	0.684	0.210	1.602	0.678	0.018
Date^2	-0.569	0.278	0.040	-1.855	1.208	0.125	-0.660	0.384	0.085
Date^3	0.336	0.233	0.149	1.331	0.700	0.057	-0.785	0.410	0.055
Occupancy									
Intercept	2.162			-0.635			-0.627		
Pond level									
Pond size	0.717	0.660	0.277	1.055	0.639	0.099			
Surrounding habitat									
Dist. activity center				0.496	0.776	0.523	0.404	0.720	0.574
Dist. forest				-1.046	0.773	0.176	-0.460	0.686	0.502

Table 1.5 Continued.

Model Variable	Pied-billed Grebe			Green Heron			Belted Kingfisher		
	β	SE	p	β	SE	p	β	SE	p
Detection									
Intercept	-3.30			-3.172			-2.55		
Date	1.360	0.578	0.775	-2.257	0.742	0.002			
$Date^2$				-0.129	0.366	0.725			
$Date^3$				0.782	0.370	0.034			
Occupancy									
Intercept	-1.143			2.090			-0.327		
Pond level									
Pond size	-0.165	0.578	0.775						
Surrounding habitat									
Dist. activity center				3.95	2.93	0.179			
Dist. forest				3.69	3.02	0.222			

Table 1.6 Occupancy models (Ψ) constructed for avian predators on commercial shrimp ponds at the Greene County, Alabama, USA, study site, 2020–2021, formed using parameters from top ranked detection models (*p*).

Model	K	AIC	ΔAIC	*w*
Great Egret				
Ψ(pond) *p*($date^3$)	6	412.2	0.0	0.67
Ψ(surroundings) *p*($date^3$)	7	414.7	2.5	0.19
Ψ(pond + surroundings) *p*($date^3$)	8	415.5	3.3	0.13
Ψ(.) *p*(.)	2	472.2	59.9	0.0
Little Blue Heron				
Ψ(surroundings) *p*($date^3$)	7	157.1	0.0	0.5
Ψ(pond) *p*($date^3$)	6	158.7	1.6	0.22
Ψ(pond + surroundings) *p*($date^3$)	8	159.0	1.9	0.19
Ψ(.) *p*(.)	2	160.5	3.4	0.09
Pied-billed Grebe				
Ψ(pond) *p*(date)	4	64.8	0.0	0.54
Ψ(surroundings) *p*(date)	5	66.7	1.9	0.21
Ψ(.) *p*(.)	2	67.0	2.2	0.18
Ψ(pond + surroundings) *p*(date)	6	68.7	3.9	0.08

Table 1.6 Continued.

Model	K	AIC	ΔAIC	*w*
Green Heron				
Ψ(surroundings) *p*($date^3$)	7	153.8	0.0	0.53
Ψ(pond + surroundings) *p*($date^3$)	8	155.4	1.6	0.24
Ψ(pond) *p*($date^3$)	6	155.5	1.7	0.22
Ψ(.) *p*(.)	2	162.0	8.2	0.01
Belted Kingfisher				
Ψ(.) *p*(.)	2	126.2	0.0	0.45
Ψ(surroundings) *p*(.)	4	127.2	1.0	0.27
Ψ(pond + surroundings) *p*(.)	3	128.2	2.0	0.17
Ψ(pond) *p*(.)	5	129.1	2.9	0.11

Table 1.7 Detection models (p) constructed for avian predators on commercial shrimp ponds at the Gulf County, Florida, USA, study site, 2020–2021.

Model	K	AIC	ΔAIC	*w*
Great Egret				
$\Psi(.)\ p(\text{date}^3)$	5	191.8	0.0	0.97
$\Psi(.)\ p(\text{date}^2)$	4	199.1	7.3	0.02
$\Psi(.)\ p(.)$	2	207.0	15.2	0.0
$\Psi(.)\ p(\text{date})$	3	207.4	15.5	0.0
Little Blue Heron				
$\Psi(.)\ p(\text{date}^3)$	5	311.6	0.0	0.52
$\Psi(.)\ p(\text{date}^2)$	4	311.9	0.2	0.47
$\Psi(.)\ p(\text{date})$	3	321.6	9.9	0.0
$\Psi(.)\ p(.)$	2	322.6	11.0	0.0
Pied-billed Grebe				
$\Psi(.)\ p(\text{date}^2)$	4	64.1	0.0	0.74
$\Psi(.)\ p(\text{date}^3)$	5	66.2	2.1	0.26
$\Psi(.)\ p(\text{date})$	3	72.9	8.9	0.0
$\Psi(.)\ p(.)$	2	88.4	24.3	0.0

Table 1.7 Continued.

Model	K	AIC	ΔAIC	*w*
Green Heron				
Ψ(.) *p*(date^2)	4	48.5	0.0	0.7
Ψ(.) *p*(date)	3	50.3	1.7	0.29
Ψ(.) *p*(.)	2	57.8	9.3	0.01
Belted Kingfisher				
Ψ(.) *p*(date^2)	4	148.4	0.0	0.53
Ψ(.) *p*(date^3)	5	148.7	0.3	0.47
Ψ(.) *p*(date)	3	159.5	11.1	0.0
Ψ(.) *p*(.)	2	171.4	23.0	0.0

Table 1.8 Parameter estimates for occupancy and detection variables from occupancy analysis of avian predators on commercial shrimp ponds at the Gulf County, Florida, USA, study site, 2020–2021.

	Great Egret			Little Blue Heron			Pied-billed Grebe		
Model Variable	β	SE	p	β	SE	p	β	SE	p
Detection									
Intercept	-0.865			0.239			-13.8		
Date	-1.038	0.546	0.057	0.233	0.375	0.534	25.2	12.48	0.043
$Date^2$	-1.402	0.474	0.003	-0.666	0.196	<0.001	-11.9	5.99	0.047
$Date^3$	1.225	0.445	0.006	-0.337	0.229	0.142			
Occupancy									
Intercept	1.90			2.023			0.223		
Surrounding habitat									
Dist. activity center	-1.02	1.06	0.333	-0.338	0.665	0.611	-1.731	1.35	0.200

Table 1.8 Continued.

	Green Heron			Belted Kingfisher		
Model Variable	*β*	SE	*p*	*β*	SE	*p*
Detection						
Intercept	-6.60			-1.55		
Date	11.56	8.35	0.166	2.16	0.712	0.002
$Date^2$	-5.52	4.17	0.186	-1.69	0.609	0.005
$Date^3$						
Occupancy						
Intercept	-1.118			1.493		
Surrounding habitat						
Dist. activity center	-0.184	0.616	0.765	-0.264	0.876	0.763

Table 1.9 Occupancy models (Ψ) constructed for avian predators on commercial shrimp ponds at the Gulf County, Florida, USA, study site, 2020–2021, formed using parameters from top ranked detection models (*p*).

Model	K	AIC	ΔAIC	*w*
Great Egret				
Ψ(surroundings) $p(\text{date}^3)$	6	192.4	0.0	1.00
Ψ(.) *p*(.)	2	207.0	14.6	0.0
Little Blue Heron				
Ψ(surroundings) $p(\text{date}^3)$	6	313.4	0.0	0.99
Ψ(.) *p*(.)	2	322.6	9.3	0.01
Pied-billed Grebe				
Ψ(surroundings) $p(\text{date}^2)$	5	61.5	0.0	1.00
Ψ(.) *p*(.)	2	88.4	26.8	0.0
Green Heron				
Ψ(surroundings) $p(\text{date}^2)$	5	50.1	0.0	0.98
Ψ(.) *p*(.)	2	57.8	7.4	0.02
Belted Kingfisher				
Ψ(surroundings) $p(\text{date}^2)$	5	150.3	0.0	1.00
Ψ(.) *p*(.)	2	171.4	21.1	0.0

Table 1.10 Continuous and categorical variables considered for abundance models of avian predators at farms in Greene County, Alabama and Gulf County, Florida, USA, 2020-2021.

		Alabama	Florida
Variable	Measurement Unit	Range	Range
Continuous			
Day	Day of season	1–159	1–147
Pond size	Hectare	0.44–1.99	1.33–1.97
Dist. forest	Meter	7.3–298.7	8.0–21.5
Dist. activity center	Meter	25.4–712.7	4.1–395.4
Shrimp size	Gram	0.02–45.9	1.29–23.15
Precipitation	Millimeter	0.04–2.36	0–2.22
Categorical			
Year		2020–2021	2020–2021
Adjacent pond index		1–3	1–2

Table 1.11 Beta (β) coefficients, standard error (SE), and p-value (p) of top general linear model variables which evaluated avian predator abundance at farms in Greene County, Alabama, USA, 2020–2021.

	Great Egret			Great Blue Heron			Little Blue Heron		
Model Variable	β	SE	p	β	SE	p	β	SE	p
Intercept	1.701			0.315			0.642[a]		
Day of season	0.541	0.119	<0.001						
Pond size	0.494	0.127	<0.001						
Dist. forest									
Dist. activity center									
Shrimp size									
Precipitation									
Adjacent pond index	0.512	0.118	<0.001	0.306	0.148	0.038			
Year (ref. 2020)									
2021									

[a]Null models used in place of inconclusive variable models.

Table 1.11 Continued.

	Pied-billed Grebe			Green Heron			Belted Kingfisher		
Intercept	*β*	SE	*p*	*β*	SE	*p*	*β*	SE	*p*
Day of season	<0.001[a]			<0.001[a]			<0.001[a]		
Pond size									
Dist. forest									
Dist. activity center									
Shrimp size									
Precipitation									
Adjacent pond index									
Year (ref. 2020)									
2021									

[a]Null models used in place of inconclusive variable models.

Table 1.12 Beta (β) coefficients, standard error (SE), and p-value (p) of top general linear model variables which evaluated avian predator abundance at farms in Greene County, Alabama, USA, 2020–2021.

	Great Egret			Great Blue Heron			Little Blue Heron			Double-crested Cormorant		
Model Variable	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Intercept	0.570			0.080[a]			0.487[a]			<0.001[a]		
Day of season	0.522	0.148	<0.001									
Pond size												
Dist. forest												
Dist. activity center												
Shrimp size												
Precipitation												
Adjacent pond index												
Year (ref. 2020)												
2021												

[a]Null models used in place of inconclusive variable models.

Table 1.12 Continued.

	Pied-billed Grebe			Green Heron			Belted Kingfisher		
	β	SE	p	β	SE	p	β	SE	p
Model Variable	0.118[a]			0.201[a]			0.069[a]		
Intercept									
Day of season									
Pond size									
Dist. forest									
Dist. activity center									
Shrimp size									
Precipitation									
Adjacent pond index									
Year (ref. 2020)									
2021									

[a]Null models used in place of inconclusive variable models.

Table 1.13 Beta (β) coefficients, standard errors (SE), and p-values (p) of general linear models which compared avian predator abundance across morning, mid-day, and afternoon survey times at the Greene County, Alabama, USA, study site, 2020.

	Great Egret			Great Blue Heron			Little Blue Heron		
Model Variable	β	SE	p	β	SE	p	β	SE	p
Intercept	2.335			0.325			1.386		
Survey time (ref. afternoon)									
Morning	0.349	0.416	0.401	0.160	0.364	0.660	-0.288	0.764	0.706
Mid-day	0.312	0.399	0.435	-0.038	0.425	0.929			

Table 1.13 Continued.

	Green Heron			Pied-billed Grebe			Belted Kingfisher		
Model Variable	β	SE	p	β	SE	p	β	SE	p
Intercept	<0.001			<0.001			<0.001		
Survey time (ref. afternoon)									
Morning	<0.001	0.817	1.00	<0.001	1.155	1.00	<0.001	0.707	1.00
Mid-day	<0.001	0.913	1.00	<0.001	0.817	1.00			

Table 1.14 Beta (β) coefficients, standard errors (SE), and p-values (p) of general linear models which compared avian predator abundance across morning, mid-day, and afternoon survey times at the Greene County, Alabama, USA, study site, 2021.

	Great Egret			Great Blue Heron			Little Blue Heron			Green Heron		
Model Variable	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Intercept	1.504			<0.001			<0.001			<0.001		
Survey time (ref. afternoon)												
Morning	-0.929	0.344	0.007	0.693	1.00	0.488	0.406	0.817	0.619	<0.001	1.225	1.00
Mid-day	-0.657	0.356	0.056				0.693	0.866	0.423	<0.001	1.225	1.00

Table 1.15 Beta (β) coefficients, standard errors (SE), and p-values (p) of general linear models which compared avian predator abundance across morning, mid-day, and afternoon survey times at the Gulf County, Florida, USA, study site, 2020.

	Great Egret			Great Blue Heron			Little Blue Heron		
Model Variable	β	SE	p	β	SE	p	β	SE	p
Intercept	1.705			0.134			0.657		
Survey time (ref. afternoon)									
Morning	-1.417	0.667	0.034	-0.134	0.512	0.794	-0.561	0.358	0.116
Mid-day	-1.417	0.470	0.003	-0.134	0.559	0.811	-0.010	0.291	0.972

Table 1.16 Beta (β) coefficients, standard errors (SE), and p-values (p) of general linear models which compared avian predator abundance across morning, mid-day, and afternoon survey times at the Gulf County, Florida, USA, study site, 2021.

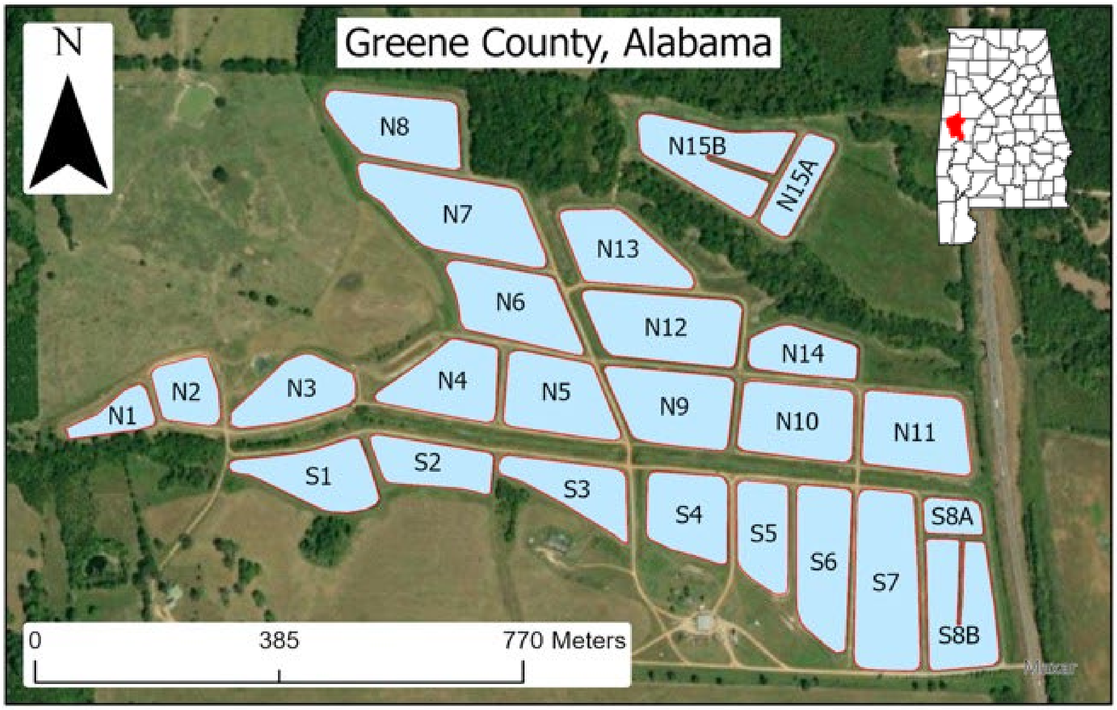
	Great Egret			Great Blue Heron			Little Blue Heron		
Model Variable	β	SE	p	β	SE	p	β	SE	p
Intercept	0.903			<0.001			0.642		
Survey time (ref. afternoon)									
Morning	-0.903	0.556	0.104	0.118	0.450	0.793	-0.082	0.195	0.673
Mid-day	-0.903	0.659	0.170	0.154	0.484	0.750	-0.508	0.221	0.021

Table 1.16 Continued.

	Pied-billed Grebe			Green Heron			Belted Kingfisher		
Model Variable	*β*	SE	*p*	*β*	SE	*p*	*β*	SE	*p*
Intercept	0.288			0.406			0.00		
Survey time (ref. afternoon)									
Morning	0.118	0.764	0.877	-0.406	1.155	0.725	0.118	0.504	0.815
Mid-day	-0.288	0.707	0.684				0.182	0.556	0.743

Figure 1.1 Commercial shrimp ponds used to conduct avian predator surveys and collections during shrimp production seasons in (a) Greene County, Alabama and (b) Gulf County, Florida, USA, 2020–2021.

a)



b)

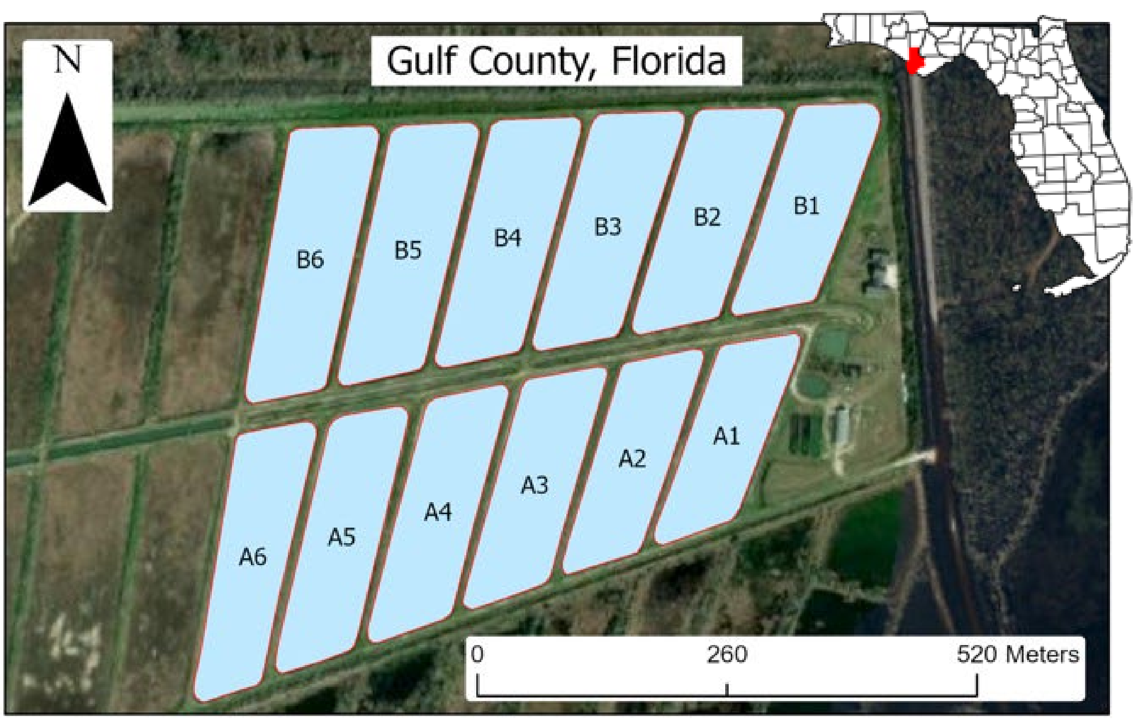


Figure 1.2 Detection probability (±95% CI) as a function of date for Green Herons, estimated from occupancy analysis of shrimp ponds at the Greene County, Alabama, USA, study site, 2020–2021.

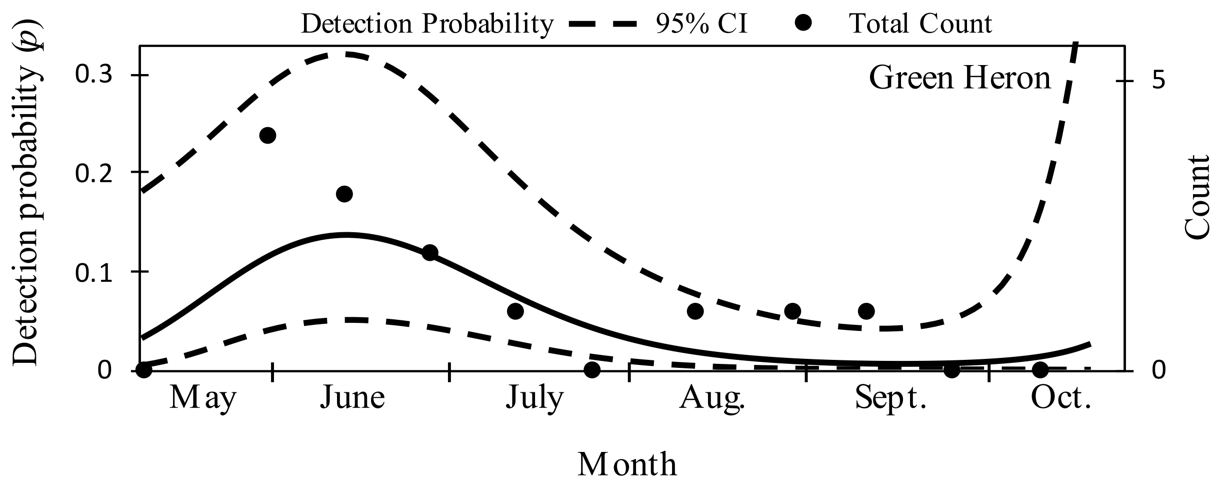


Figure 1.3 Detection probability (±95% CI) as a function of date for avian predators, estimated from occupancy analysis of shrimp ponds at the Gulf County, Florida, USA, study site, 2020–2021.

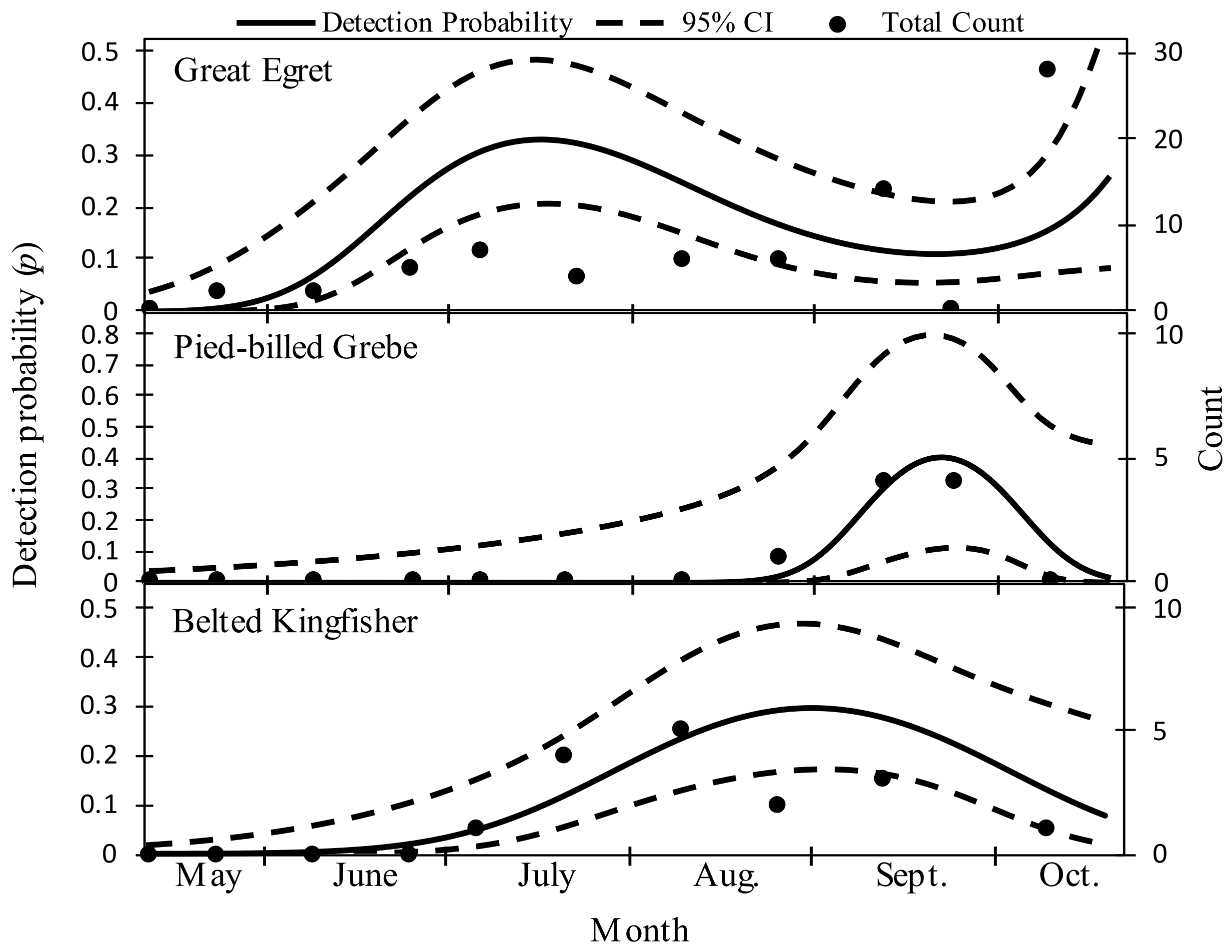


Figure 1.4 Relationship between Great Egret abundance and day of shrimp production season, pond size, and adjacent pond index at the Greene County, Alabama, USA, study site, 2020–2021.

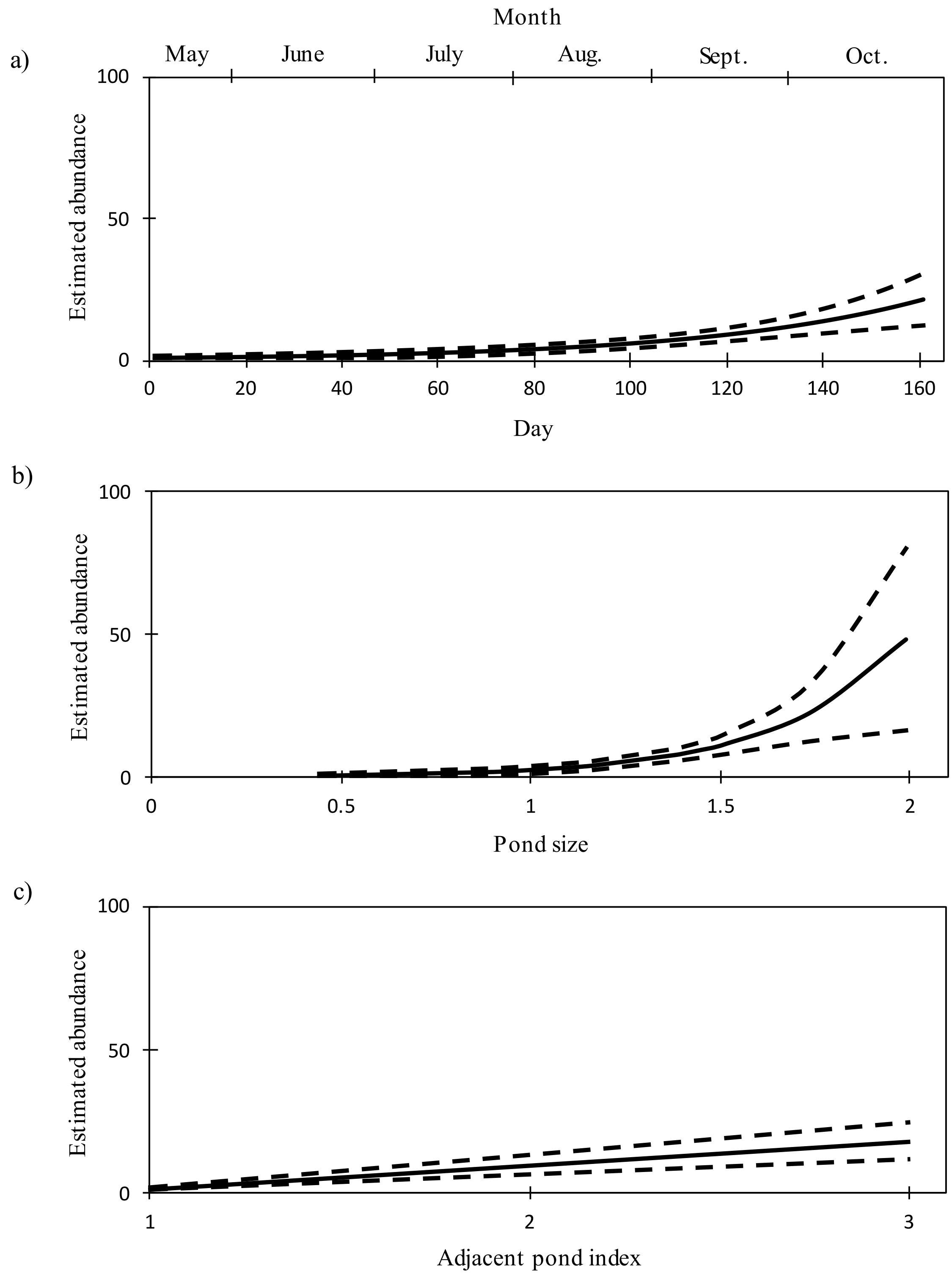


Figure 1.5 Relationship between Great Blue Heron abundance and adjacent pond index at the Greene County, Alabama, USA, study site, 2020–2021.

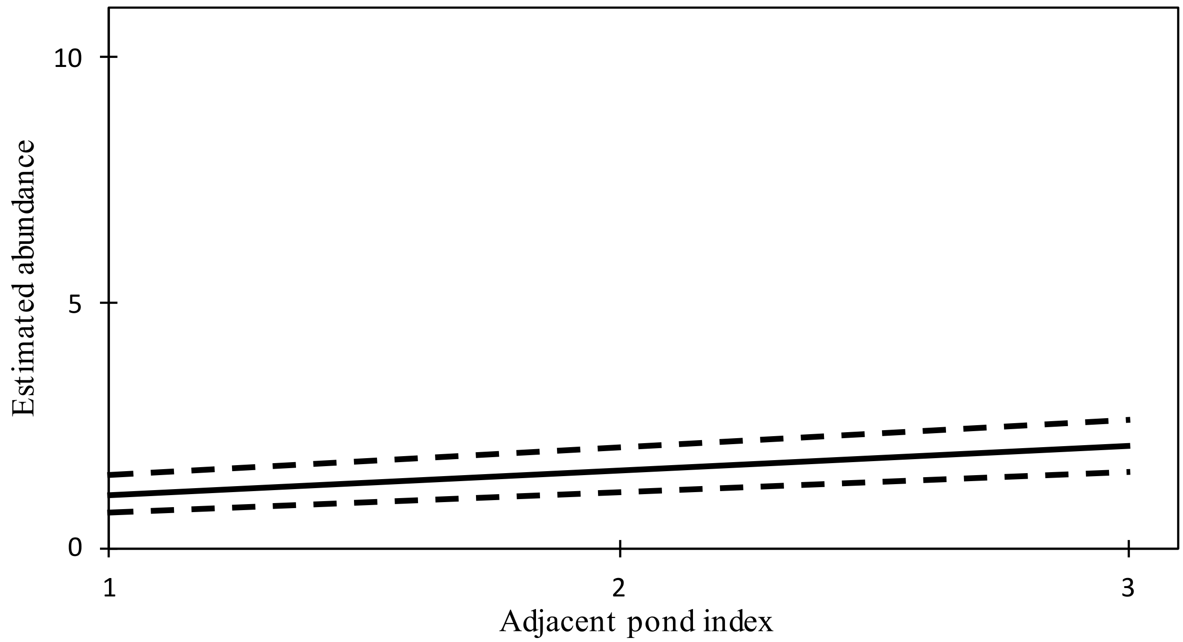
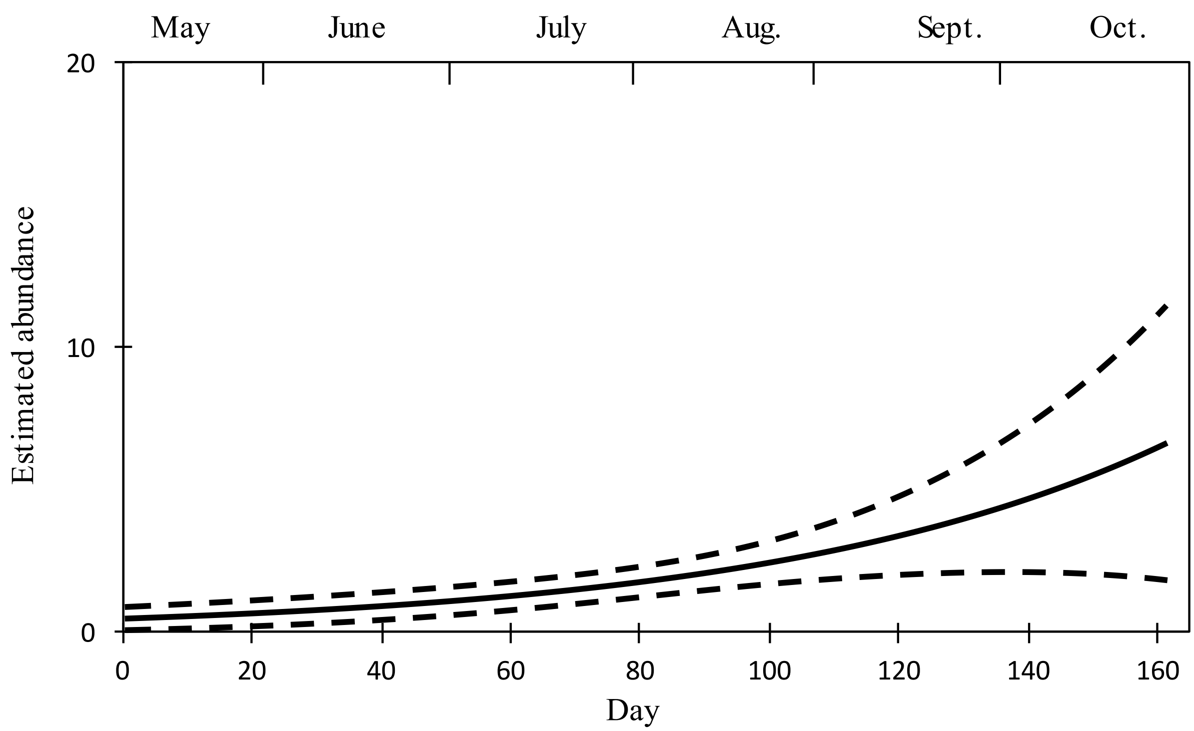


Figure 1.6 Relationship between Great Egret abundance and day of shrimp production season at the Gulf County, Florida, USA, study site, 2020–2021.



Chapter 2: Food Habits of Predatory Birds at Shrimp Farms in Alabama and Florida

ABSTRACT

Wading bird and waterfowl populations are known to occupy areas near and around aquaculture production sites. The use of low-salinity water and earthen ponds to produce Pacific white shrimp (*Litopenaeus vannamei*) is a popular aquaculture practice throughout Alabama, Florida, and Texas. However, there have been no studies quantifying the amount of damage caused by avian predators on U.S. shrimp production. Moreover, no studies have reported basic information regarding the diets of avian predators that use farms during the shrimp production season. During the 2020 and 2021 shrimp production seasons (i.e., April–October), we conducted surveys to estimate the abundance and distribution of avian predators at commercial farms in Alabama and Florida. Following surveys, we collected avian predators and then conducted necropsies to quantify their diets relative to the amounts of shrimp, fish, and invertebrates. A total of 106 avian predators (7 species) were collected during 2020 (n = 58) and 2021 (n = 48) with most being collected during the shrimp harvesting months of September and October. Of birds with stomach contents, shrimp consumption was variable across state and year with shrimp accounting for 30.6% (2020) and 5% (2021) occurrence in Alabama versus 73.3% (2020) and 15.8% (2021) in Florida. Shrimp found among stomach contents averaged 4.3g/bird (2020) and 0.1g/bird (2021) in Alabama with 2.15g/bird (2020) and 0.7g/bird (2021) in Florida. great egrets (*Ardea alba*) and great blue herons (*Ardea herodias*) were found to consume the most shrimp in Alabama while great egrets, great blue herons, little blue herons, (*Egretta caerulea*), double-crested cormorants (*Nannopterum auratus*), and pied-billed grebes (*Podilymbus podiceps*) were Florida's dominant shrimp predators on commercial farms.

INTRODUCTION

Due to an increased demand for fishery products and a decline in wild harvests worldwide, the global aquaculture trade currently supplies more than one-third of the world's population with aquatic species for consumption (Parker 2001). In 2018, the U.S. produced 5.2 million tons of fish and crustaceans with a value of 7,063.5 million USD. Of this seafood production, 17% came from aquaculture and 83% from wild fisheries. The quantity of wild caught and farmed fish and crustaceans produced between 2008 and 2018 increased by 7% while its value increased by 29% (OECD 2021). Given this aquaculture production, fish-eating birds are commonly found on aquaculture facilities throughout the U.S. (Hatch et al. 2014, Rhoades et al. 2019, Burr et al. 2020) exploiting these relatively abundant sources of concentrated prey items. A variety of avian species may use these aquaculture facilities and vary geographically but are typically classified based on prey selection, physiology, and life history (Stickley 1990, Rhoades et al. 2019). Consequently, their impacts on aquaculture production are highly variable but may be substantial in some cases.

For example, in the Southeastern United States, avian predation has been found to negatively impact aquaculture production in states across the southeastern U.S. including Texas, Louisiana, Mississippi, Arkansas, Alabama, and Florida (Mott and Brunson 1995, Burr et al. 2020, Clements et al. 2020). These avian groups include waterfowl, waterbirds birds, and seabirds which are often located in nearby wetland or coastal ecosystems. These birds commonly take advantage of the abundant prey items available to them during production of aquaculture commodities. Double-crested cormorants (*Nannopterum auritus*), great blue herons (*Ardea herodias*), great egrets (*Ardea Alba*), cattle egrets (*Bubulcus ibis*), tricolored herons (*Egretta tricolor*), black-crowned night herons (*Nycticorax nycticorax*), snowy egrets (*Egretta thula*), and little blue herons (*Egretta caerulea*) are some of the most common predators of catfish (Burr et al. 2019), baitfish, and shrimp aquaculture in the southeastern U.S. (Stickley 1990, Hatch et al. 2014). The foraging habits of many of these wading bird species are influenced by food abundance and availability, prey types, migration patterns, and habitat conditions (Kushlan et al. 1985). Wading birds prefer wetlands with shallow water and sparse or intermediate vegetation density (Lantz et al. 2011). Aquaculture facilities provide these fish-eating birds with potential foraging sites while providing a resource rich environment that facilitates efficient foraging with minimal energy expenditure (Wooten and Werner 2004).

More than half of the entire U.S. coastal wading bird and colonial water bird populations breed in coastal Florida, Alabama, Mississippi, and Louisiana (Keller et al. 1984) where open-water aquaculture is also prevalent. With increased nutritional demands associated with reproduction, many of these birds seek habitats that provide abundant forage. For example, Fleury and Sherry (1984) found that increasing wading bird populations correlated with crayfish aquaculture growing seasons in the Gulf Coast region of the U.S. However, predation is not only limited to the summer growing season. Burr et al. (2020) found an increased number of avian predators associated with fish aquaculture in the Mississippi Delta during winter months. Likewise, Clements et al. (2020) reported a combined 61,140 kg loss of golden shiner (*Notemigonus crysoleucas*), goldfish (*Carassius spp.),* and sunfish (*Lepomis spp*) across two seasons due to overwintering predator birds at baitfish production facilities in Arkansas.

Given increased numbers of predatory birds as the summer production season progresses, many studies have been conducted to quantify the financial loss experienced by aquaculture producers (Glahn 2002, Dorr and Fielder 2017, Burr et al. 2020). For example, Wooten and Werner (2004) reported an estimated $23,990–$29,990/farm in losses of golden shiner and goldfish to lesser scaup (*Aythya affinis*) consumption during Arkansas' winter-spring months.

Similarly, Clements et al. (2020) reported the number of baitfish consumed by scaup (*Aythya spp.*) in Arkansas varied across years but found consumption increased during periods of lower temperatures. Christie (2019) estimated that catfish farmers lost an average of 434.7 g/bird/day due to wintering double-crested cormorants depredating catfish farms in the Mississippi Delta. Likewise, Beynon et al. (1981) found that herons (*Ardea spp.*) commonly feed on shrimp and account for 60–70% of shrimp mortality on Texas mariculture ponds. Foreign studies reported similar results with cormorants (*Nannopterum spp.*), herons (*Ardea spp.*), and egrets (*Egretta spp.*) responsible for 30% of shrimp loss on farms in India (Roshnath 2014). Howard and Lowe (1984) discussed the negative impacts of spoonbills (*Platalea spp.*) predation on the adult recruitment and low survival of shrimp in coastal Australia seagrass beds.

Most of the above studies report financial losses from models based upon food habit studies of birds collected on aquaculture farms. These food habits found that the consumption of commercial aquaculture species (e.g., catfish, baitfish) varied throughout the growing season. For example, Christie et al. (2021) reported greater consumption of catfish in juvenile growth stages while Dorr et al. (2012) found similar results of catfish consumed during adolescent phases of life. However, Clements et al. (2020) and Wooten and Werner (2004) recorded similar findings of little variation in baitfish depredation relative to fish size but rather a correlation in increased consumption as ambient temperatures decreased. Coincidentally, many studies reported that birds not only consume the crop species, but also a diversity of other organisms ranging from arthropods to other non-crop fish, amphibians, and vegetative matter. For example, Clements et al. (2020) found 38 animal species and 9 plant species in food items from 123 scaup (*Aythya spp.*) frequenting baitfish aquaculture facilities in Arkansas. Wooten and Werner (2004), similarly, found that scaup consumed seven different prey types consisting of invertebrates and vegegation when collected on Arkansas baitfish aquaculture. As such, daily consumption of crop species may be highly variable and dependent upon other factors such as relative abundance of alternative prey items, habitat conditions, exposure to predation, and management actions of producers.

Whereas many studies examined the food habits of predatory birds at baitfish, catfish, and crayfish aquaculture facilities in the southeastern United States (Mott and Brunson 1995, Burr et al. 2020, and Clement et al. 2020), few studies have examined the food habits of predatory birds at low-salinity shrimp aquaculture facilities. This information is essential for understanding how these birds forage throughout the growing season and for the development of bioenergetic models to estimate overall consumption of crop species and ultimately the development of best management practices to reduce predation. Therefore, our objectives were to quantify the diet of predatory birds at low-salinity shrimp farms in Alabama and Florida.

METHODS

Study Area

Our study was conducted on two shrimp aquaculture farms in, one Greene County, Alabama and one in Gulf County, Florida. The Alabama farm was in rural west central Alabama where catfish was the dominant aquaculture species but was currently home to shrimp production also. The Florida farm was in northwest Florida approximately 1.6 km from the coast. Both farms were privately owned and focused primarily on commercial shrimp production. Both farms had multiple (~12–20) aquaculture ponds of approximately 0.6–1.99 ha each that were used for shrimp production. In both regions, LSW has been used for the cultivation of shrimp for decades with farmers using wells to pump ground water into earthen production ponds. The Alabama farm had 20 ponds in production in 2020 and 15 ponds in 2021, while the Florida farm had 12 ponds in production both years. The Alabama farm also used ponds for crayfish production during 2020 and 2021 (n = 5). All study ponds had a depth of approximately 1−1.5m. Pond size in Alabama ranged from 0.6−1.99 ha ($\bar{x}$ = 1.20 ha) while the farm in Florida had pond sizes that ranged from 1.33−1.97 ha ($\bar{x}$ = 1.65 ha).

Avian Predator Field Collections

Because no previous research had been conducted on predatory birds at shrimp aquaculture farms in the Southeast, we developed a list of 11 birds that may be consumers of shrimp using combinations of life history characteristics and foraging ecology of water birds, range maps to determine potential species present at our study sites, review of peer-refereed literature of predatory birds at aquaculture farms in the Southeast, and observations from local aquaculture producers. These birds included great blue heron, little blue heron, great egret, double-crested cormorant, green heron (*Butorides virescens*), lesser scaup, greater scaup (*Aythya marila*), ring-necked duck (*Aythya collaris*), pied-billed grebe (*Podilymbus podiceps*), hooded merganser (*Lophodytes cucullatus*), and belted kingfisher (*Megaceryle alcyon*). Likewise, no measures of expected variability were available that could be used to compute an estimated sample size. However, a sample size of 50 birds/species/year/study site was determined from Duffy and Jackson (1986) and Cochran (1953) using a 95% confidence interval, a 10% margin of error, and an 85% proportion of shrimp in stomachs that would provide a reasonable estimate of species-specific diet throughout the growing season. Whereas the proportion of shrimp prey in the diet was unknown, studies of double-crested cormorants collected from catfish aquaculture ponds may be somewhat similar (Glahn et al. 1995). As such, our goal was to collect a maximum of 5 birds of each species during each of the two sampling periods each month from May–October each year.

During each sampling period, we conducted morning (0700–0800), mid-day (1100–1200), and late afternoon (1800–1900) ground surveys to estimate the relative abundance of predatory birds at each farm. These counts were then used to determine the available depredating bird species during each sampling period. We used binoculars to monitor the behavior of these most common predatory birds from 50-300 meters away from inside a vehicle for ≥ 5 minutes to determine whether birds were actively foraging at production ponds and presumably consuming shrimp (Swanson and Bartonek 1970). Once these observations were completed, we attempted to collect these birds using either a 12-guage shotgun or .22 caliber rimfire rifle. Researchers stalked birds on foot or shot them from a temporary blind or a stationary vehicle and then recovered birds. Birds that did not die immediately from the initial gunshot were shot again or euthanized via cervical dislocation or blunt force trauma to the head. All collections were conducted under Alabama (no. #2020073627268680), Florida (no. #LSSC-20-0036B) and federal, (no. #MB019065-4) scientific collection permits and in accordance with the Auburn University Institutional Animal Care and Use Committee (permit no. 2020-3748).

To slow digestion following collections, the digestive tract of collected birds were injected with ≤ 60ml of cold phosphate buffered saline (PBS) and a zip tie was attached at the base of the neck to retain the fluid. If a collected bird's neck was punctured or contained prey items, multiple zip ties were added to secure the bird's ingested contents. Tyvek tags were used to label all collections and marked with the individual's corresponding species, farm of collection, pond number, date, and mass (kg). Collected birds were then sealed in plastic bags and placed in a cooler containing an icy slush until transported to a necropsy lab at Auburn University's College of Forestry, Wildlife, and Environment for processing within 72 hours of being collected.

Necropsy

During necropsies, the gastrointestinal tract (GI tract), gizzard, and stomach was removed as one sample. Intestines were placed in a 70:30 mixture of ethanol and warm water for later parasite analysis. Gizzards and stomachs were frozen and then later thawed and dissected to remove all prey items. Using scissors, we cut open the esophagus, proventriculus, gizzard, and stomach of each bird to extract the contents of this portion of the digestive system. Food items collected from the esophagus and proventriculus of each bird were placed on plastic trays for sorting. We then used dissecting microscopes and magnifying lenses to identify and sort contents based upon food type which included fish, invertebrates, and vertebrates (other than fish). Fish were classified to family whereas vertebrates (other than fish) were identified to Order. Most invertebrates, mainly Insecta, were identified only to Order whereas Decapods (shrimp and crayfish) were identified to Genus. For each Order we also included separate categories of "unknown" and "parts" for items we were not able to classify into a specific Order, Family, or Genus. Once identified, we placed all items into their respective aluminum pans and weighed each pan containing contents to the nearest mg (Hoppe et al. 1986) using an electronic scale (Phoenix GH-120 Analytical Balance) and then subtracted the pan weight to estimate the total wet-weight proportion of each prey item within each bird's total diet. Each pan was then dried for 22–24 hrs at 60°C in a soil drying oven designed for drying aggregate samples (Afton et al. 1991, Foth et al. 2014). We then re-weighed dried contents and again subtracted pan weight to determine the dry weight of prey items in each bird's diet.

Diet Composition

The diets of predatory birds were described using similar methods from previous research on waterfowl depredating baitfish aquaculture (Clements et al. 2020). We computed aggregate percentage dry weight (AP; Prevett et al. 1979) and percentage occurrence (PO; Swanson et al. 1974) values for all stomach contents for each bird species for each farm each year. We use AP because it provides a different expression of diet volume in relation to the total amount of each prey type consumed while PO provides insight into the proportion of each prey type consumed. Additionally, we treated each farm as the experimental unit rather than individual ponds due to the lack of spatial independence among ponds. To minimize bias associated with collected birds with no stomach contents, we only included collected individuals with stomach contents when computing AP and PO values.

Relative Prey Importance

We grouped ingested food items into 10 primary groups which comprised most (>90%) of the food items consumed by birds in our study. Shrimp was chosen because it was the primary variable and we were interested in analyzing with respect to avian diets on commercial shrimp ponds. Crayfish were included because they are commonly farmed alongside commercial shrimp and because crayfish and shrimp are closely related, belonging to the taxonomic order Decapoda. Fish were frequently preyed upon by the avian species in our study, so it was selected due to its regular occurrence among stomach contents. The remaining groups were created by combining similar prey types to reduce the variation of stomach contents across all species (e.g., combining all frogs into one group representing the order Anura). Other groups include 6 Orders of arthropods (Hemiptera, Orthoptera, Odonata, Stratiomyidae, Coleoptera, Araneae) and Anurans.

Relative prey importance was first described by Costello (1990) and later adapted by Amundsen et al. (1996) to better quantify which prey groups are prioritized during prey selection. Once calculated, prey groups are displayed to show which groups are consumed based on the predator’s specialized or generalized niche requirements. The method involves plotting the prey-specific abundance (PSA_i) against each prey groups' PO. Prey-specific abundance of prey group i (PSA_i) was calculated as:

$$PSA_i = \left(\frac{\sum S_i}{\sum S_{ti}}\right) x\ 100$$

where S_i represents the total dry mass of prey group i across sites, and S_{ti} signifies the total dry mass of all prey groups in ponds containing prey group i. The PO used during this calculation was determined for each prey group as described above.

Statistical Analysis

To compare the diets of each predator species between years and among prey types, sex, pond size, and shrimp size, we used double square root transformed relative biomass data for prey items in ponds to develop a Bray-Curtis similarity matrix. Applying a double square root transformation to data reduced the relative influence of dominant prey items (Clarke and Warwick 2001, Clements et al. 2020). The Bray-Curtis similarities matrix was then used to examine similarities in prey consumption within categories using an Analysis of Similarities (ANOSIM) within the *vegan* package of RStudio. Individual ANOSIMs were created for year, sex, pond size, and shrimp size across all predators containing prey items. Pond size was simplified down to a Pond Size Index (PSI) value corresponding to PSI categories of 1 (0.0–0.66 ha), 2 (0.66–1.32 ha), or 3 (1.32–2.0 ha; Table 2.1). These PSI categories were created by determining our pond size maximum range of values and then creating three equally sized categories of small, medium, and large ponds. Transforming pond size from continuous to categorical variables helped determine if avian predators preferred occupying different pond sizes within our ANOSIM models. This allowed us to understand the relationship between avian shrimp consumption and pond size. PSI was only applied to Alabama because Florida's ponds were approximately the same size and therefore difference in pond size was not significant.

Investigating the relationship between predator diets and shrimp size was evaluated by determining when consumption occurred while product size increased throughout the season. Shrimp sizes (gm) were obtained from producers' records that were maintained throughout the production season and applied to a Shrimp Size Index (SSI): Small (0.0−14.0 gm), Medium (14.0–24.5 gm), and Large (24.5+ gm; Table 2.1). Shrimp sized as 24.5+ gm denotes a harvestable shrimp size based on our producer's standards. These size categories were used to describe shrimp size classes consumed during the season. Because shrimp sizes increased throughout the season, we were able to examine the relationship in avian shrimp consumption and shrimp sizes as size changed.

ANOSIM is a non-parametric hypothesis-testing framework used for determining differences among sample groups. Though ANOSIM tests do not provide the range of other mixed-factor counterparts like permutational multivariate analyses of variance (PERMANOVAs), ANOSIM is seen to parallel the random-effects of other multivariate analyses while allowing a broader inference about the area from which random effects are drawn (Somerfield et al. 2021). Due to low sample size, each species was grouped by farm across both years. Additionally, we were not able to examine monthly differences in consumption due to low sample sizes. Within ANOSIM models where we detected a significant difference ($\alpha < 0.05$), we performed a similarities percentage analysis (SIMPER) to further investigate the overall contribution of each prey group to the dissimilarity of prey group levels consumed.

RESULTS

We collected 106 avian predators of 7 species in Alabama and Florida during the shrimp production seasons of 2020 and 2021 (Table 2.2). During 2020, we collected 41 avian predators in Alabama and 17 in Florida whereas in 2021 we collected 26 in Alabama and 22 in Florida. We collected significantly fewer birds at the Alabama farm in 2021 compared to the previous year while Florida's collection numbers were similar. Foraging predators were more difficult to collect during both seasons due to low overall abundances. Across both seasons, great egrets collected in Alabama were the only species with sufficient sample sizes for developing consumption estimates. Of birds collected 88.1% (total collected, n = 42) and 77.8% (total collected, n = 27) combined avian predators collected in Alabama during 2020 and 2021, respectively, had stomach contents containing identifiable prey items. Birds collected in Florida displayed similar results with 88.9% (total collected, n = 18) and 87% (total collected, n = 23) avian predators having distinguishable stomach contents during the 2020 and 2021 seasons, respectively.

Diet Composition

Prey items varied among species between years and farms. Shrimp occurred in 50% and 7.7% of great egrets collected in Alabama during 2020 and 2021, respectively (Table 2.3). However, of those egrets with stomach contents, shrimp comprised 74.9% and 9.2% of the diet during 2020 and 2021 (Figure 2.1). Shrimp was found in 100% and 40% of great egrets in Florida during 2020 and 2021 respectively (Table 2.3). Of these great egrets, shrimp comprised 91.1% and 45.2% of the diet during 2020 and 2021 (Figure 2.2). Fish comprised 11.2% and 62.6% of great egret diets in Alabama (Figure 2.1) with 8.5% and 10.3% in Florida (Figure 2.2) during 2020 and 2021, respectively. Crayfish was present in stomach contents also but averaged a relatively low occurrence in Alabama (16.5%) with a higher occurrence in Florida (40%). Excluding shrimp and crayfish groups, all other invertebrates, although frequent, averaged <11% of stomach contents across all great egrets during both years. The order Anura was the only terrestrial vertebrate category preyed upon by predator species. Anura was only found in 7.7% of great egrets in Alabama during 2021 and totaled ~1% of stomach content.

Great blue herons were not collected during the 2021 season (Table 2.4) at either farm. Of the three great blue herons collected during 2020, shrimp was the most frequently occurring prey in 1 of the 2 great blue herons collected in Alabama and the only great blue heron collect in Florida. (Table 2.4). In 2020, shrimp made up 70.2% of the total stomach contents of great blue herons collected in Alabama (Figure 2.1) and 100% of the total stomach content of great blue herons collected in Florida (Figure 2.2). Fish items were found in all great blue herons in Alabama (Table 2.4) but only comprised 29.8% of total prey items consumed (Figure 2.2). Of the 21 little blue herons collected in both states during 2020 and 2021 (Table 2.5), all contained identifiable stomach contents. Second to great egrets, little blue herons exhibited the largest variety of prey type occurrence. Shrimp were only present in little blue herons in Florida during 2020 occurring in 40% of birds containing stomach contents (Table 2.5). Shrimp made up 70.7% of the diet of little blue heron in Florida. Little blue herons were found to consume fish in Alabama in 2020 and Florida in 2021 (Table 2.5). Crayfish were found in 50% of Florida's little blue herons (2021) and averaged 78.2% of their total diet contents (Figure 2.2). A variety of other invertebrate types were found in little blue heron stomachs from both states across both years. Anura was present in 75% of little blue herons collected in Alabama during 2021 (Table 2.5) and comprised 60.1% of stomach contents dry weight biomass (Figure 2.1). Double-crested cormorants (*n* = 3) were only collected in Florida and only shrimp were found in their stomach contents (Table 2.6).

We collected 9 pied-billed grebes containing stomach items across both years of data sampling (Table 2.7). Shrimp were only found among grebes collected in Florida (66.7%) during

2020 (Table 2.7) and comprised 54.9% of stomach contents (Figure 2.2). Fish were found in 100% (2020) and 50% (2021) (Table 2.7) of grebes in Alabama and comprised 53.5% (2020) and 18.8% (2021) of stomach contents (Figure 2.1), respectively. Fish also occurred in 66.7% of Florida's grebes (2021), comprising 5.4% of stomach contents (Figure 2.2). Crayfish were found in pied-billed grebes at both farms, occurring in 100% of pied-billed grebes in Alabama (2020) (Table 2.7) and accounting for 46.5% of stomach contents (Figure 2.1). Crayfish occurrence in pied-billed grebes in Florida was 33.3% (2020) and 66.6% (2021) (Table 2.7) while occupying 33.3% (2020) and 74.7% (2021) of stomach contents (Figure 2.2).

Green herons were only collected in Alabama (*n* = 9) during sampling seasons of which 87.5% (Table 2.8) consumed fish encompassing 89% of their stomach contents (Figure 2.1). When combining crayfish and other invertebrate groups, green herons containing prey items (66.7%) averaged 16.7% of the aforementioned prey groups. Of the belted kingfishers collected (*n* = 6), only 3 contained prey items across both states and years (Table 2.9). In 2020, Alabama's belted kingfishers only consumed fish which made up 100% of stomach contents (Table 2.9) and diet proportion (Figure 2.1). Belted kingfishers collected in Florida (2021) were found only to have consumed crayfish which occupied 100% of their stomach contents (Table 2.9) and diet proportion (Figure 2.2).

Relative Prey Importance

The relationships between prey-specific abundance (PSA) and percent occurrence (PO) of prey types consumed by avian predators during shrimp production seasons varied among species and by year. Nine of the ten food item groups (i.e., Fish, Shrimp, Crayfish, Hemiptera, Odonata, Coleoptera, Stratiomyidae, Orthoptera, and Araneae) composed 90.1% of avian predator diets during 2020 in Alabama while composing 96.9% and 97.1% of diets in Florida during 2020 and 2021, respectively. These 9 prey groups represented 79.4% of predator diets during Alabama's 2021 shrimp season while the Anura prey group provided an additional 14.3%.

During 2020 in Alabama, great egrets and great blue herons opportunistically selected greater amounts of shrimp but lesser amounts in 2021 with shrimp only occurring as a general prey item in great egrets (Figure 2.1). Fish was a common prey item in Alabama and was opportunistically preyed upon by pied-billed grebes, belted kingfishers, and green herons during 2020 and great egrets during 2021. We found shrimp were opportunistically selected by great egrets, great blue herons, double-crested cormorants, pied-billed grebes, and little blue herons in Florida during 2020 but were only prioritized by double-crested cormorants in 2021 (Figure 2.2). Shrimp were favored by double-crested cormorants during 2020 and 2021 both in terms of occurrence (100%) and the proportion of mass consumed (100%). We also discovered pied-billed grebes, little blue herons, and belted kingfishers opportunistically consumed crayfish in Florida during 2021. When available, shrimp were prominently selected as an opportunistic prey item across multiple species during 2020 and 2021 in Alabama and Florida. Other prey items, like fish and invertebrate groups, varied across all avian predators and displayed generalized and opportunistic feeding strategies across both seasons.

Diet Composition Variation

We discovered similar prey groups among all bird species although the proportions of prey items varied. Great Egret diets differed between Medium and Large shrimp size categories (ANOSIM, $P = 0.044$). Our SIMPER analysis indicated that shrimp (18.9%), Hemiptera (17.7%), fish (16.8%), Orthoptera (13.1%), crayfish (7.4%), Odonata (5.5%), and Stratiomyidae (3.0%) accounted for 82.4% of the dissimilarity. Great egrets collected while shrimp were medium sizes contained greater average aggregate percentages of shrimp than those collected when shrimp were in the Large category.

DISCUSSION

The diets of avian predators using commercial shrimp farms during production seasons were composed entirely of animal prey which accounted for 100% of prey in all predator species per aggregate percent. Diets varied among predator species and between farms and seasons. Clements et al. (2020) determined waterfowl using baitfish aquaculture were consuming similar animal prey items but to a lesser degree as waterfowl were also consuming vegetation items. Shrimp consumption during 2020 and 2021 across both farms was substantially different with more shrimp being consumed during the 2020 season. We attribute the lower amounts of shrimp consumed in 2021 diets to lower populations of great egrets and great blue herons responsible for most of the shrimp consumed during 2020. We do not have a reasonable explanation as to why specific avian predator populations were lower during 2021 and believe it may be due to year-to-year variation.

Only a small portion of Alabama's avian predator species were found consuming shrimp versus nearly all avian predators in Florida. Of the avian predators consuming shrimp, nearly all were found to consume shrimp mainly during the shrimp harvest months of September and October on both farms. Only 58.8% of Great egrets and 33.3% of great blue herons collected in 2020 at the Alabama farm were found to have consumed shrimp but only 7.7% of great egrets were found to have consumed shrimp in 2021. The consumption of shrimp by avian predators in Florida during 2020 followed a similar trend with all great egrets, great blue herons, and double-crested cormorants and a third of little blue herons, and two thirds of pied-billed grebes predating shrimp but only during harvest months (Table 2.3–9). Throughout the 2021 production season in

Florida, only double-crested cormorants (100%) were found consuming shrimp during this period, consuming an average of 10.6 g dry weight of shrimp/bird. Considering shrimp consumption primarily occurred late in the season and during harvest months, we believe this is due to mature shrimp sizes and lowered water levels necessary for harvesting. Although shrimp were present throughout the growing season, the energy invested during the predation of larger shrimp near the end of the season likely resulted in a greater return on investment in terms of foraging efficiency due to the greater nutritional composition of larger shrimp combined with lower water levels which reduced search time. Lowered pond levels allowed avian predator greater access to shrimp during the final stages of the shrimp production cycle. Though this does not support the concept of shrimp predation increasing as shrimp sizes increase, we believe great egrets actively foraged for shrimp as their size increased throughout the production cycle due to the low aggregate percentages of shrimp found in egrets collected when shrimp were small. A larger sample size would benefit further analysis investigating the correlation between great egret shrimp predation and shrimp sizes.

A variety of invertebrate prey items were consumed across our sampled avian predators. In most cases, invertebrates were a common prey item and represented generalized feeding behaviors which has been reported in similar diet analyses studies of avian predators at aquaculture ponds. (Figures 2.1 and 2.2). In the case of great egrets, little blue herons, pied-billed grebes, and green herons, these species were consuming invertebrate prey items also consumed by waterfowl on baitfish aquaculture. Although similar, the invertebrate diets of our avian predators on aquaculture were not as extensive as those of waterfowl depredating aquaculture (Clements 2020).

A variety of invertebrates were found among the diets where shrimp were present, but the aggregate percent dry weight and the prey-specific abundance of shrimp was greater than other invertebrate items and revealed shrimp consumption as opportunistic behavior by great egrets, great blue herons, little blue herons, double-crested cormorants, and pied-billed grebes (Figure 2.1-2). Larger birds (great egrets, great blue herons, and double-crested cormorants) were found predominantly consuming shrimp which was likely indicative of their physical attributes that allow them to stalk and capture larger prey items. Double-crested cormorants and pied-billed grebes are diving predators which provide an advantage when foraging on aquatic species like shrimp.

Shrimp, crayfish, and invertebrate parts were identified and considered when determining our aggregate percent dry weights of avian predator stomach contents (Table 2.3-9). At times, it was difficult to differentiate between these prey group parts when categorizing stomach contents. These items were factored into our findings as shrimp, crayfish, and invertebrate parts but were not considered with the 10 prey groups used to conduct ANOSIM and SIMPER analyses and had minimal influence due to each making up a small proportion of the diet. Fish parts were calculated with dry weights as these items were easily identifiable compared to other stomach contents.

There are few studies investigating the impacts of avian predators on low-salinity aquaculture in earthen ponds within the U.S. Previous studies have acknowledged the predation of shrimp by avian predators (Stickley 1990) and the damage caused by these avian predators at foreign shrimp farms (Roshnath 2014). Investigation into the diets of wading birds in coastal, Caribbean marshes confirms the presence of crustaceans among the stomach contents of avian predators (Miranda and Collazo 1997). Our research focused on diurnal (daylight) foraging of bird species. Since the avian species we studied are primarily diurnal foragers and producers have not experienced nocturnal (nightly) avian activity, we did not investigate the potential impacts of nocturnal depredation. However, some research suggests that some avian species may forage at night on aquaculture and therefore our estimates may be conservative with respect to total predation.

Like other wetland systems, invertebrates, fish, and shrimp provide multiple avian predator species with a stable diet derived from commercial aquaculture ponds. The perception among producers that avian predators consume shrimp is supported by the results of this study. Specifically, our results suggest that avian predators are more likely to consume shrimp later in the production season during the harvest months of September and October, with the exception of little blue herons who favored July and August. To help mitigate shrimp crop depredation by avian predators, we suggest producers increase bird harassment efforts during the harvest months of shrimp growing seasons. In our study, most avian predators tended to congregate in large flocks along the pond edges while exhibiting stalking behaviors and returned to ponds relatively slowly (i.e., >30 minutes) following harassment. Some predators displayed diving behaviors following harassment which is often more challenging to alleviate when occurring. For future consideration, we recommend that producers increase harassment leading up to and during harvest months as well as when predators congregate in large flocks exhibiting foraging activities.

Although our study suggests that predation mostly occurs during harvest months, further research is necessary to fully understand the predation behaviors and diet composition of avian predators on low-salinity shrimp aquaculture. The ability to increase species samples sizes across the shrimp growing season would provide more evidence into the diet of these suspected avian predators. Also, incorporating multiple shrimp farms from different regions would help researchers better understand the eating habits of avian predators in that region and provide more evidence in the realm of avian depredation for future endeavors.

REFERENCES

Afton, A. D., R. H. Hier, and S. L. Paulus. 1991. Lesser scaup diets during migration and winter in the Mississippi flyway. Canadian Journal of Zoology 69:328–333.

Amundsen, P. A., H. M. Gabler, and F. J. Staldvik. 1996. A new approach to graphical analysis of feeding strategy from stomach contents data – modification of the Costello (1990) method. Fish Biology 48:607–614.

Beynon, J. L., D. L. Hutchins, A. J. Rubino, A. L. Lawrence, and B. R. Chapman. 1981. Nocturnal activity of birds on shrimp mariculture ponds. Journal of the World Mariculture Society 12:63–70.

Burr, P. C., J. L. Avery, G. M. Street, B. K. Strickland, and B. S. Dorr. 2020. Fine scale characteristics of catfish aquaculture ponds influencing piscivorous avian species foraging use in the Mississippi Delta. PLOS ONE 15(2):e0229402.

Christie, T.W. 2019. Predation risk of Double-crested Cormorants (Phalacrocorax auratus) on commercial catfish production in the Mississippi Delta. Thesis, Mississippi State, Mississipi, USA.

Christie, T. W., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2021. Food habits of wintering double-crested cormorants in the Mississippi Delta. Food Webs 26:e00185.

Clarke, K. R., and R. M. Warwick. 2001. Change in marine communities: an approach to statistical analysis and interpretation, second edition. PRIMER-E, Plymouth, Devon, United Kingdom.

Clements, S. A., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2020. Diets of scaup occupying baitfish and sportfish farms in eastern Arkansas. Food Webs 23:e00141.

Cochran, W. G. 1953. Sampling techniques. New York: John Wiley & Sons.

Costello, M. J. 1990. Predator feeding strategy and prey importance: a new graphical analysis. Fish Biology 36:261–263.

Dorr, B. S., and D. G. Fielder. 2017. Double-crested cormorants: Too much of a good thing? American Fisheries Society 42(9):468–477.

Dorr, B. S., L.W. Burger, S.C. Barras, and K. Godwin. 2012. Economic impact of Double-crested Cormorant (Phalacrocorax auritus) depredation on Channel Catfish (*Ictalurus punctatus*) aquaculture in Mississippi, USA. Journal of the World Aquaculture Society 43:502–513.

Duffy, D. C., and S. Jackson. 1986. Diet studies of seabirds: a review of methods. Colonial Waterbirds 9:1–17.

Fleury, B. E., and T. W. Sherry. 1995. Long-term population trends of colonial wading birds in the southern United States: the impact of crayfish aquaculture on Louisiana populations. The Auk 112:613–632.

Foth, J. R., J. N. Straub, R. M. Kaminski, J. B. Davis, and T. D. Leininger. 2014. Aquatic invertebrate abundance and biomass in Arkansas, Mississippi, and Missouri bottomland hardwood forests during winter. Journal of Fish and Wildlife Management 5:243–251.

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 18:168–175.

Glahn J. F., B. S. Dorr, J. B. Harrel and L. Khoo. 2002. Foraging ecology and depredation of Great blue herons at Mississippi catfish farms. The Journal of Wildlife Management 66:194–201.

Hatch, J. J., D. V. Weseloh, and B. S. Dorr. 2014. Double-crested Cormorant (Phalacrocorax auritus). The Birds of North America Online (A. Poole, Ed.). Cornell Lab of Ornithology, Ithaca, New York.

Hoppe, R. T., L. M. Smith, and D. B. Wester. 1986. Foods of wintering diving ducks in South Carolina. Journal of Field Ornithology 57:126–134.

Howard, R. K., and K. W. Lowe. 1984. Predation by birds as a factor influencing the demography of an intertidal shrimp. Journal of Experimental Marine Biology and Ecology 74(1):35–52.

Keller, C. E., J. A. Spendelow, and R. D. Greer. 1984. Atlas of wading bird and seabird nesting colonies in coastal Louisiana, Mississippi, and Alabama: 1983. U.S. Fish and Wildlife Service FWS/OBS-84/13 p.133.

Kushlan, J. A., G. Morales, and P. C. Frohring. 1985. Foraging niche relations of wading birds in tropical wet savannas. Ornithological Monographs 36:663–682.

Lantz, S. M., D. E. Gawlik, and M. I. Cook. 2011. The effects of water depth and emergent vegetation on foraging success and habitat selection of wading birds in the everglades. Waterbirds 34:439–447.

Miranda, L., and J. A. Collazo. 1997. Food habits of four species of wading birds (Ardeidae) in a tropical mangrove swamp. Colonial Waterbirds 20:413–418

Mott, D. F and M. W. Brunson.1995. A historical perspective of catfish production in the southeast in relation to avian predation. Seventh Eastern Wildlife Damage Management Conference p.23-30. Jackson, Mississippi: Mississippi State University.

Organization for Economic Co-operation and Development [OECD]. 2021. Fisheries and aquaculture in the United States, January 2021. <https://www.oecd.org/agriculture/topics/fisheries-and-aquaculture/documents/report_cn_fish_usa.pdf>. Accessed 3 August 2022.

Parker, H. S. 2001. Aquaculture research is key to the future of U.S. fish farming. Agricultural Research 49:2.

Rhoades, C. A., P. J. Allen, and D. T. King. 2019. Using unmanned aerial vehicles for bird harassment on fish ponds. Proceedings of the Wildlife Damage Management Conference 18:13–23.

Roshnath, R. 2014. Fishing for living-shrimp farmer's perception of heronry birds in Kannur District Kerala- India. International Journal of Research 1(6):188-199.

Somerfield, P. J., K. R. Clarke, and R. N. Gorley. 2021. Analysis of similarities (ANOSIM) for 3-way designs. Austral Ecology 46: 927–941.

Stickley, A. R. 1990. Avian predators on southern aquaculture. Southern Regional Aquaculture Center Publication No. 400.

Swanson, G. A., and J. C. Bartonek. 1970. Bias associated with food analysis in gizzards of Blue-winged Teal. The Journal of Wildlife Management 34:739–746.

Wooten, D. E., and S. J. Werner. 2004. Food habits of Lesser Scaup *Aythya affinis* occupying baitfish aquaculture facilities in Arkansas. Journal of the World Aquaculture Society 35:70–77.

Table 2.1 Variables and measurement units used when conducting ANOSIM and SIMPER analysis for predator diets.

Variable	Category	Measurement Scale
Year	2020	
	2021	
Sex	Male	
	Female	
Pond Size Index (PSI)	1	0 – 0.66 (hectares)
	2	0.66 – 1.32
	3	1.32 – 2.00
Shrimp Size Index (SSI)	Small	0 – 14.0 (grams)
	Medium	14.0 – 24.5
	Large	24.5 – 31.5+

Table 2.2 Collected avian predator species on commercial shrimp and crayfish ponds at farms in Greene County, Alabama and Gulf County, Florida, USA 2020–2021 during shrimp production seasons .

	Alabama		Florida	
Species	2020	2021	2020	2021
Great Egret	24	17	4	5
Great Blue Heron	3	0	2	0
Little Blue Heron	4	4	5	8
Double-crested Cormorant	0	0	2	1
Pied-billed Grebe	1	4	3	4
Green Heron	8	1	0	0
Belted Kingfisher	1	0	1	4

Table 2.3 Aggregate percent dry weight (percent occurrence) of prey types from Great Egrets containing stomach contents (n = 42) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Great Egret			
	Alabama		Florida	
Food Item	2020 (n = 20)	2021 (n = 13)	2020 (n = 4)	2021 (n = 5)
Fish[a]	28.97 (55)	48.53 (61.54)	19.21 (50)	34.82 (80)
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)	9.28 (30)	21.77 (46.15)		20.00 (20)
Centrarchidae				
Lepomis spp. (e.g. bluegill)		7.69 (7.69)		
Unidentified Fish	2.19 (10)			11.09 (40)
Fish Parts	17.5 (40)	19.07 (38.46)	19.21 (50)	3.73 (20)
Invertebrate	70.99 (75)	51.25 (75.11)	80.78 (100)	65.17 (80)
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]	44.99 (50)	6.52 (5.88)	79.85 (100)	24.64 (40)
Shrimp Parts	2.36 (10)			
Cambaridae (crayfish)[a]	1.44 (10)	7.86 (23.08)		11.63 (40)
Cambaridae Parts	0.06 (5)	4.02 (15.38)		1.61 (20)

[a]Prey groups used in diet analysis.

Table 2.3 Continued.

Insecta				
Hemiptera[a]	5.94 (15)			
Heteroptera (giant water bug)	4.06 (15)	8.00 (23.08)		
Odonata[a]		0.8 (7.69)		
Anisoptera (dragonfly)	4.43 (10)	1.86 (23.08)	0.93 (25)	
Zygoptera (damselfly)	<0.05 (5)	0.11 (15.38)		
Ephemeroptera (mayfly)[a]				
Coloeptera[a]	0.39 (5)			
Diptera				
Stratiomyidae (soldierfly)	2.3 (5)	0.01 (7.69)		
Tabanidae (horse-fly)		1.1 (7.69)		
Trichoptera (caddisfly)				
Lepidoptera (butterfly)				
Orthoptera[a]	0.78 (10)	5.11 (7.69)		10.67 (20)
Gryllidae (cricket)	1.49 (10)			
Tettigoniidae (brush cricket)				
Caelifera (grasshopper)		10.84 (30.77)		16.27 (20)
Arachnida				
Araneae[a]				
Pisauridae				
Unidentified Invertebrate	2.65 (20)	4.27 (15.38)		

[a]Prey groups used in diet analysis.

Table 2.3 Continued.

Invertebrate Parts	0.05 (5)	0.75 (7.69)		0.35 (20)
Vertebrate		0.2 (7.69)		
Amphibia				
Anura[a]		0.2 (7.69)		
Total animal	100 (100)	100 (100)	100 (100)	100 (100)

[a]Prey groups used in diet analysis.

Table 2.4 Aggregate percent dry weight (percent occurrence) of prey types from Great Blue Herons containing stomach contents (n = 3) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Great Blue Heron			
	Alabama		Florida	
Food Item	2020 (n = 2)	2021 (n = 0)	2020 (n = 1)	2021 (n = 0)
Fish[a]	52.18 (100)			
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)	2.18 (50)			
Centrarchidae				
Lepomis spp. (e.g. bluegill)				
Unidentified Fish				
Fish Parts	50 (50)			
Invertebrate	47.81 (50)		100 (100)	
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]	47.81 (50)		100 (100)	
Shrimp Parts				
Cambaridae (crayfish)[a]				
Cambaridae Parts				

[a]Prey groups used in diet analysis.

Table 2.4 Continued.

Insecta
Hemiptera[a]
Heteroptera (giant water bug)
Odonata[a]
Anisoptera (dragonfly)
Zygoptera (damselfly)
Ephemeroptera (mayfly)[a]
Coloeptera[a]
Diptera
Stratiomyidae (soldierfly)
Tabanidae (horse-fly)
Trichoptera (caddisfly)
Lepidoptera (butterfly)
Orthoptera[a]
Gryllidae (cricket)
Tettigoniidae (brush cricket)
Caelifera (grasshopper)
Arachnida
Araneae[a]
Pisauridae
Unidentified Invertebrate

[a]Prey groups used in diet analysis.

Table 2.4 Continued.

Invertebrate Parts				
Vertebrate				
Amphibia				
Anura[a]				
Total animal	100 (50)	0 (0)	100 (100)	0 (0)

[a]Prey groups used in diet analysis.

Table 2.5 Aggregate percent dry weight (percent occurrence) of prey types from Little Blue Herons containing stomach contents (*n* = 21) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Little Blue Heron			
	Alabama		Florida	
Food Item	2020 (*n* = 4)	2021(*n* = 4)	2020 (*n* = 5)	2021 (*n* = 8)
Fish[a]	21.69 (50)			16.8 (25)
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)	15.52 (25)			2.33 (12.5)
Centrarchidae				
Lepomis spp. (e.g. bluegill)	3.27 (25)			
Unidentified Fish				
Fish Parts	2.9 (25)			14.47 (25)
Invertebrate	78.26 (100)	64.41 (100)	11.79 (100)	83.2 (87.5)
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]			27.57 (40)	
Shrimp Parts				
Cambaridae (crayfish)[a]				47.25 (50)
Cambaridae Parts				8.11 (12.5)

[a]Prey groups used in diet analysis.

Table 2.5 Continued.

Insecta				
Hemiptera[a]	0.17 (25)			
Heteroptera (giant water bug)	29.76 (75)	3.45 (50)	16.50 (80)	6.27 (50)
Odonata[a]				
Anisoptera (dragonfly)	4.62 (50)	8.35 (25)	16 (40)	0.48 (12.5)
Zygoptera (damselfly)			0.05 (20)	
Ephemeroptera (mayfly)[a]	7.06 (25)			
Coloeptera[a]				0.28 (12.5)
Diptera				
Stratiomyidae (soldierfly)	19.92 (50)	3.56 (25)	4.47 (60)	4.26 (37.5)
Tabanidae (horse-fly)				
Trichoptera (caddisfly)		0.72 (25)		
Lepidoptera (butterfly)				0.8 (12.5)
Orthoptera[a]	0.62 (25)	2.25 (25)	22.30 (40)	0.5 (12.5)
Gryllidae (cricket)	3.65 (25)			
Tettigoniidae (brush cricket)				
Caelifera (grasshopper)	7.31 (75)	23.36 (50)	0.11 (20)	3.15 (12.5)
Arachnida				
Araneae[a]	1.27 (25)	16.8 (50)	3.14 (20)	12.1 (37.5)
Pisauridae			<0.05 (20)	
Unidentified Invertebrate	3.89 (50)		8.77 (40)	

[a]Prey groups used in diet analysis.

Table 2.5 Continued.

Invertebrate Parts		5.92 (75)	1.05 (20)	
Vertebrate		35.6 (75)		
Amphibia				
Anura[a]		35.6 (75)		
Total animal	100 (100)	100 (100)	100 (100)	100 (100)

[a]Prey groups used in diet analysis.

Table 2.6 Aggregate percent dry weight (percent occurrence) of prey types from Double-crested cormorants containing stomach contents (*n* = 3) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Double-crested Cormorant			
	Alabama		Florida	
Food Item	2020 (*n* = 0)	2021(*n* = 0)	2020 (*n* = 2)	2021 (*n* = 1)
Fish[a]				
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)				
Centrarchidae				
Lepomis spp. (e.g. bluegill)				
Unidentified Fish				
Fish Parts				
Invertebrate			100 (100)	100 (100)
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]			100 (100)	100 (100)
Shrimp Parts				
Cambaridae (crayfish)[a]				
Cambaridae Parts				

[a]Prey groups used in diet analysis.

Table 2.6 Continued.

Insecta
Hemiptera[a]
Heteroptera (giant water bug)
Odonata[a]
Anisoptera (dragonfly)
Zygoptera (damselfly)
Ephemeroptera (mayfly)[a]
Coloeptera[a]
Diptera
Stratiomyidae (soldierfly)
Tabanidae (horse-fly)
Trichoptera (caddisfly)
Lepidoptera (butterfly)
Orthoptera[a]
Gryllidae (cricket)
Tettigoniidae (brush cricket)
Caelifera (grasshopper)
Arachnida
Araneae[a]
Pisauridae
Unidentified Invertebrate

[a]Prey groups used in diet analysis.

Table 2.6 Continued.

Invertebrate Parts				
Vertebrate				
Amphibia				
Anura[a]				
Total animal	0 (0)	0 (0)	100 (100)	100 (100)

[a]Prey groups used in diet analysis.

Table 2.7 Aggregate percent dry weight (percent occurrence) of prey types from Pied-billed Grebes containing stomach contents (n = 9) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Pied-billed Grebe			
	Alabama		Florida	
Food Item	2020 (n = 1)	2021(n = 2)	2020 (n = 3)	2021 (n = 3)
Fish[a]	53.53 (100)	2.28 (50)		35.81 (66.6)
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)				
Centrarchidae				
Lepomis spp. (e.g. bluegill)				
Unidentified Fish	53.53 (100)			
Fish Parts		2.28 (50)		35.81 (66.6)
Invertebrate	46.46 (100)	97.69 (50)	99.99 (100)	64.17 (66.6)
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]			41.21 (66.6)	
Shrimp Parts				
Cambaridae (crayfish)[a]	46.46 (100)		19.22 (33.3)	49.37 (66.6)
Cambaridae Parts			6.23 (33.3)	14.80 (33.3)

[a]Prey groups used in diet analysis.

Table 2.7 Continued.

Insecta		
Hemiptera[a]		
Heteroptera (giant water bug)	4.82 (50)	33.33 (33.3)
Odonata[a]		
Anisoptera (dragonfly)	8.86 (100)	
Zygoptera (damselfly)	30.7 (50)	
Ephemeroptera (mayfly)[a]		
Coloeptera[a]		
Diptera		
Stratiomyidae (soldierfly)		
Tabanidae (horse-fly)		
Trichoptera (caddisfly)		
Lepidoptera (butterfly)		
Orthoptera[a]		
Gryllidae (cricket)		
Tettigoniidae (brush cricket)		
Caelifera (grasshopper)		
Arachnida		
Araneae[a]	10.90 (50)	
Pisauridae		
Unidentified Invertebrate		

[a]Prey groups used in diet analysis.

Table 2.7 Continued.

Invertebrate Parts				
Vertebrate				
Amphibia				
Anura[a]				
Total animal	100 (100)	100 (100)	100 (100)	100 (100)

[a]Prey groups used in diet analysis.

Table 2.8 Aggregate percent dry weight (percent occurrence) of prey types from Green Herons containing stomach contents (n = 9) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Green Heron			
	Alabama		Florida	
Food Item	2020 (*n* = 8)	2021(*n* = 1)	2020 (*n* = 0)	2021 (*n* = 0)
Fish[a]	78.15 (87.5)			
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)	40.71 (75)			
Centrarchidae				
Lepomis spp. (e.g. bluegill)				
Unidentified Fish	3.61 (12.5)			
Fish Parts	33.83 (50)			
Invertebrate	21.83 (75)	99.98 (100)		
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]				
Shrimp Parts				
Cambaridae (crayfish)[a]	0.02 (12.5)			
Cambaridae Parts				

[a]Prey groups used in diet analysis.

Table 2.8 Continued.

Insecta		
Hemiptera[a]	2.3 (25)	
Heteroptera (giant water bug)		
Odonata[a]	<0.05 (12.5)	
Anisoptera (dragonfly)	7.72 (25)	
Zygoptera (damselfly)	4.1 (25)	39.51 (100)
Ephemeroptera (mayfly)[a]	4.57 (12.5)	
Coloeptera[a]		
Diptera		
Stratiomyidae (soldierfly)		
Tabanidae (horse-fly)		
Trichoptera (caddisfly)		
Lepidoptera (butterfly)		
Orthoptera[a]		
Gryllidae (cricket)		
Tettigoniidae (brush cricket)	1.01 (12.5)	
Caelifera (grasshopper)		58.70 (100)
Arachnida		
Araneae[a]		
Pisauridae		
Unidentified Invertebrate	2.09 (37.5)	

[a]Prey groups used in diet analysis.

Table 2.8 Continued.

Invertebrate Parts		1.77 (100)		
Vertebrate				
Amphibia				
Anura[a]				
Total animal	100 (100)	100 (100)	0 (0)	0 (0)

[a]Prey groups used in diet analysis.

Table 2.9 Aggregate percent dry weight (percent occurrence) of prey types from Belted Kingfishers containing stomach contents (n = 3) collected from commercial shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

	Belted Kingfisher			
	Alabama		Florida	
Food Item	2020 (n = 1)	2021(n = 0)	2020 (n = 0)	2021 (n = 2)
Fish[a]	100 (100)			
Poeciliidae				
Gambusia spp. (e.g. mosquitofish)	100 (100)			
Centrarchidae				
Lepomis spp. (e.g. bluegill)				
Unidentified Fish				
Fish Parts				
Invertebrate				100 (100)
Malacostraca				
Decapoda				
Penaeidae				
L. vannamei[a]				
Shrimp Parts				
Cambaridae (crayfish)[a]				100 (100)
Cambaridae Parts				

[a]Prey groups used in diet analysis.

Table 2.9 Continued

Insecta
Hemiptera[a]
Heteroptera (giant water bug)
Odonata[a]
Anisoptera (dragonfly)
Zygoptera (damselfly)
Ephemeroptera (mayfly)[a]
Coloeptera[a]
Diptera
Stratiomyidae (soldierfly)
Tabanidae (horse-fly)
Trichoptera (caddisfly)
Lepidoptera (butterfly)
Orthoptera[a]
Gryllidae (cricket)
Tettigoniidae (brush cricket)
Caelifera (grasshopper)
Arachnida
Araneae[a]
Pisauridae
Unidentified Invertebrate

[a]Prey groups used in diet analysis.

Table 2.9 Continued.

Invertebrate Parts				
Vertebrate				
Amphibia				
Anura[a]				
Total animal	100 (100)	0 (0)	0 (0)	100 (100)

[a]Prey groups used in diet analysis.

Figure 2.1 Prey-specific abundance versus percent occurrence of prey items found in (a) Great Egrets, (b) Great Blue Herons, (c) Pied-billed Grebes, (d) Little Blue Herons, and (e) Green Herons, and (f) Belted Kingfishers containing shrimp prey at the Greene County, Alabama, USA, study site, 2020–2021 (FI = Fish, SHR = Shrimp, CR = Crayfish, HE = Hemiptera, OD = Odonata, CO = Coleoptera, ST = Stratiomyidae, OR = Orthoptera, AN = Araneae). Panel (g) Explanatory diagram in Amundsen et al. (1996) explaining relative prey importance and the interpredation of feeding strategy, niche width (BPC = between-phenotype component; WPC = within-phenotype components) and prey importance for a predator species.

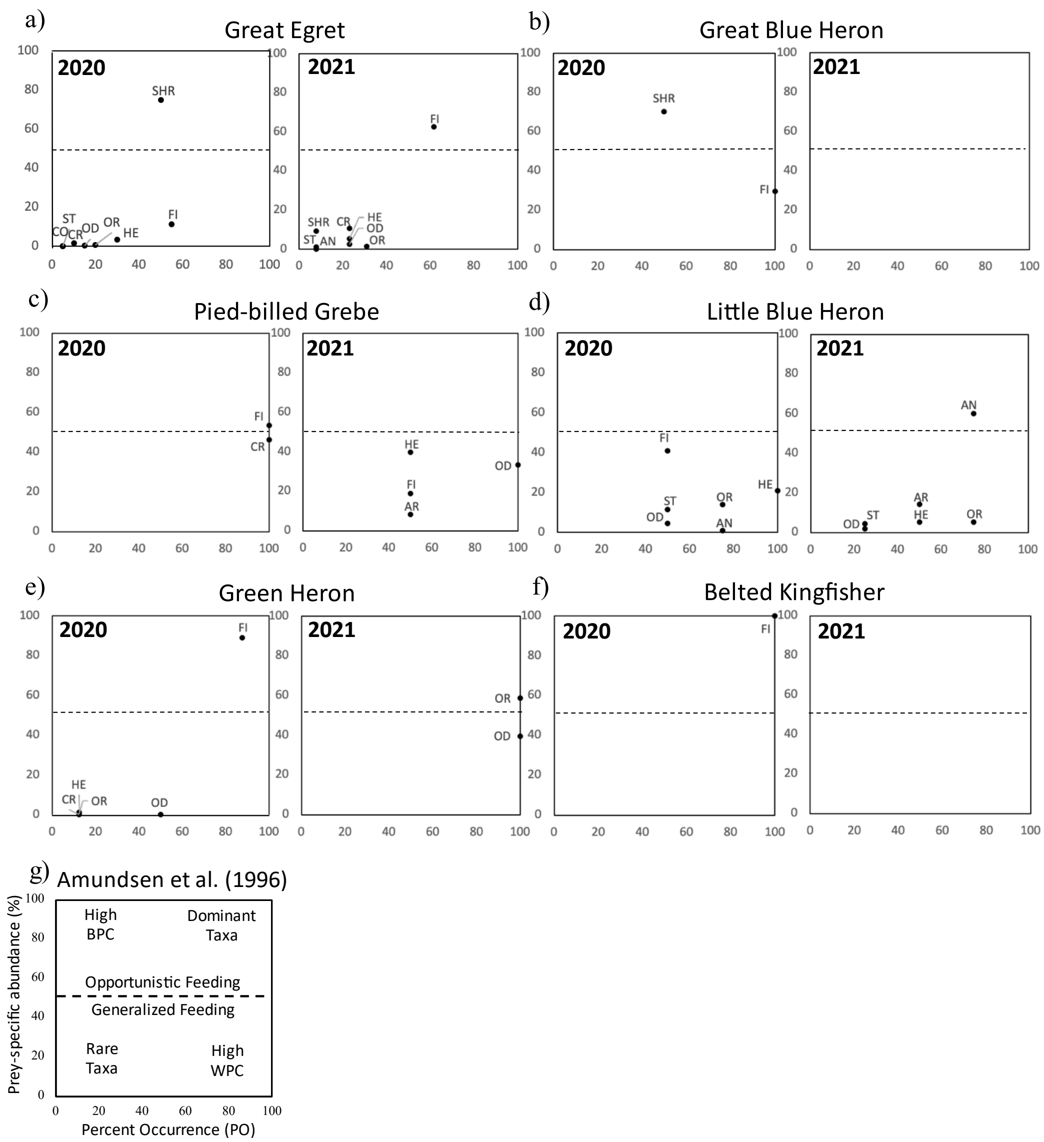
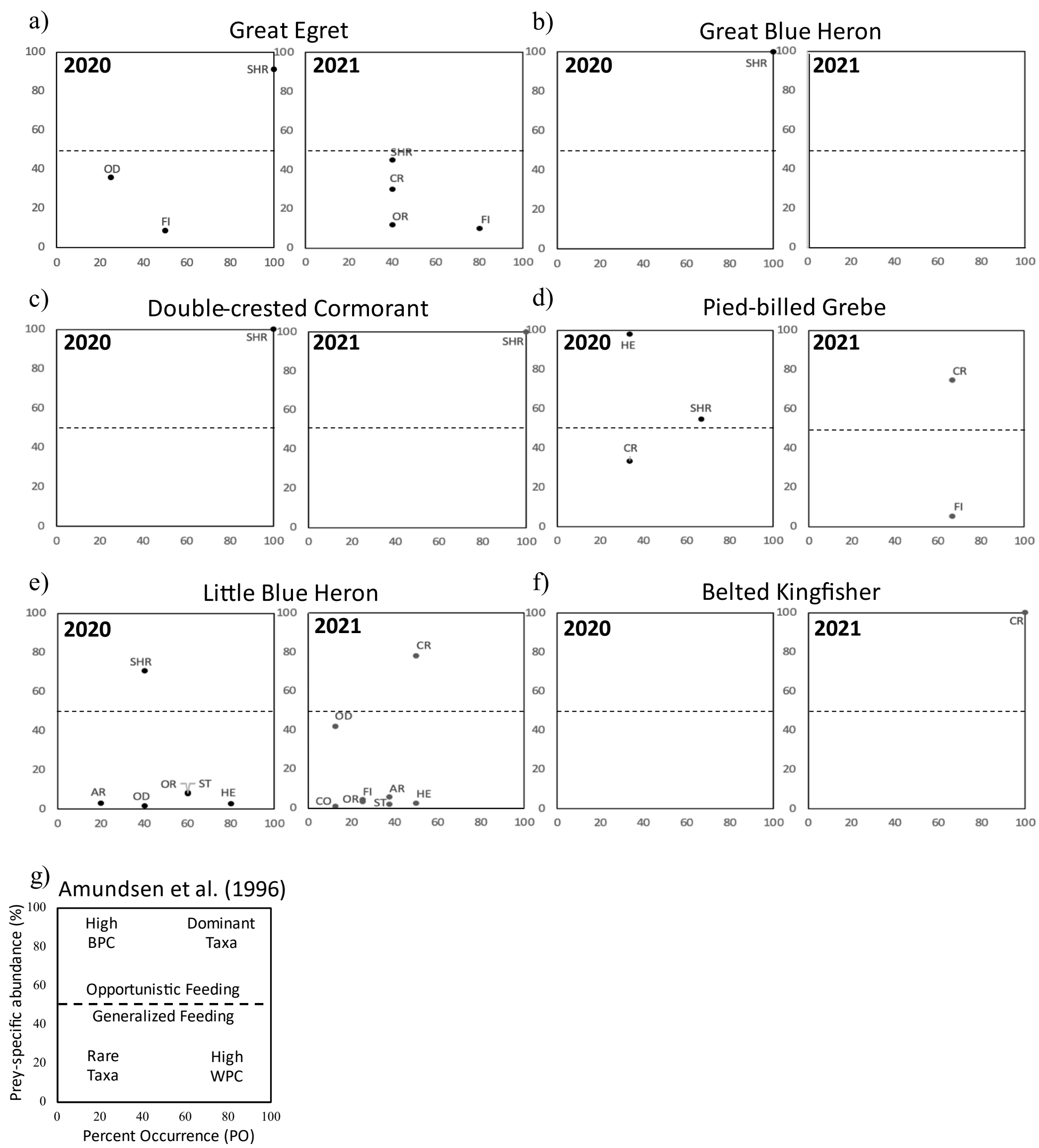


Figure 2.2 Prey-specific abundance versus percent occurrence of prey items found in (a) Great Egrets, (b) Great Blue Herons, (c) Double-crested Cormorants, (d) Pied-billed Grebes, and (e) Little Blue Herons, and (f) Belted Kingfishers containing shrimp prey at the Gulf County, Florida, USA, study site, 2020–2021 (FI = Fish, SHR = Shrimp, CR = Crayfish, HE = Hemiptera, OD = Odonata, CO = Coleoptera, ST = Stratiomyidae, OR = Orthoptera, AN = Araneae). Panel (g) Explanatory diagram in Amundsen et al. (1996) explaining relative prey importance and the interpredation of feeding strategy, niche width (BPC = between-phenotype component; WPC = within-phenotype components) and prey importance for a predator species.



Chapter 3: Estimating Shrimp Consumption by Predatory Birds on Commercial Shrimp Farms in Alabama and Florida

ABSTRACT

The use of low-salinity aquaculture and earthen ponds to produce Pacific white shrimp is a popular aquaculture practice throughout Alabama, Florida, and Texas. Multiple species of avian predators have been suspected of consuming Pacific white shrimp (*Litopenaeus vannamei*) produced at low-salinity aquaculture facilities, but there have been no studies quantifying the amount of damage caused by avian predators on U.S. shrimp production. Moreover, no studies have reported basic information regarding the diets of avian predators that use farms during the shrimp production season. Research is needed to understand the potential economic impact created by avian predators on low-salinity shrimp aquaculture in the U.S. During the 2020 and 2021 shrimp production seasons (i.e., April–October), we conducted surveys to estimate the abundance of avian predators at commercial shrimp farms in Alabama and Florida. Following surveys, we collected and necropsied avian predators to determine the proportion of these predators consuming shrimp and the proportion of their diets containing shrimp. A total of 106 avian predators (7 species) were collected during 2020 (n = 58) and 2021 (n = 48) with most being collected during the months of September and October when shrimp are typically harvested. Shrimp consumption was variable across state and year. Great egrets created the largest financial impact due to shrimp consumption with losses of approximately $570.00 (57,000 g; 2020) and $0.30 (30 g; 2021) in Alabama and $53.50 (5,350 g; 2020) and $1.30 (130 g; 2021) in Florida. Losses due to great blue and little blue herons totaled approximately $16.30 (1,630 g) across Alabama and Florida during 2020 and 2021. This study provides producers with shrimp depredation estimates and potential financial burdens created by avian predators. Our

findings can be used to help producers determine management strategies and implement the appropriate mitigation techniques.

INTRODUCTION

Shrimp products are some of the top commodities consumed within the U.S. seafood industry. The quantity of wild caught and farmed fish and crustaceans captured and produced between 2008 and 2018 increased by 7% while its value increased by 29% (OECD 2021). In 2019, the U.S. imported just over 900 metric tons of shrimp products while only exporting approximately 17 metric tons (Fisheries of the United States 2019). Over the 2020 U.S. production season, Alabama produced 69.4 metric tons, Florida produced 362.9 metric tons, and Texas produced 1,651 metric tons of shrimp through aquaculture production (G. Treece, Treece and Associates, personal communication).

Predatory birds have been shown to have significant impacts to aquaculture through direct consumption of fish. For example, Wooten and Werner (2004) reported an estimated $23,990-$29,990/farm in losses of golden shiner and goldfish to lesser scaup (*Aythya affinis*) consumption during winter-spring months in Arkansas. Christie et al. (2019) estimated catfish farmers lost an average of 649 metric tons of catfish biomass due to wintering double-crested cormorants (*Nannopterum auritus*) depredating catfish farms in the Mississippi Delta. Likewise, Beynon et al. (1981) found that herons (*Ardea spp.*) commonly feed on shrimp and account for 60-70% of shrimp mortality on Texas mariculture ponds. International studies reported similar results with cormorants (*Nannopterum spp.*), herons (*Ardea spp.*), and egrets (*Egretta spp.*) responsible for 30% of shrimp loss on farms in India (Roshnath 2014). Despite the growth of the commercial inland shrimp production industry, few studies have investigated the impacts that predatory birds may have on the final yield of shrimp produced through aquaculture using earthen semi-intensive production ponds. In recent years, Alabama shrimp farmers have reported greater mortality following harvest of production ponds in the fall which may be a significant factor in reducing overall production and yield (Roy et al. 2018).

Aquaculture facilities often occur near coastal environments, overlapping with the home ranges of many avian species that typically feed on freshwater fish, saltwater fish, and crustaceans, hence creating a potential for conflicts with aquaculture (Nagarajan and Thiyagesan 2006). Rhoades (2019) found that the shallow depths and high stocking rates of catfish ponds created ideal foraging environments while natural wetlands in the Mississippi Delta provided loafing, roosting and/or breeding habitats for fish-eating birds involved with aquaculture conflicts. Doornbos (1984) recorded shrimp consumption in European, saline waterbodies by Great Crested Grebes (*Podiceps cristatus*) and Red-breasted Mergansers (*Mergus serrator*). Multiple avian species are known to feed on commercial shrimp ponds including: great blue herons (*Ardea herodias*), great egrets (*Ardea alba*), and double-crested cormorants. Herons commonly feed on both fish and shrimp and have accounted for 60–70% of shrimp mortality on mariculture ponds during nocturnal predation with prey-capture rates ranging from 50–65% (Beynon et al. 1981). Avian depredation has been shown to negatively impact catfish aquaculture (Burr et al. 2020). Likewise, Clements et al. (2020) found that lesser and greater scaup (*Aythya marila*) frequently consume golden shiners (*Notemigonus crysoleucas*), fathead minnows (*Pimephales promelas*), and goldfish (*Carassius auratus*) at baitfish and ornamental aquaculture operations in Arkansas. Historically, fish-eating birds have been a concern at fish-rearing facilities because of the correlation between avian presence and economic losses (Rhoades et al. 2019, Burr et al. 2020). These same species are often found near shrimp aquaculture facilities where an abundance of prey is available (Beynon et al. 1981) and shrimp consumption is believed to be significant.

Although various methods have been used to estimate the consumption of fish by predatory birds such as the average weight of fish consumed by bird per day multiplied by total number of bird consumption days (Doornbos 1984), bioenergetic models are commonly used to estimate consumption. Our research adapted methods used by Dorr et al. (2012) and Christie et al. (2019) investigating the amount of catfish depredated by double-crested cormorants wintering in the Mississippi Delta using cormorant bioenergetics. Dorr et al. (2012) estimated the total catfish loss by combining monthly bird foraging days, the percent of catfish biomass in cormorant diet, biomass consumed in g/bird/day from fingerling and food fish aquaculture ponds, and the proportion of each pond type in the study region. These estimates were then combined with the financial losses from fingerling ponds and opportunity costs required to produce harvestable fish to calculate the total loss in catfish biomass due to cormorant consumption. Similarly, Christie et al. (2019) combined monthly foraging days, the average proportion of catfish in cormorant diets per month, and average monthly daily fish intake to calculate total loss in catfish biomass due to cormorant depredation. Clements et al. (2020) investigated the depredation of Arkansas baitfish aquaculture by lesser and greater scaup using scaup bioenergetics and comparable methods. Multiplying monthly foraging days, the proportion of scaup consuming fish, and the biomass of fish consumed in g/bird/day, Clements et al. (2020) calculated the total fish lost due to scaup consumption. By incorporating the annual relative abundance of predatory birds, DED of each bird species, and the amount of individual prey items found in avian predators, we could estimate the average amount of shrimp consumed throughout a season per species (Wooten and Werner 2004, Christie et al. 2019, Clements et al. 2020).

Therefore, our objectives were to estimate the total amount of shrimp consumed annually by avian predators and to estimate the economic loss in shrimp production at low-salinity water (LSW) shrimp aquaculture farms in Alabama and Florida.

METHODS

Study Area

Our study was conducted on two shrimp aquaculture farms, one in Greene County, Alabama and one in Gulf County, Florida. The Alabama farm was in rural west central Alabama where catfish is the dominant commercial aquaculture species but is currently home to shrimp production also. The Florida farm was in northwest Florida approximately 1.6 km from the coast. Both farms were privately owned and focused primarily on commercial shrimp production. Both farms had multiple (~12–20) aquaculture ponds of approximately 0.6–1.99 ha each that were used for shrimp production. In both regions, LSW has been used for the cultivation of shrimp for decades with farmers using wells to pump ground water into earthen production ponds. The Alabama farm had a greater number of ponds used for shrimp farming in 2020 (n = 20) than 2021 (n = 15) while the Florida farm's production pond total was constant from 2020 and 2021 (n = 12). The Alabama farm also used ponds for red swamp crayfish (*Procambarus clarkii*) production during 2020 and 2021 (n = 5). All study ponds had a depth of approximately 1–1.5m. Pond size in Alabama ranged from 0.6–1.99 ha ($\bar{x}$ = 1.20 ha) while Florida's pond size ranged from 1.33–1.97 ha ($\bar{x}$ = 1.65 ha).

Avian Surveys

To determine the distribution and relative abundance of avian predators on shrimp farms, we conducted biweekly ground surveys during the shrimp production seasons (April–October) in 2020 and 2021. During each sampling period (usually about 2–3 days) we conducted three surveys: morning, midday, and afternoon, beginning at 0700, 1100, and 1800 local time, respectively. Surveys were conducted by researchers using trucks to slowly drive along the levee system of each farm and surveying each pond for at least 5 minutes. Surveyors used binoculars and spotting scopes from distances that minimized bird disturbance but allowed for an unobstructed view of the pond's surface (i.e., 50–300 m from the pond's edge; Swanson and Bartonek 1970). Multiple survey routes (Alabama: n = 3, Florida: n =2) were used at each farm and randomly assigned among surveys (morning, midday, and afternoon). Randomly selecting a survey route helped better estimate avian counts by eliminating surveyor bias. During each survey, all potential shrimp-eating bird species and their behaviors (foraging from pond, foraging from land, swimming, loafing, or flushed) were recorded along with any other anecdotal information influencing avian use such as farmers passing on levees or equipment disturbing bird presence. Because no previous research had been conducted on predatory birds at shrimp aquaculture farms in the Southeast, we developed a list of 11 birds that were likely consumers of shrimp. We used combinations of life history characteristics and foraging ecology of water birds, range maps to determine potential species present at our study sites, review of peer-refereed literature of predatory birds at aquaculture farms in the Southeast, and observations from local aquaculture producers (Beynon et al. 1981, Christie et al. 2019, Burr et al. 2020, Clements et al. 2020) to compile this list. These birds included great blue heron, little blue heron, great egret, double-crested cormorant, green heron (*Butorides virescens*), lesser scaup, greater scaup, ring-necked duck (*Aythya collaris*), pied-billed grebe (*Podilymbus podiceps*), hooded merganser (*Lophodytes cucullatus*), and belted kingfisher (*Megaceryle alcyon*).

Although most observations were of individual or small (<10 birds) groups of birds, in a few instances larger congregations (e.g., >100 birds) of birds were encountered. In these instances, we estimated the total number of birds by counting each group of a single species to the tenth bird then summing the number of groups of similar sizes to estimate total flock size. This method is described by Arbib (1972) who uses repeated counts of bird groups to determine flock size when it is difficult to count individuals. The location and species of individual birds were marked on high resolution imagery captured by the National Agriculture Imagery Program (NAIP) and obtained from the USDA Geospatial Gateway for later integration into a Geographic Information Systems (GIS) database using ArcMap. We also noted the movement of birds on these maps as we progressed through the sampling route to avoid double counting. If travel or any other activity disturbed birds on ponds, observers waited 15 minutes before beginning surveys to allow birds to resume normal activity. In Alabama, some ponds were inactive during the 2021 production season, so these ponds were not surveyed and removed from survey routes.

Avian Predator Field Collections

Given the lack of previous research examining shrimp consumption by predator birds in North America, no measures of expected variability were available that could be used to compute an estimated sample size. However, a sample size of 50 birds/species/year/study site was determined from Duffy and Jackson (1986) and Cochran (1953) using a 95% confidence interval, a 10% margin of error, and an 85% proportion of shrimp in stomachs that would provide a reasonable estimate of species-specific diet throughout the growing season. Whereas the proportion of shrimp prey in the diet was unknown, studies of double-crested cormorants collected from catfish aquaculture ponds may be somewhat similar (Glahn et al. 1995, USDA, National Wildlife Research Center Quality Assurance Protocol QA-3166, unpublished document). As such, our goal was to collect a maximum of 5 birds of each species during each of the two sampling periods each month from May–October each year.

During each sampling period, predatory bird observations gathered during avian surveys were used to determine the available bird species and their relative locations within each farm. Once morning, midday, and afternoon surveys were complete, we attempted to collect these birds using either a 12-gauge shotgun or .22 caliber rimfire rifle. Researchers stalked birds on foot or shot them from a temporary blind or a stationary vehicle and then recovered birds. Birds that did not die immediately from the initial gunshot were shot again or euthanized via cervical dislocation or blunt force trauma to the head. All collections were conducted under Alabama (no. #2020073627268680), Florida (no. #LSSC-20-0036B) and federal, (no. #MB019065-4) scientific collection permits and in accordance with the Auburn University Institutional Animal Care and Use Committee (permit no. 2020-3748).

To slow digestion following collections, the digestive tract of collected birds were injected with ≤ 60ml of cold phosphate buffered saline (PBS) and a zip tie was attached at the base of the skull to retain the fluid. If a collected bird's neck was punctured or contained prey items, multiple zip ties were added to secure the bird's ingested contents. Tyvek tags were used to label all collections and marked with the individual's corresponding species, farm of collection, pond number, date, and mass (kg). Collected birds were then sealed in plastic bags and placed in a cooler containing an icy slush until transported to a necropsy lab at Auburn University's College of Forestry, Wildlife, and Environment for processing within 72 hours of being collected.

Necropsy

During necropsies, the gastrointestinal tract (GI tract), gizzard, and stomach was removed as one sample. Intestines were placed in a 70:30 mixture of ethanol and warm water for later parasite analysis. Gizzards and stomachs were frozen and then later thawed and dissected to remove all prey items. Using scissors, we cut open the esophagus, proventriculus, gizzard, and stomach of each bird to extract the contents of this portion of the digestive system. Food items collected from the esophagus and proventriculus of each bird were placed on plastic trays for sorting. We then used dissecting microscopes and magnifying lenses to identify and sort contents based upon food type which included fish, invertebrates, and vertebrates (other than fish). Fish were classified to family whereas vertebrates (other than fish) were identified to Order. Most invertebrates, mainly Insecta, were identified only to Order whereas Decapods (shrimp and crayfish) were identified to Genus. For each Order we also included separate categories of "unknown" and "parts" for items we were not able to classify into a specific Order, Family, or Genus. Once identified, we placed all items into their aluminum pans and weighed each pan containing contents to the nearest mg (Hoppe et al. 1986) using an electronic scale (Phoenix GH-120 Analytical Balance) and then subtracted the pan weight to estimate the total wet-weight proportion of each prey item within each bird's total diet. Each pan was then dried for 22–24 hrs at 60°C in a soil drying oven designed for drying aggregate samples (Afton et al. 1991, Foth et al. 2014). We then re-weighed dried contents and again subtracted pan weight to determine the dry weight of prey items in each bird's diet.

Diet Composition

The diets of predatory birds were described using similar methods from previous research on waterfowl depredating baitfish aquaculture (Clements et al. 2020). We computed aggregate percentage dry weight (AP; Prevett et al. 1979) and percentage occurrence (PO; Swanson et al. 1974) values for all stomach contents for each bird species for each farm each year. We used AP because it provides a different expression of diet volume in relation to the total amount of each prey type consumed while PO provides insight into the proportion of each prey type consumed.

Additionally, we treated each farm as the experimental unit rather than individual ponds due to the lack of spatial independence among ponds. To minimize bias associated with collected birds with no stomach contents, we only included collected individuals with stomach contents when computing AP and PO values.

We grouped ingested food items into 10 primary groups which comprised most (>90%) of the food items consumed by birds in our study. Shrimp was chosen because it was the primary variable we were interested in analyzing with respect to avian diets on commercial shrimp ponds. Crayfish and fish were frequently preyed upon by the avian species in our study, so they were selected due to their regular occurrence among stomach contents. The remaining groups were created by combining similar prey types (e.g., combining all frogs into one group representing the order Anura). Other groups include 6 Orders of arthropods (Hemiptera, Orthoptera, Odonata, Stratiomyidae, Coleoptera, Araneae) and Anurans.

Estimating Shrimp Consumption

We used species-specific Field Metabolic Rates (FMR) combined with True Metabolizable Energy (TME) values to estimate the total amount of shrimp a predator would need to ingest per day to meet their DED. We sourced our FMR and TME values from previous studies investigating the energetic value of diet items. Specifically, we used FMR of 1,479.5 (kJ/day) for great egrets (Nagy et al. 1999), 3,054.87 (kJ/day) for great blue herons (Nagy et al. 1999), and 656.73 (kJ/day) for little blue herons (Nagy et al. 1999). Likewise, we used estimates of TME of 5.51 kcal/g for fish (Pizazz and Peyre 2010, Eggleton and Schramm 2011), 1.06 kcal/g for shrimp (USDA 2017), and 0.98 kcal/g for other invertebrates (Sherfy 1999, Clements et al. 2020, Moreau et al. 2021). The AP of each prey group among avian predator diets by month was used for this analysis. Additionally, the wet weight (g) of each prey item found within a predator's stomach was used to determine how much of each prey group was needed by each species to reach DED. We then combined these consumed prey amounts with our predator abundance estimates, adjusted by the proportion of those predators observed consuming shrimp, for each sampling period at each site to estimate the total amount (in g) of shrimp consumed by predators monthly and throughout the production season.

During each sampling period of avian surveys, we selected the survey (morning, midday, or afternoon) which had the greatest count of each species to use for estimating the relative abundance during the 24-hour sample period. The maximum count for the day represents the minimum number of unique individuals of a species who foraged on the ponds. This estimate is likely a conservative estimate of the total number of birds using the ponds. Prior to estimating abundance, we determined total seasonal observations of birds ≥ 20 were sufficient sample sizes. This is justified since Gotelli and Ellison (2004) states a sample size of 10–20 per predictor is appropriate for ecological studies. Abundance was then modeled as a polynomial function of counts by species during each sampling period throughout the production season. Using the sampling period specific count estimates, we applied polynomial terms of ordinal date from first order (linear) up to the ninth order to describe avian predator species abundances over a season (Clements et al. 2020). We defined each season as the time from when shrimp brood stock was incorporated into ponds to the last day shrimp were harvested from each farm resulting in a 160- and 143-day season for Alabama in 2020 and 2021, respectively, and a 148- and 143-day production season for the Florida farm in 2020 and 2021, respectively. We selected the top linear or polynomial model that described avian abundance by examining a plot of the sum of squares of residuals (SSR) then selecting the order that minimized the SSR while determining the addition of another parameter did not benefit the model according to a partial F-test (Clements et al. 2020). After selecting species specific models of abundance, the estimated abundance was derived by integrating our models to obtain a cumulative count of birds for each species and survey period.

With individual species-specific models for each year, the estimated number of each species present for each day during the production season were summed to produce the total number of bird use-days (BUDs). We applied the same approach to help estimate BUDs under the upper and lower 95% confidence limits of each model, to calculate a high and low for both years across our study area. By pooling the diet of a given bird species in each state during each season, we used the presence/absence of shrimp within birds to estimate the average proportion of birds consuming shrimp during each sample period that surveys occurred. This method allowed us to calculate the number of BUDs for each species and associate them with the number of birds only consuming shrimp (i.e., Bird Consumption Days, BCDs). To determine the amount of shrimp consumed during those BCDs, the aggregate percent of each predator's diet from shrimp was estimated for each month using the individuals that contained shrimp and other identifiable food items. The following equation was used to calculate the total amount of shrimp consumed monthly:

Total shrimp consumed (g month^{-1}) =

Shrimp consumed (g bird^{-1} day^{-1}) x *total bird consumption-days* (month^{-1})

The annual shrimp loss for each season can be determined by summing the total shrimp consumed for each month. We incorporated actual seafood market values of $4.50/lb ($0.01/g) used by our producers to estimate monthly and annual financial losses. The price/g for shrimp was multiplied by our shrimp losses in g/month to determine the total financial impact created annually per species. To estimate how the variation in avian abundance may affect financial loss we estimated low, average, and high levels of abundance based on 95% CI's of abundance from our surveys. We then estimated the effects on financial loss for certain predators to visualize potential losses during seasons of variable predator abundance based on shrimp losses (in g) for low, average, and high monthly abundance for each species.

RESULTS

Avian Predator Abundance

Avian predator abundance estimates varied across season and state and were only determined for the species found consuming shrimp each season. In Alabama, only great egret and great blue heron samples were available to compute shrimp loss during 2020, followed by great egrets in 2021. In Florida, we were able to produce shrimp consumption estimates for great egrets, great blue herons, and little blue herons during 2020, followed by followed by great egrets in 2021. Although recorded during surveys in 2020 and 2021, few observations or collections were available for double-crested cormorants or pied-billed grebes throughout production seasons in Florida, so no consumption estimates were made for these species.

Alabama's avian predator abundance was greater in 2020 than 2021 with great egrets being the most abundant followed by great blue herons. During the 2020 production season, 608 great egrets were surveyed versus 53 in 2021. Based on R^2 value and partial F-test the best fit polynomial models were a 5th and 7th order polynomial regression for years 1 and 2, respectively (Figure 3.1; Table 3.1). We estimated great egret BUDs to be 8,275 (95% CI, 3,390–18,381) in year 1 and 639 (95% CI, 7–2,388) in year 2. In year 1, most of our great egret BUDs occurred in September (39.5%) and October (42.7%) whereas BUDs in year 2 were greatest in September (36.8%). Abundance at the Florida farm followed a similar trend with greater avian predator abundance during 2020 than 2021. In 2020 we survey 41 great egrets followed by 37 in 2021.

Based on R^2 and partial F-test the best fit polynomial models were a 7th and 3rd order polynomial, respectively (Figure 3.3; Table 3.2). Great egret BUDs totaled 772 (95% CI, 176−1,888) in year 1 and 481 (95% CI, 77−1,303) in year 2. September (59.8%) experienced the highest proportion of great egret BUDs during year 1 compared to October (39.1%) in year 2.

Based on R^2 value and partial F-test the best fit polynomial model for great blue herons in Alabama during 2020 was a 2nd order polynomial regression (Figure 3.2; Table 3.1). Great blue heron BUDs totaled 448 (95% CI, 241−836) in year 1 with majority occurring in September (38.2%) and October (38.2%). Based on R^2 value and partial F-test we selected a 7th order polynomial for great blue heron counts in Florida during 2020, respectively (Figure 3.4; Table 3.2) while estimating a total abundance of 417 (95% CI, 49−1,071). The highest proportion of great blue herons occurred during September (42.4%) in Florida. Based on R^2 value and partial F-test little blue herons in Florida were fit with a 9th order polynomial, respectively (Figure 3.5; Table 3.2) during 2020. We estimated little blue heron abundance of 558 (95% CI, 0−10,172) BUDs, peaking in July (28.7%).

Diet Composition

Prey items varied among species between years and farms. In Alabama, we collected 24 (2020) and 17 (2021) great egrets. Shrimp occurred in 50% (n = 10) and 7.7% (n = 1) of great egrets containing stomach contents collected in Alabama during 2020 (n = 20) and 2021 (n = 13), respectively (Table 2.3; This Theses, Chapter 2). However, of those egrets consuming shrimp, shrimp comprised 74.9% and 9.2% of the diet during 2020 and 2021 (Figure 2.1; This Theses, Chapter 2). In Florida, we collected 4 (2020) and 5 (2021) great egrets. Of great egrets with stomach contents (n = 4, n = 5), shrimp was found in 100% (n = 4) and 40% (n = 2) during 2020 and 2021, respectively (Table 2.3; This Theses, Chapter 2). Of these great egrets, shrimp comprised 91.1% and 45.2% of the diet during 2020 and 2021 (Figure 2.2; This Theses, Chapter 2).

Great blue herons were not collected during the 2021 season at either farm (Table 2.4; This Theses, Chapter 2). Of the great blue herons collected in 2020 (*n* = 5), we collected three in Alabama and two in Florida. Stomach contents were present in three of those collected. Of the three containing stomach contents, shrimp occurred in 1 of the 2 great blue herons collected in Alabama and the only great blue heron collect in Florida. (Table 2.4; This Theses, Chapter 2). Shrimp made up 70.2% of the total stomach contents of great blue herons collected in Alabama (Figure 2.2; This Theses, Chapter 2) while comprising 100% of the great blue heron stomach contents in Florida (Figure 2.2; This Theses, Chapter 2). Of the 21 little blue herons collected in both states during 2020 and 2021 (Table 2.5; This Theses, Chapter 2), all contained identifiable stomach contents. Shrimp were only present in little blue herons in Florida during 2020 occurring in 40% (*n* = 2) of birds containing stomach contents (*n* = 5; Table 2.5; This Theses, Chapter 2). Shrimp made up 70.7% of little blue heron diets in Florida.

Avian Shrimp Consumption

The estimated bird use days, proportion of birds that consumed shrimp, shrimp consumed (g $bird^{-1}$ day^{-1}), and monthly shrimp loss totals differed considerably across season and state for all species. Employing species-specific FMR (Table 3.3) and TME values (Table 3.4) for prey items consumed coupled with the proportion of shrimp in predator diets were used to estimate the approximate amount of shrimp consumed throughout the 2020 and 2021 production seasons.

In 2020, the proportion of great egrets that consumed shrimp in Alabama was lower in September (25%, SE = 25) and greater in October (75%, SE = 13.1; Table 3.5). Less shrimp was consumed in 2021 with the greatest proportion of shrimp consumed by birds in September

(12.5%, SE = 12.5; Table 3.6). In Florida, the proportion of great egrets that consumed shrimp in 2020 peaked in September (100%, SE = 0) and October (100%, SE = 0; Table 3.7). During 2021, shrimp consumption decreased with a small proportion of egrets that consumed shrimp in August (33%, SE = 33) and July (50%, SE = 50; Table 3.8).

Of the great blue herons collected in 2020, shrimp primarily occurred in the diets of herons in September (33.3%, SE = 33.3; Table 3.5) in Alabama. Similarly, the greatest proportion of great blue herons that consumed shrimp in Florida occurred in September also (50%, SE = 50; Table 3.7). Little blue herons consumed shrimp in Florida during 2020. Shrimp primarily occurred in little blue heron diets in July (50%, SE = 50) and August (33%, SE = 33; Table 3.7).

We found shrimp consumption occurred primarily during September and October for most avian predators. Great egrets in Alabama consumed the most shrimp across species with a peak of 19.75 g $bird^{-1}$ day^{-1} in October of year 1. Shrimp consumption was significantly less in year 2 (1 g $bird^{-1}$ day^{-1}) and occurred only in September. We estimated the total shrimp loss in Alabama due to great egrets was 57,000 g and 30 g in 2020 and 2021, respectively (Table 3.5 and Table 3.6). Great egrets in Florida displayed a similar pattern and consumed the most shrimp in October (14.83 g $bird^{-1}$ day^{-1}) of year 1. However, great egret BUDs were higher in September which resulted in the highest monthly shrimp loss (4,680 g). Year 2 differed significantly as the highest consumption occurred in July (2.23 g $bird^{-1}$ day^{-1}) but only 120 g of total loss. Overall, we estimated great egret shrimp consumption resulted in 5,350 and 130 g in 2020 and 2021, respectively (Table 3.7 and Table 3.8).

A lack of evidence of shrimp consumption among other species limited our ability to effectively estimate shrimp loss across all avian predators. Alabama's great blue herons only consumed shrimp in October (7.76 g $bird^{-1}$ day^{-1}) of year 1 with an estimated total loss of 440 g, respectively (Table 3.5). Florida's great blue herons displayed similar results as consumption occurred in October (10.26 g $bird^{-1}$ day^{-1}) with an estimated total loss of 910 g in year 1, respectively (Table 3.7). Little blue heron shrimp consumption in Florida was the highest in August (5.39 g $bird^{-1}$ day^{-1}) with an estimated total shrimp loss of 280 g in year 1, respectively Table 3.7).

Once we determined the total shrimp loss, we were able to estimate the financial impacts created using seafood market values sourced from our producers. Using the market value of \$4.50/lb (\$0.01/g), we multiplied the total shrimp loss (in g) by \$0.01/g to find the total financial losses generated by avian predators across states and years. Great egrets were found consuming the most shrimp in Alabama with average annual losses of approximately 57,000 g (\$565.50) with low/high loss estimates of 12,460 g –192,520 g (\$123.61–\$1,909.92) during 2020 and in 2021 averaging 30 g (\$0.30) with low/high loss estimates of <0.01 g –70 g (\$0.00–\$0.69). In Florida great egrets consumed 5,350 g (\$53.08) with low/high loss estimates of 40 g –42,550 g (\$0.09–\$422.12) during 2020 and 130 g (\$1.29) with low/high loss estimates of <0.01 g –4,960 g (\$0.00–\$49.21) during 2021 (Figure 3.6). Great blue heron consumption only occurred in 2020 with annual losses of 440 g (\$4.37) with low/high loss estimates of <0.01 g –4,240 g (\$0.00–\$42.06) in Alabama and 910 g (\$9.10) with low/high loss estimates of <0.01 g –10,580 g (\$0.00–\$104.96) in Florida (Figure 3.7). Little blue herons only consumed shrimp in Florida during 2020 with estimated annual losses of 280 g (\$2.80) with low/high loss estimates of <0.01 g – 36,010 g (\$0.00–\$357.24), respectively (Figure 3.8).

DISCUSSION

Overall, shrimp consumption by avian predators was relatively low across years and states. Apart from great egrets, the avian predators we investigated on these farms were found to have little impact on shrimp production and dollar loss. When abundant, great egrets were found consuming the most shrimp with the potential to generate moderate financial impacts. Implementing management strategies to decrease populations when abundant may further reduce the impact created by great egrets. Though we observed other species actively consuming shrimp in both states, low abundance and consumption estimates yielded low losses for such predators. Producers attempted to disturbed birds when present however we do not know what magnitude of harassment was completed. We evaluated shrimp losses while avian management was ongoing across farms, suggesting estimated losses may be higher without active harassment measures. This is supported by Kumar et. al (2021) who found avian depredation at aquaculture facilities is significantly higher without the implementation of avian harassment or dispersal methods. When abundant, the avian predators we observed could potentially impose higher financial losses if left undisturbed.

Avian Predator Abundance

Farms in Alabama and Florida experienced more shrimp consumption in 2020 versus 2021. In general, we observed larger quantities of birds on farms in Alabama and Florida during 2020 than farms in both states during 2021. Avian species life history events such as breeding and annual migration are subject to environmental aspects that may influence annual population fluctuations (Robinson et al. 2010). Burr et al. (2023) states that avian predator (e.g., double-crested cormorant) populations are likely affected by landscape factors such as aquaculture availability and seasonal changes which may influence avian presence over time. These seasonal changes include precipitation and high temperatures throughout productions seasons. We locally sourced monthly precipitation and temperature averages from the National Oceanic and Atmospheric Administration (NOAA) Online Weather Data but found there was not a change in either statistic between years that would influence seasonal bird numbers at either farm. The implementation of non-lethal harassment supported by lethal removal has helped producers deter avian presence at both farms for multiple years. These practices are supported by Reinhold and Sloan (1997) who claim these methods are an efficient when harassing roosting and non-roosting avian species on aquaculture farms. However, the intensity of production efforts has limited our producer's ability to effectively harass enough predators to substantially reduce avian numbers. Our presence may have increased avian removal efforts during 2020 and 2021 by providing producers with additional harassment support. It is possible our supplemented harassment during 2020 reduced overall avian presence at both farms during 2021. Variable avian abundance and shrimp consumption estimates give insight into the relationship between the two. We believe these findings indicate that shrimp loss due to avian predation can change year to year.

When evaluating our results from both years, it is difficult to determine which year was experiencing normal conditions in terms of shrimp depredation. Interactions with producers indicate the high avian presence we witnessed in year one mimicked the abundances they experience annually. However, our sample of two farms over two seasons restricted our ability to evaluate this claim. Increasing the number of shrimp farms sampled and adding more years to the study would provide a greater number of sampling sites and improve our ability to determine which years may be considered average avian presence and shrimp consumption. This was not logistically feasible for our study as other shrimp farms were widely dispersed across states. Further research regarding bird presence on additional shrimp farms can help clarify the relationship between avian predators and shrimp aquaculture.

Diet Composition

When estimating shrimp loss, we modified methods used by other studies investigating the impacts of avian predators on other types of aquaculture. Our calculations primarily adapted the techniques used by Clements et al. (2020) which investigated how the proportions of specific prey items contributed to the species-specific DEDs. These concepts have not been used to investigate the impacts of avian predators on shrimp aquaculture. Incorporating FMR helped to understand the energy requirements of each avian species, but the lack of species specific FMR may have limited our ability to accurately predict consumption estimates. However, using FMR based on allometric equations for related avian groups allowed us to reasonably estimate shrimp consumption. While species specific FMR would more accurately estimate shrimp consumption, exact FMR for species who consumed relatively low amounts of shrimp (e.g., little blue heron, pied billed grebe) would not substantially change our results.

The investigation of avian predator stomach contents provided evidence about the prey items consumed by each species during production seasons. Recognizing the proportion of each prey item in avian diets helped us estimate the amount each time consumed throughout the season based on obtainable energy. Sourcing the TME values of prey groups from other literature (Table 3.4) enabled us to estimate each predator's daily diet. Understanding there are limitations and data restrictions, we consider it appropriate to assume our average TME values of diet items found across avian predators represent the energy obtained by our predators. Determining the amount of each prey group needed to reach the DED of our predators allows us to more accurately estimate the total shrimp loss based on the proportion of each avian predator consuming shrimp and amount of shrimp consumed. Enhancing our methods by including specific TME values for prey items may provide more accurate consumption estimates, but it is unlikely to substantially change our estimated shrimp loss.

When comparing the TME values of top prey items consumed on shrimp ponds, we can understand the desire for avian predators to consume shrimp when available. Of the prey groups consumed most by our predators, Pacific-white shrimp contain 1.06 Kcal/g compared to 0.98 Kcal/g of energy in other invertebrates. We observed the impact of little blue herons on shrimp availability based on the amount of shrimp consumed by these herons during July and August in 2020. Shrimp consumed by little blue herons during these months ranged in lengths of 115−121 mm. Little blue herons may choose to consume shrimp earlier in the production cycle because of their inability to consume shrimp as size increases. We did not collect little blue herons during September or October. Therefore, we cannot conclude if little blue herons can consume shrimp > 121 mm. Smith (1997) found little blue herons primarily consume grass shrimp and other invertebrates while determining shrimp occurred in the diets of 80.7% little blue herons. Based on the breeding chronology observed by Rodgers (1987) and the nestling period described by Rodgers and Smith (2020) regarding little blue herons in west central Florida, we would expect heron adults to provide chicks with shrimp prey during June-August. The feeding of diet items to little blue heron nestlings that adults are also consuming is supported by Kushlan (1978) who stated most wading bird adults feed young the same prey items they're consuming. Life history strategies such as those exhibited by little blue herons pose further risks to producers when timing coincides with shrimp production seasons.

During our study, we found wading birds were the primary predators depredating shrimp ponds. These aquaculture ponds provide avian predators with an advantageous opportunity to consume a readily available food source (Dorr and Taylor 2003). Shrimp ponds provide avian predators with spans of foraging habitat along pond perimeters. Pond edges allow wading species to patrol these shallow depths suitable to wading bird stalking behaviors and depredation of shrimp that may venture into these regions. Great egrets were our most abundant species and readily consumed shrimp resulting in highest amount of shrimp depredation in both states (Tables 3.5, 3.6, 3.7, and 3.8). Great blue and little blue herons were less abundant, but both were also found consuming shrimp. In this study these species did not cause substantial depredation loss but if larger numbers are observed, shrimp loss, particularly by great egrets and great blue herons, could be substantial.

Farmed shrimp primarily amass at lower depths of aquaculture ponds. Because of this, shrimp are relatively protected from wading birds present at shallow depths. Once shrimp reach mature age, they are harvested late in the production season. Prior to shrimp harvests, farmers decrease water depths across ponds. While water levels recede, shrimp residing at lower depths become available to avian predation. We discovered avian populations and the amount of shrimp consumed by predators increased during these harvest months. Similar studies have found bird populations peaked on crayfish aquaculture in Louisiana during pond drawdowns (Fleury and Sherry 1995). Our seasonal abundance trends reveal great egret and great blue heron populations tend to increase at farms while pond levels decrease. Although little blue heron abundance did not correspond as closely to water depth as other bird species, they were still found consuming shrimp earlier in the production season. Willard (1977) stated little blue herons commonly forage at shallow water depths of 5−15 cm. However, little blue herons may not consume shrimp during drawdown periods because of their inability to consume harvestable shrimp (e.g., ~20 g, 140 mm). Research shows predators in the Florida everglades, such as great egrets and great blue herons, actively select for habitats with water availability and water depths of ≤50 cm (Bancroft et al. 2002). Beerens et al. (2015) stated great egrets actively select shallow over deep waterbody habitat while also selecting shallow pools due to high prey concentration. Great egrets have a broad depth tolerance but may opportunistically feed in shallow waters that provide increased prey densities. While great egrets face intraspecific competition when foraging in flocks, these egrets will cluster in groups when profitable prey resources are plentiful (Gawlik 2002). Gawlik (2002) also found great blue herons did not select water bodies based on prey density or water depth but were still viewed feeding among other wading birds at these sites. Similarly, Dowd and Flake (1985) claimed great blue herons exhibited opportunistic foraging behavior by selecting a variety of pools and streams as foraging sites. The readily available food source on shrimp ponds combined with conditions suitable for foraging wading birds increases the chance of substantial shrimp loss due to predator consumption. Because wading birds favor lower pond levels, producers may prioritize harassment during periods of low water levels. This would allow producers to increase harassment efficiency when birds are abundant and conserve resources during periods of minimum impact.

Waterbirds like double-crested cormorants and pied-billed grebes exhibit diving behaviors which allow these predators to consume shrimp at multiple water levels. Though grebes were surveyed, only a small portion of these were found consuming shrimp. When present, pied-billed grebes were only viewed during the months of September and October. Bleich (1975) observed pied-billed grebes diving in water depths of 2–5 m while most dives occurred at 2–3 m. Shrimp pond depths of 1–1.5 m provide grebes with diving depths within their capable range. Eared grebes have been viewed consuming brine shrimp (Jehl 2017) while we observed pied-billed grebes consuming Pacific-white shrimp. We also discovered feathers in grebe gizzards among ingested prey items. This supports the findings of Jehl (2017) who stated multiple grebe species consume their feathers to increase digestion efficiency of rigid invertebrates, such as shrimp, that are difficult to digest. We were not able to model cormorant impacts on shrimp aquaculture because they occurred infrequently during our surveys. However, when present, a large proportion of cormorant diets consisted of shrimp. Double-crested cormorants often feed on shrimp, crayfish, and other crustaceans (Dorr et al. 2021). Given this, diving predators could be a potential issue on commercial shrimp farms if large flocks are present.

Relative Prey Importance

A variety of prey items were consumed across our sampled avian predators. In most cases, invertebrates were a common prey item and represented generalized feeding behaviors according to our findings (Figures 2.1 and 2.2; This Theses, Chapter 2). Great egret diets were the most diverse of our predators, primarily consuming invertebrates and fish. Our findings are consistent with Smith (1997) who found great egrets consuming invertebrates, fish, and crustaceans. The diets of great egrets we observed in Alabama, opportunistically favored shrimp in 2020 and fish in 2021 (Figure 2.1; This Theses, Chapter 2). The diets of great egrets in Florida were similar to egrets in Alabama with Florida egrets primarily consuming shrimp during 2020 while shrimp and fish were consumed as general diet items in 2021 (Figure 2.2; This Theses, Chapter 2). Great blue herons were observed opportunistically selecting shrimp as prey in Alabama and Florida during 2020 (Figure 2.1 and Figure 2.2; This Theses, Chapter 2). Martin et al. (1961) also identified great blue herons as opportunistic foragers, stating these herons consume a variety of organisms including invertebrates, fish, crustaceans, and amphibians. Little blue herons were observed only consuming invertebrates in Florida during 2020 while opportunistically selecting for shrimp (Figure 2.2; This Theses, Chapter 2). These results correlate with the findings of Smith (1997) who observed grass shrimp and invertebrates as favored prey items by little blue herons. Shrimp was the only prey item found among stomach contents of double-crested cormorants in Florida during 2020 and 2021 (Figure 2.2; This Theses, Chapter 2). Dorr et al. (2021) identified double-crested cormorants as opportunistic foragers who consume a range of aquatic prey items when available, including shrimp. We observed pied-billed grebes only consuming invertebrates while opportunistically selecting for the order hemiptera and shrimp in Florida during 2020 (Figure 2.2; This Theses, Chapter 2). Similarly, Muller and Storer (1999) recognize pied-billed grebes as opportunistic carnivores whose diet primarily consists of crustaceans, invertebrates, and fish. The diving ability of double-crested cormorants and pied-billed grebes give these species an advantageous behavior, allowing for foraging opportunities in deeper water often missed by other avian predators of shrimp ponds.

Avian Shrimp Consumption

Despite the variation in monthly shrimp consumption across years, we believe increased shrimp consumption is directly correlated with high avian predator abundance. Our research suggests that avian populations that use shrimp farms as a food source tend to increase later in production seasons, specifically during the months of September and October when shrimp attain their largest size. During these months, lowered pond levels for harvests and mature shrimp provide predators with opportunities to depredate shrimp. Based on our findings, we can see the impact created by the most abundant predators when present during September and October. Great egrets were found to be the most abundant predator during our study which raises concerns for months and years when great egret abundance is prominent later in production seasons. Great egrets were found consuming the most shrimp in Alabama with average annual losses of approximately 57,000 g ($565.50) during 2020 and in 2021 averaging 30 g ($0.30). In Florida great egrets consumed 5,350 g ($53.08) during 2020 and 130 g ($1.29) during 2021.

Our loss estimates are likely conservative for several reasons; our abundance estimates represent the minimum estimate of individual birds using the ponds during a given survey period, our estimates of bird abundance occurred while farmers were harassing birds from their farms and our collections may have potentially reduced bird abundance and avian counts Furthermore, we did not investigate the potential impacts of nocturnal depredation, so our estimates may be less than those combining diurnal and nocturnal consumption estimates. We estimated potentially larger and smaller consumption estimates based on 95% CI of BUD counts. Given the high estimates, losses estimated for great egrets in Alabama in 2020 could result in losses of approximately $2,000 annually.

Though minuscule in our findings, other avian species could potentially create larger financial burdens during years of greater abundance and increased presence. Great blue heron consumption only occurred in 2020 with annual losses of 440 g ($4.37) in Alabama and 910 g ($9.03) in Florida. Little blue herons only consumed shrimp in Florida during 2020 with an estimated annual loss of 280 g ($2.78), respectively. We did not model double-crested cormorant impacts because they occurred infrequently on the shrimp farms surveyed. When present, a large proportion of cormorant diets consisted of shrimp. Because of this, cormorants could be a potential issue on these farms if their numbers increase or if catfish acreage continues to shrink in the region. Pied-billed grebes were also present and found consuming shrimp in Florida, but with marginal abundance and miniscule shrimp consumption.

Because of these observed avian foraging tendencies, we suggest producers should focus harassment techniques during periods of increased bird presence, primarily later in the production season. Refraining from employing harassment strategies too early will reduce the chance for predators to acclimate themselves, particularly to non-lethal methods, and minimizes the potential financial burdens and allocation of time for harassment to the producer. Allocating resources for ‘high risk’ periods may potentially increase harassment success while providing the best opportunity to reduce shrimp loss to avian predators. Analysis into the factors influencing avian predator presence is available in other portions of our research. Applying these farm dynamics to avian harassment will possibly increase harassment efficiency on ponds deemed to be priority (e.g., ponds with lowered water levels). Optimum harassment strategies may differ among avian species. Therefore, we suggest focusing avian dispersal towards the species we investigated in this study who risk imposing the greatest amount of shrimp loss.

Producers apply for annual depredation permits which allow the removal of select avian predators during production seasons. Many of these predators were investigated during our study. We believe our research supports the need to allow producers to continue nonlethal and potentially lethal avian harassment to help minimize the potential risk of these predators, particularly when abundant. Our findings also provide permitting agencies with proof of shrimp consumption by specific avian predators in which the evidence of shrimp depredation was previously unknown. We suggest producers implement non-lethal harassment techniques such as vehicles or propane cannons with the reinforcement of lethal measures to effectively harassment birds on ponds. These methods are supported by Kumar et al. (2021) who suggests non-lethal harassment is less effective and losses can be substantial unless used in combination with lethal control methods.

A limitation often experienced by aquaculture producers is the difficultly of efficiently harassing birds due to the availability of few staff members working on the farm. Shrimp production and harvest requires several personnel to ensure a successful season. These individuals are also the workforce responsible for continued harassment across seasons. We suggest our discoveries should be used to support the need for continued issuance of depredation permits to help minimize the pressure of avian predators on shrimp producers in Alabama and Florida. Increasing harassment efforts during periods of intense avian activity, while focusing energy on avian removal is the best solution to mitigate shrimp loss due to avian predators.

REFERENCES

Afton, A. D., R. H. Hier, and S. L. Paulus. 1991. Lesser scaup diets during migration and winter in the Mississippi flyway. Canadian Journal of Zoology 69:328–333.

Amundsen, P. A., H. M. Gabler, and F. J. Staldvik. 1996. A new approach to graphical analysis of feeding strategy from stomach contents data – modification of the Costello (1990) method. Fish Biology 48:607–614.

Arbib, R. S. 1972. On the art of estimating numbers. American Birds 26:706–712.

Bancroft, G. T., D. E. Gawlik, and K. Rutchey. 2002. Distribution of wading birds relative to vegetation and water depths in the northern everglades of Florida, USA. Waterbirds: The International Journal of Waterbirds Biology 25:265–277.

Beerens, J. M., E. G. Noonburg, and D. E. Gawlik. 2015. Linking dynamic habitat selection with wading bird foraging distributions across resource gradients. PLoS ONE 10: e0128182.

Bleich, V. C. 1975. Diving times and distances of pied-billed grebe. The Wilson Bulletin 87:278–280.

Burr, P. C., J. L. Avery, G. M. Street, B. K. Strickland, and B. S. Dorr. 2020. Fine scale characteristics of catfish aquaculture ponds influencing piscivorous avian species foraging use in the Mississippi Delta. PLoS ONE 15(2): e0229402.

Burr, P. C., B. S. Dorr, J. L. Avery, G. M. Street, and B. K. Strickland. 2023. Long term changes in aquaculture influence migration, regional abundance, and distribution of an avian species. PLoS ONE 18: e0284265.

Christie, T. W., J. B. Davis, and B. S. Dorr. 2019. Predation risk of Double-crested Cormorants (*Phalacrocorax auritus*) on commercial catfish production in the Mississippi Delta. Master of Science Thesis. Mississippi State University. Starkville, Mississippi.

Christie, T. W., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2021. Food habits of wintering double-crested cormorants in the Mississippi Delta. Food Webs 26: e00185.

Clements, S. A., B. S. Dorr, J. B. Davis, L. A. Roy, C. R. Engle, K. C. Hanson-Dorr, and A. M. Kelly. 2020. Diets of scaup occupying baitfish and sportfish farms in eastern Arkansas. Food Webs 23: e00141.

Costello, M. J. 1990. Predator feeding strategy and prey importance: a new graphical analysis. Fish Biology 36:261–263.

Cochran, W. G. 1953. Sampling techniques. New York: John Wiley & Sons.

Doornbos, G. 1984. Piscivorous birds on the saline Lake Grevelingen, the Netherlands: abundance, prey selection and annual food consumption. Netherlands Journal of Sea Research 18:457–479.

Dorr, B. S., L.W. Burger, S. C. Barras, and K. Godwin. 2012. Economic impact of Double-crested Cormorant (*Phalacrocorax auritus*) depredation on Channel Catfish (*Ictalurus punctatus*) aquaculture in Mississippi, USA. Journal of the World Aquaculture Society 43:502–513.

Dorr, B. S., J. J. Hatch, and D. V. Weseloh. 2021. Double-crested cormorant (*Nannopterum auritum*). Bird of the World. Cornell Lab of Ornithology, Ithaca, New York, New York, USA. <https://doi.org/10.2173/bow.doccor.01.1>

Dorr, B. S., and J. D. Taylor II. 2003. Wading bird management and research on North American aquaculture facilities. Pages 52–61 *in* Proceedings of the 2003 Wildlife Damage Management Conference. The Wildlife Damage Management Working Group of The Wildlife Society, 6 April–9 April 2003, Fort Collins, Colorado, USA.

Dowd, E. M., and L. D. Flake. 1985. Foraging habitats and movements of nesting great blue herons in a prairie river ecosystem. Journal of Field Ornithology 56:379–387.

Duffy, D. C., and S. Jackson. 1986. Diet studies of seabirds: a review of methods. Colonial Waterbirds 9:1–17.

Fisheries of the United States. 2019. NOAA current fishery statistics. U.S. Department of Commerce. <https://www.fisheries.noaa.gov/resource/document/fisheries-united-states-2019>.

Fleury, B. E., and T. W. Sherry. 1995. Long-term population trends of colonial wading birds in the southern United States: the impact of crayfish aquaculture on Louisiana populations. The Auk 112:613–632.

Foth, J. R., J. N. Straub, R. M. Kaminski, J. B. Davis, and T. D. Leininger. 2014. Aquatic invertebrate abundance and biomass in Arkansas, Mississippi, and Missouri bottomland hardwood forests during winter. Journal of Fish and Wildlife Management 5:243–251.

Gawlik, D. E. 2002. The effects of prey availability on the numerical response of wading birds. Ecological Monographs 72:329–346.

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 18:168–175.

Gotelli, N. J., and A. M. Ellison. 2004. A primer of ecological statistics, 2nd edition. Sinauer Associates, Incorporated, Sunderland, Massachusetts.

Hoppe, R. T., L. M. Smith, and D. B. Wester. 1986. Foods of wintering diving ducks in South Carolina. Journal of Field Ornithology 57:126–134.

Jehl, J. R. 2017. Feather-eating in grebes: a 500-year conundrum. The Wilson Journal of Ornithology 129:446–458.

Kumar, G., S. Hegde, D. J. Wise, C. C. Mischke, B. S. Dorr. 2021. Economic losses of catfish to avian predation: a case report. North American Journal of Aquaculture 83:127–137.

Kushlan, J. A. 1978. Feeding ecology of wading birds. Wading Birds, National Audubon Society, New York, New York, USA 249–296.

Martin, A. C., H. S. Zim, and A. L. Nelson. 1961. American wildlife and plants: a guide to wildlife food habits. Dover Publications, Incorporated, New York, New York. 500pp

Moreau, A., C. Dupuy, P. Bocher, S. Farau. 2021. Morphological, caloric and nutritive characteristics of 656 freshwater invertebrate taxa. Biodiversity Data Journal 9:e70214.

Muller, M. J. and R. W. Storer. 1999. Pied-billed grebe (*Podilmbus podiceps*). The Birds of North America, Incorporated, Philadelphia. <https://guides.nynhp.org/pied-billed-grebe/>

Nagy, K. A., I. A. Girard, and T. K. Brown. 1999, Energetics of free-ranging mammal, reptiles, and birds. Annual Review of Nutrition 19:247–277.

Organization for Economic Co-operation and Development [OECD]. 2021. Fisheries and aquaculture in the United States, January 2021. <https://www.oecd.org/agriculture/topics/fisheries-and-aquaculture/documents/report_cn_fish_usa.pdf>.

Reinhold, D. S., and C. A. Sloan. 1997. Strategies to reduce double-crested cormorant depredation at aquaculture facilities in Mississippi. Symposium on Double-crested Cormorant: Population Status and Management Issues in the Midwest. 10. USDA National Wildlife Research Center Symposia.

Robinson, W. D., M. Bowlin, I. Bisson, J. Shamoun-Barnes, K. Thorup, R. H. Diehl, T. H. Kunz, S. Mabey, and D. W. Winkler. 2010. Integrating concepts and technologies to advance the study of bird migration. Frontiers in Ecology and the Environment 8:354–361.

Rodgers, Jr., J. A. 1987. Breeding chronology and reproductive success of cattle egrets and little blue herons on the west coast of Florida, USA. Colonial Waterbirds 10:38–44.

Rodgers, Jr., J. A., and H. T. Smith. 2020. Little blue heron (*Egretta caerulea*). Birds of the World. Cornell Lab of Ornithology, Ithaca, New York, New York, USA. <https://doi.org/10.2173/bow.libher.01>

Roshnath, R. 2014. Fishing for living-shrimp farmer's perception of heronry birds in Kannur District Kerala- India. International Journal of Research 1:188–199.

Roy, L. A., D. Teichert-Coddington, S. Laramore, S. Dahl, J. James, G. N. Whitis, B. H. Beck, and C. A. Shoemaker. 2018. Commercial evaluation of a probiotic mixture to enhance Pacific white shrimp production in inland ponds of Alabama and Florida. World Aquaculture 49:42–49.

Sherfy, M. H. 1999. Nutritinal value and management of waterfowl and shorebird foods in the Atlantic coastal moist-soil impoundments. Doctor of Philosophy Dissertation. Virginia Polytechnic Institute and State University, Blacksburg, USA.

Smith, J. P. 1997. Nesting season food habits of 4 species of herons and egrets at Lake Okeechobee, Florida. Colonial Waterbirds 20:198–220.

Swanson, G. A., and J. C. Bartonek. 1970. Bias associated with food analysis in gizzards of Blue-winged Teal. The Journal of Wildlife Management 34:739–746.

Swanson, G. A., G. L. Krapu, J. C. Bartonek, J. R. Serie, and D. H. Jognson. 1974. Advantages in mathematically weighting waterfowl food habits data. Journal of Wildlife Management 38:302–307.

U.S. Department of Agriculture. 2017. Agricultural Research Service, FoodData Central. <https://fdc.nal.usda.gov/fdc-app.html#/food-details/2442026/nutrients>

Willard, D. E. 1977. The feeding ecology and behavior of five species of herons in southeastern New Jersey. The Condor 79:462–470.

Wooten, D. E., and S. J. Werner. 2004. Food habits of Lesser Scaup *Aythya affinis* occupying baitfish aquaculture facilities in Arkansas. Journal of the World Aquaculture Society 35:70–77.

Table 3.1 Adjusted R^2 and partial F-test statistics of polynomial models for avian predators consuming shrimp at farms in Greene County, Alabama, USA, 2020–2021 (orders 1–9).

Polynomial Order	2020			2021		
	Adjusted R^2	F^a	P^b	Adjusted R^2	F^a	P^b
Great Egret						
1	0.57			0.05		
2	0.71	814.42	0.03*	-0.05	0.06	0.84
3	0.68	51.23	0.09	-0.19	0.03	0.88
4	0.66	88.12	0.07	-0.37	0.05	0.86
5	0.77	492.73	0.03*	-0.59	0.12	0.79
6	0.90	393.45	0.03*	-0.97	0.04	0.87
7	0.95	129.93	0.06	0.10	2.37	0.37
8	0.97	41.98	0.10	-0.16	0.18	0.75
9	0.12	28.88	0.12	-1.18	0.06	0.84

[a]*F* statistic from partial F-test comparing the respective polynomial model to the previous order.
[b]*P* indicates the probability that the sum of squares of the residuals differs from the previous lower order.
*Represents significant values

Table 3.1 Continued

Great Blue Heron			
1	0.57		
2	0.71	11.08	0.19
3	0.81	6.83	0.23
4	0.89	4.86	0.27
5	0.87	0.07	0.83
6	0.85	0.33	0.67
7	0.81	0.06	0.84
8	0.87	2.21	0.38
9	0.86	0.87	0.52

[a]*F* statistic from partial F-test comparing the respective polynomial model to the previous order.
[b]*P* indicates the probability that the sum of squares of the residuals differs from the previous lower order.
[*]Represents significant values

Table 3.2 Adjusted R^2 and partial F-test statistics of polynomial models for avian predators consuming shrimp at farms in Gulf County, Florida, USA, 2020–2021 (orders 1–9).

Polynomial Order	2020			2021		
	Adjusted R^2	F^a	P^b	Adjusted R^2	F^a	P^b
Great Egret						
1	0.27			0.10		
2	0.19	0.09	0.81	0.10	4.90	0.27
3	0.12	1.35	0.45	0.48	20.72	0.14
4	0.0	0.67	0.56	0.85	15.67	0.16
5	-0.17	0.69	0.56	0.90	2.40	0.37
6	-0.20	4.34	0.29	0.90	0.63	0.57
7	0.61	14.85	0.16	0.92	0.88	0.52
8	0.71	2.42	0.36	0.89	0.07	0.84
9	0.76	1.36	0.45	0.83	0.24	0.71

[a]*F* statistic from partial F-test comparing the respective polynomial model to the previous order.
[b]*P* indicates the probability that the sum of squares of the residuals differs from the previous lower order.
[*]Represents significant values

Table 3.2 Continued.

Great Blue Heron			
1	0.04		
2	0.08	1.62	0.42
3	-0.05	0.0	0.97
4	-0.22	0.02	0.91
5	-0.12	2.20	0.38
6	-0.39	0.01	0.93
7	0.56	5.35	0.26
8	0.44	0.25	0.70
9	0.20	0.40	0.64

[a]*F* statistic from partial F-test comparing the respective polynomial model to the previous order.
[b]*P* indicates the probability that the sum of squares of the residuals differs from the previous lower order.
[*]Represents significant values

Table 3.2 Continued.

Little Blue Heron			
1	-0.10		
2	-0.24	0.0	0.96
3	-0.17	1.23	0.47
4	-0.30	0.43	0.63
5	-0.55	0.0	0.99
6	-0.39	1.63	0.42
7	-0.80	0.14	0.77
8	-1.45	0.38	0.65
9	-0.32	2.70	0.35

[a]*F* statistic from partial F-test comparing the respective polynomial model to the previous order.
[b]*P* indicates the probability that the sum of squares of the residuals differs from the previous lower order.
[*]Represents significant values

Table 3.3 Field Metabolic Rates of predator species found consuming shrimp from shrimp ponds in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

Species	Field Metabolic Rate (kJ/day)[a]	Source	Average Body Mass (g)[b]
Great Egret	1,479.5	Nagy et al. 1999	949.64
Great Blue Heron	3,054.87	Nagy et al. 1999	2,242
Little Blue Heron	656.73	Nagy et al. 1999	362.77

[a]Field Metabolic Rates were determined using allometric and biological scaling equations.
[b]Average mass was determined from avian predators collected across both seasons.

Table 3.4 True metabolizable energy (TME, kcal/g) values of prey types found in avian species collected at farms in Greene County, Alabama and Gulf County, Florida, USA, 2020–2021.

Prey Type	TME	Source
Fish[b]		
Gambusia spp.	6.24	Pizazz and Peyre 2010
Lepomis spp.	4.77	Eggleton and Schramm 2011
	5.51[a]	
Shrimp[b]		
Litopenaeus spp.	1.06[a]	USDA 2017
Invertebrates[b]		
Cambaridae	1.73	Clements et al. 2020
Hemiptera	0.48	Sherfy 1999
Odonata	0.63	Moreau et al. 2021
Coleoptera	1.49	Moreau et al. 2021
Stratiomyidae	0.27	Sherfy 1999
Orthoptera	1.01	Moreau et al. 2021
Araneae	1.27	Moreau et al. 2021
	0.98[a]	

[a]Represents mean values for each prey type. Numbers were averaged to determine one value for each prey category. (i.e. Fish=5.51; Shrimp=1.06; Invertebrates=0.98).
[b]Represents >90% of total prey items found in collected avian predators both years.

Table 3.5 Estimated bird use days (BUDs), proportion of birds consuming shrimp (pBCS), shrimp consumption (SC), and total shrimp loss per month (SL) on commercial shrimp ponds in Greene County, Alabama, USA, May-October 2020.

Great Egret					SC	SC_{Low}	SC_{High}	tSL	tSL_{Low}	tSL_{High}
Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(10^3 g)	(10^3 g)	(10^3 g)
May	3	0	1,149	NA	NA	NA	NA	NA	NA	NA
June	259	0	2,100	0 (0)	0	0	0	0	0	0
July	859	0	2,610	0 (0)	0	0	0	0	0	0
Aug.	351	0	2,169	0 (0)	0	0	0	0	0	0
Sept.	3,267	1,327	5,343	0.25 (0.25)	5.66	0	55.66	4.62	<0.01	74.35
Oct.	3,536	2,063	5,010	0.75 (0.131)	19.75	8.05	31.45	52.38	12.46	118.17
Total	8,275	3,390	18,381					57	12.46	192.52

Table 3.5 Continued

Great Blue Heron					SC	SC_{Low}	SC_{High}	tSL	tSL_{Low}	tSL_{High}
Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(10^3 g)	(10^3 g)	(10^3 g)
May	11	0	77	NA	NA	NA	NA	NA	NA	NA
June	3	0	70	NA	NA	NA	NA	NA	NA	NA
July	19	0	85	NA	NA	NA	NA	NA	NA	NA
Aug.	73	15	137	NA	NA	NA	NA	NA	NA	NA
Sept.	171	106	237	NA	NA	NA	NA	NA	NA	NA
Oct.	171	120	230	0.333 (0.333)	7.76	0	55.33	0.44	<0.01	4.24
Total	448	241	836					0.44	<0.01	4.24

Table 3.6 Estimated bird use days (BUDs), proportion of birds consuming shrimp (pBCS), shrimp consumption (SC), and total shrimp loss per month (SL) on commercial shrimp ponds in Greene County, Alabama, USA, May-October 2021.

Great Egret					SC	SC_{Low}	SC_{High}	tSL	tSL_{Low}	tSL_{High}
Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	(g bird^{-1} day^{-1})	(g bird^{-1} day^{-1})	(g bird^{-1} day^{-1})	(10^3 g)	(10^3 g)	(10^3 g)
May	61	0	191	NA	NA	NA	NA	NA	NA	NA
June	90	0	480	0 (0)	0	0	0	0	0	0
July	173	0	508	0 (0)	0	0	0	0	0	0
Aug.	70	0	448	0 (0)	0	0	0	0	0	0
Sept.	235	7	577	0.125 (0.125	1.00	0	12.93	0.03	<0.01	0.07
Oct.	10	0	184	0 (0)	0	0	0	0	0	0
Total	639	7	2,388					0.03	<0.01	0.07

Table 3.7 Estimated bird use days (BUDs), proportion of birds consuming shrimp (pBCS), shrimp consumption (SC), and total shrimp loss per month (SL) on commercial shrimp ponds in Gulf County, Florida, USA, May-October 2020.

Great Egret					SC	SC_{Low}	SC_{High}	tSL	tSL_{Low}	tSL_{High}
Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(10^3 g)	(10^3 g)	(10^3 g)
May	21	0	76	NA	NA	NA	NA	NA	NA	NA
June	53	0	282	NA	NA	NA	NA	NA	NA	NA
July	101	0	294	NA	NA	NA	NA	NA	NA	NA
Aug.	90	5	284	NA	NA	NA	NA	NA	NA	NA
Sept.	462	168	756	1.0 (0)	10.12	0	51.97	4.68	<0.01	39.29
Oct.	45	3	196	1.0 (0)	14.83	13.01	16.65	0.67	0.04	3.26
Total	772	176	1,888					5.35	0.04	42.55

Table 3.7 Continued.

Great Blue Heron Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	SC (g bird^{-1} day^{-1})	SC_{Low} (g bird^{-1} day^{-1})	SC_{High} (g bird^{-1} day^{-1})	tSL (10^3 g)	tSL_{Low} (10^3 g)	tSL_{High} (10^3 g)
May	12	0	44	NA	NA	NA	NA	NA	NA	NA
June	22	0	147	NA	NA	NA	NA	NA	NA	NA
July	134	32	248	NA	NA	NA	NA	NA	NA	NA
Aug.	52	1	167	NA	NA	NA	NA	NA	NA	NA
Sept.	177	16	351	0.50 (0.50)	10.26	0	60.26	0.91	<0.01	10.58
Oct.	20	0	114	NA	NA	NA	NA	NA	NA	NA
Total	417	49	1,071					0.91	<0.01	10.58

Table 3.7 Continued.

Little Blue Heron Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	SC (g $bird^{-1}$ day^{-1})	SC_{Low} (g $bird^{-1}$ day^{-1})	SC_{High} (g $bird^{-1}$ day^{-1})	tSL (10^3 g)	tSL_{Low} (10^3 g)	tSL_{High} (10^3 g)
May	90	0	877	NA	NA	NA	NA	NA	NA	NA
June	156	0	2,286	NA	NA	NA	NA	NA	NA	NA
July	160	0	1,546	0.50 (0.50)	1.05	0	25.46	0.08	<0.01	19.68
Aug.	111	0	1,477	0.33 (0.33)	5.39	0	33.50	0.20	<0.01	16.33
Sept.	9	0	2,159	NA	NA	NA	NA	NA	NA	NA
Oct.	32	0	1,827	NA	NA	NA	NA	NA	NA	NA
Total	558	0	10,172					0.28	<0.01	36.01

Table 3.8 Estimated bird use days (BUDs), proportion of birds consuming shrimp (pBCS), shrimp consumption (SC), and total shrimp loss per month (SL) on commercial shrimp ponds in Gulf County, Florida, USA, May-October 2021.

Great Egret					SC	SC_{Low}	SC_{High}	tSL	tSL_{Low}	tSL_{High}
Month	BUDs	$BUDs_{Low}$	$BUDs_{High}$	pBCS(SE)	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(g $bird^{-1}$ day^{-1})	(10^3 g)	(10^3 g)	(10^3 g)
May	0	0	39	NA	NA	NA	NA	NA	NA	NA
June	96	0	273	NA	NA	NA	NA	NA	NA	NA
July	111	0	282	0.50 (0.50)	2.23	0	25.10	0.12	<0.01	3.54
Aug.	12	0	167	0.33 (0.33)	1.65	0	25.85	0.01	<0.01	1.42
Sept.	74	5	238	0 (0)	NA	NA	NA	NA	NA	NA
Oct.	188	72	304	0 (0)	NA	NA	NA	NA	NA	NA
Total	481	77	1,303					0.13	<0.01	4.96

Figure 3.1 Peak daily counts of Great Egrets estimated from AM, Noon, and PM ground surveys on commercial shrimp ponds at the Greene County, Alabama, USA, study site, (a) 2020 and (b) 2021 and their respective polynomial model (solid line) with 95% confidence intervals (dotted line) used to calculate low and high estimates of BUDs.

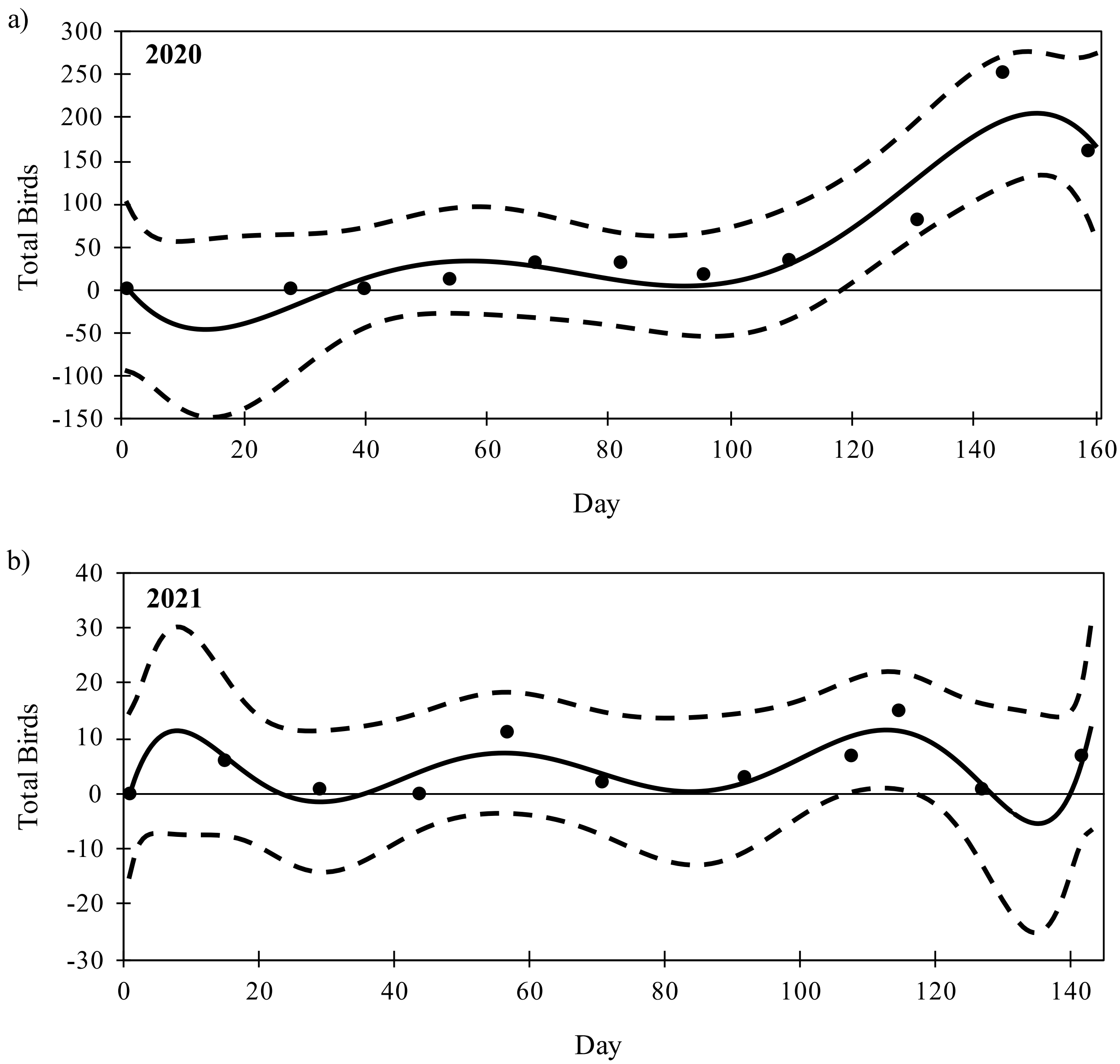


Figure 3.2 Peak daily counts of Great Blue Herons estimated from AM, Noon, and PM ground surveys on commercial shrimp ponds at the Greene County, Alabama, USA, study site, 2020 and the respective polynomial model with 95% confidence intervals used to calculate low and high estimates of BUDs.

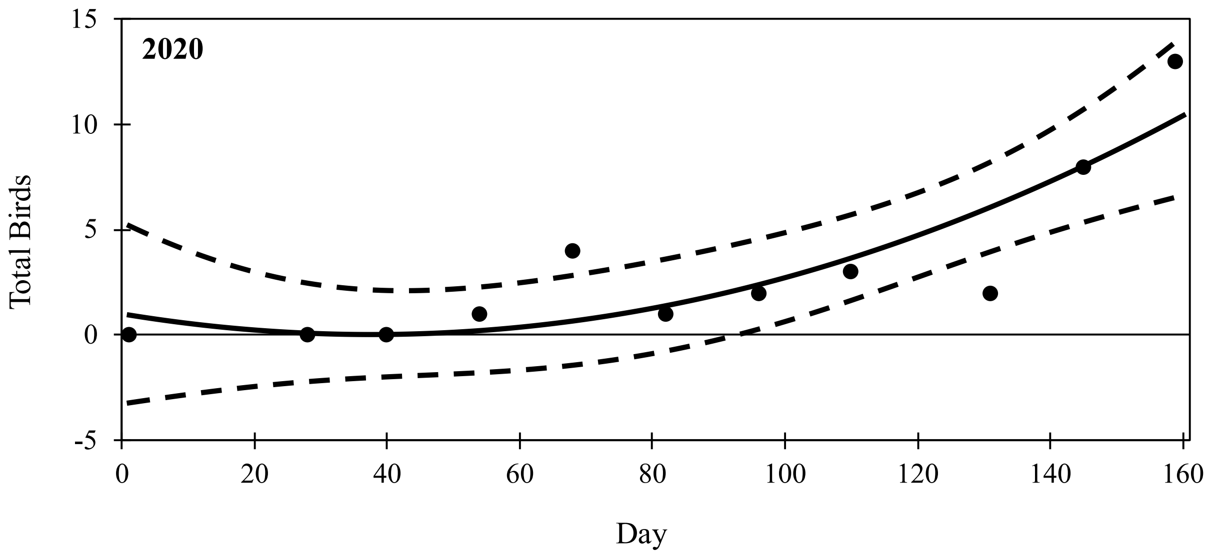


Figure 3.3 Peak daily counts of Great Egrets estimated from AM, Noon, and PM ground surveys on commercial shrimp ponds at the Gulf County, Florida, USA, study site, (a) 2020 and (b) 2021 and their respective polynomial model with 95% confidence intervals used to calculate low and high estimates of BUDs.

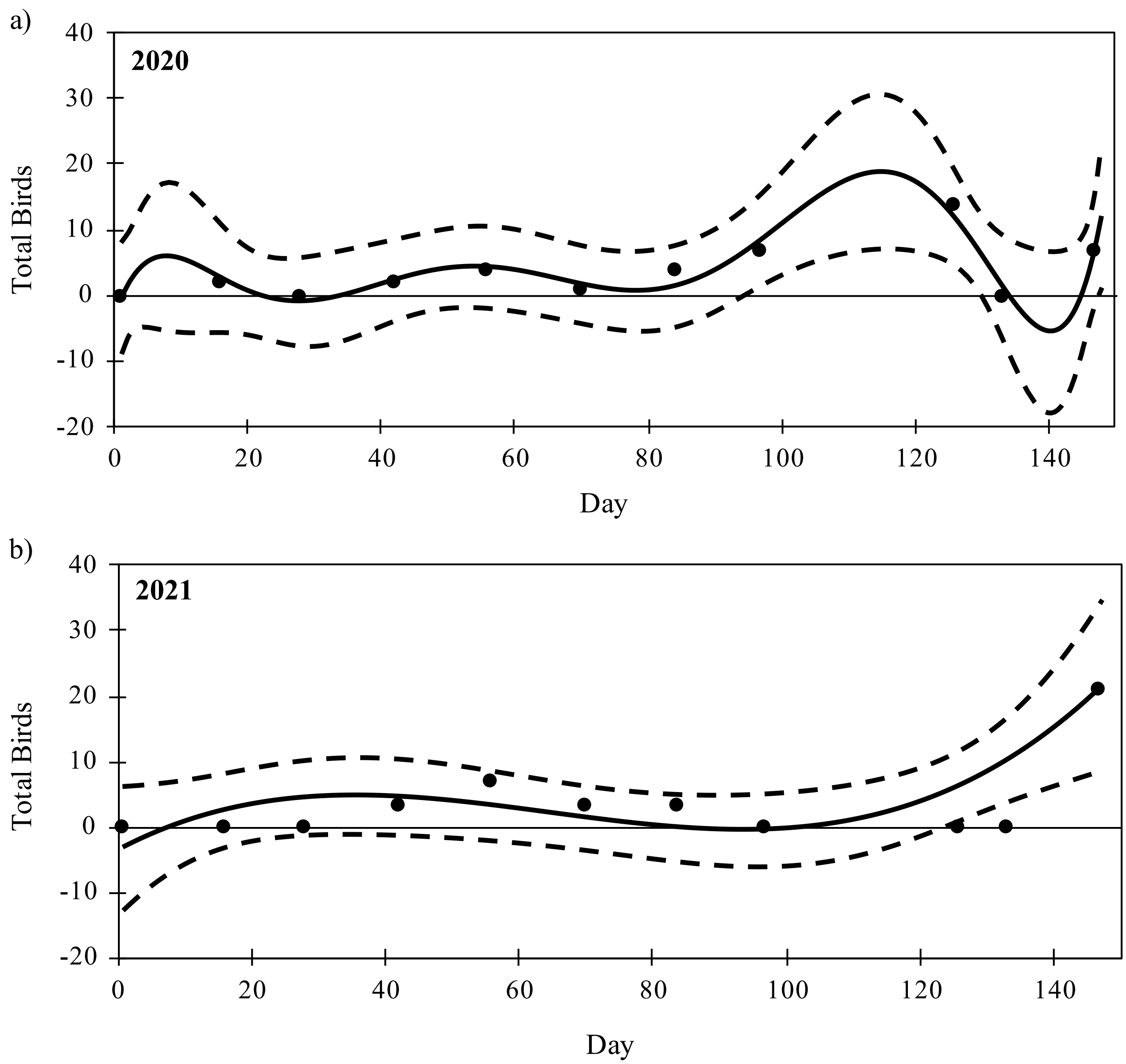


Figure 3.4 Peak daily counts of Great Blue Herons estimated from AM, Noon, and PM ground surveys on commercial shrimp ponds at the Gulf County, Florida, USA, study site, 2020 and the respective polynomial model with 95% confidence intervals used to calculate low and high estimates of BUDs.

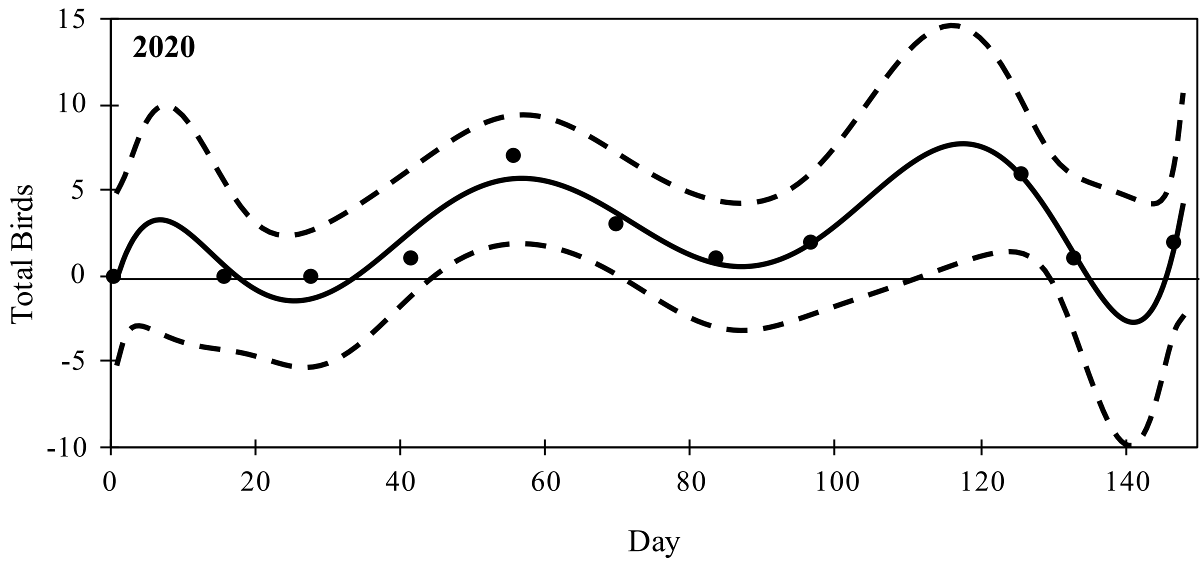


Figure 3.5 Peak daily counts of Little Blue Herons estimated from AM, Noon, and PM ground surveys on commercial shrimp ponds at the Gulf County, Florida, USA, study site, 2020 and the respective polynomial model with 95% confidence intervals used to calculate low and high estimates of BUDs.

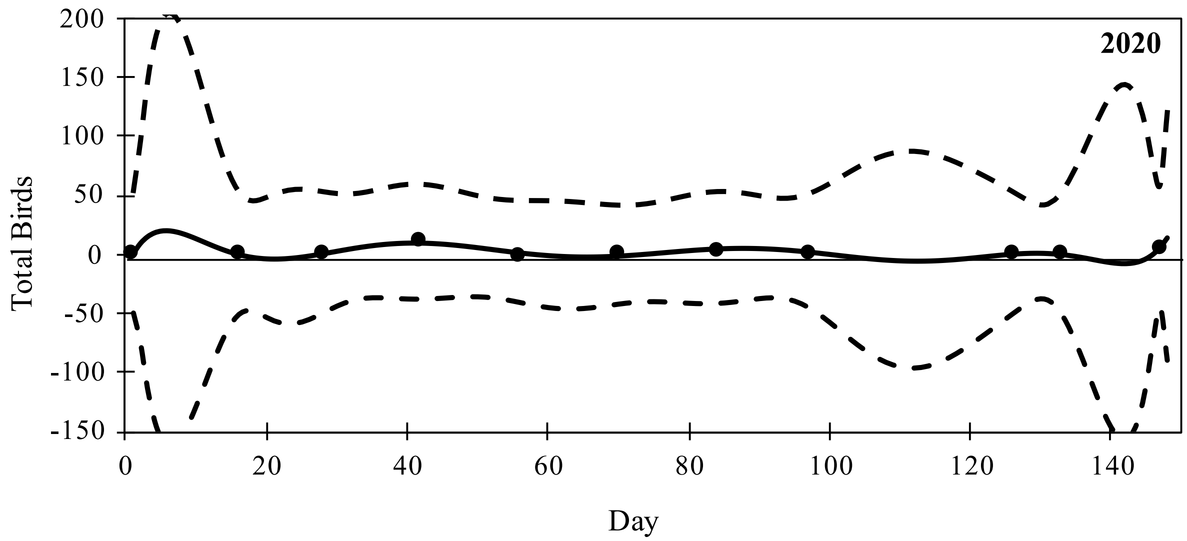


Figure 3.6 Potential low, average, and high financial losses due to Great Egret shrimp consumption throughout the production season for farms in Greene County, Alabama (a) 2020 and (b) 2021 and Gulf County, Florida, USA, (c) 2020 and (d) 2021.

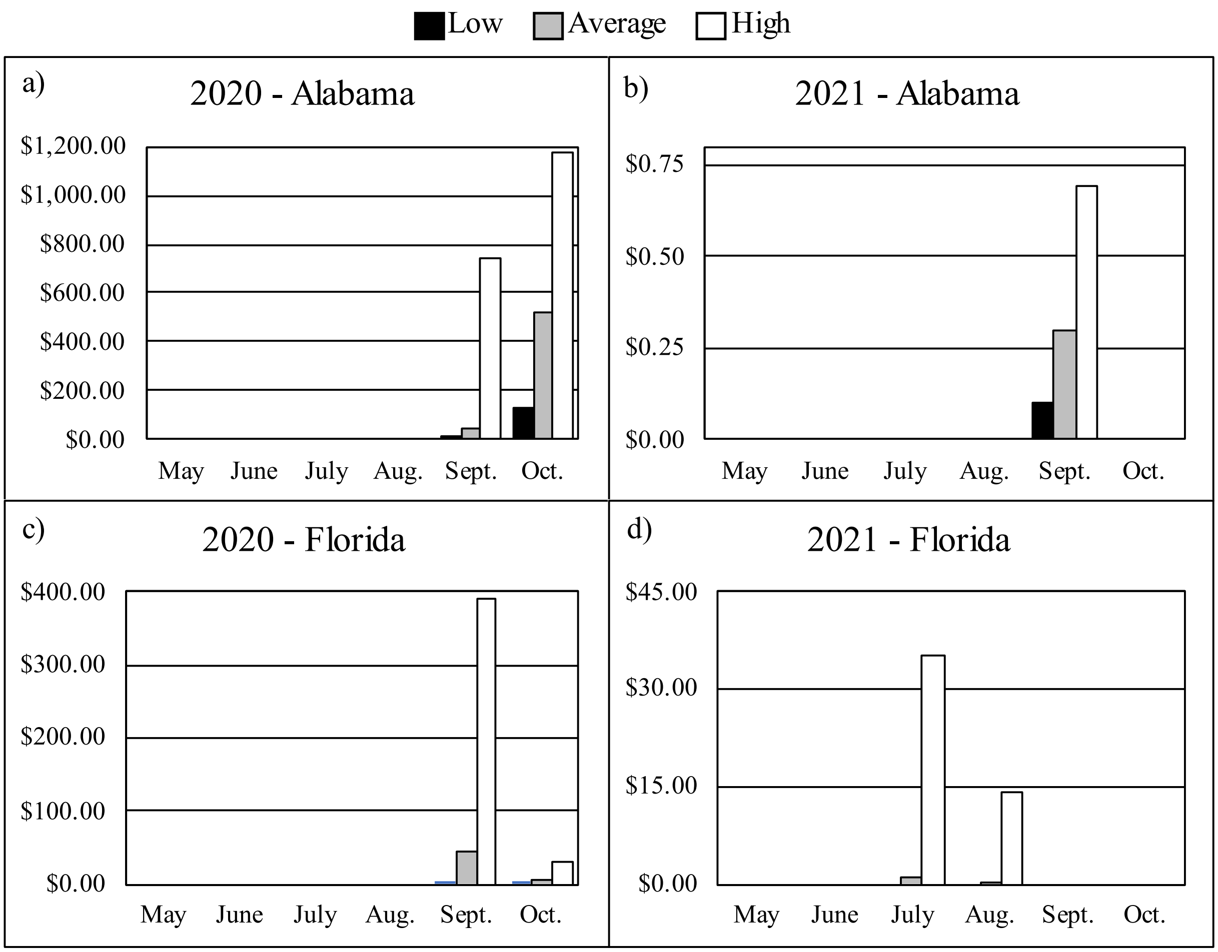


Figure 3.7 Potential low, average, and high financial losses due to Great Blue Heron shrimp consumption throughout the production season for farms in Greene County, Alabama, (a) 2020 and Gulf County, Florida, USA, (b) 2020.

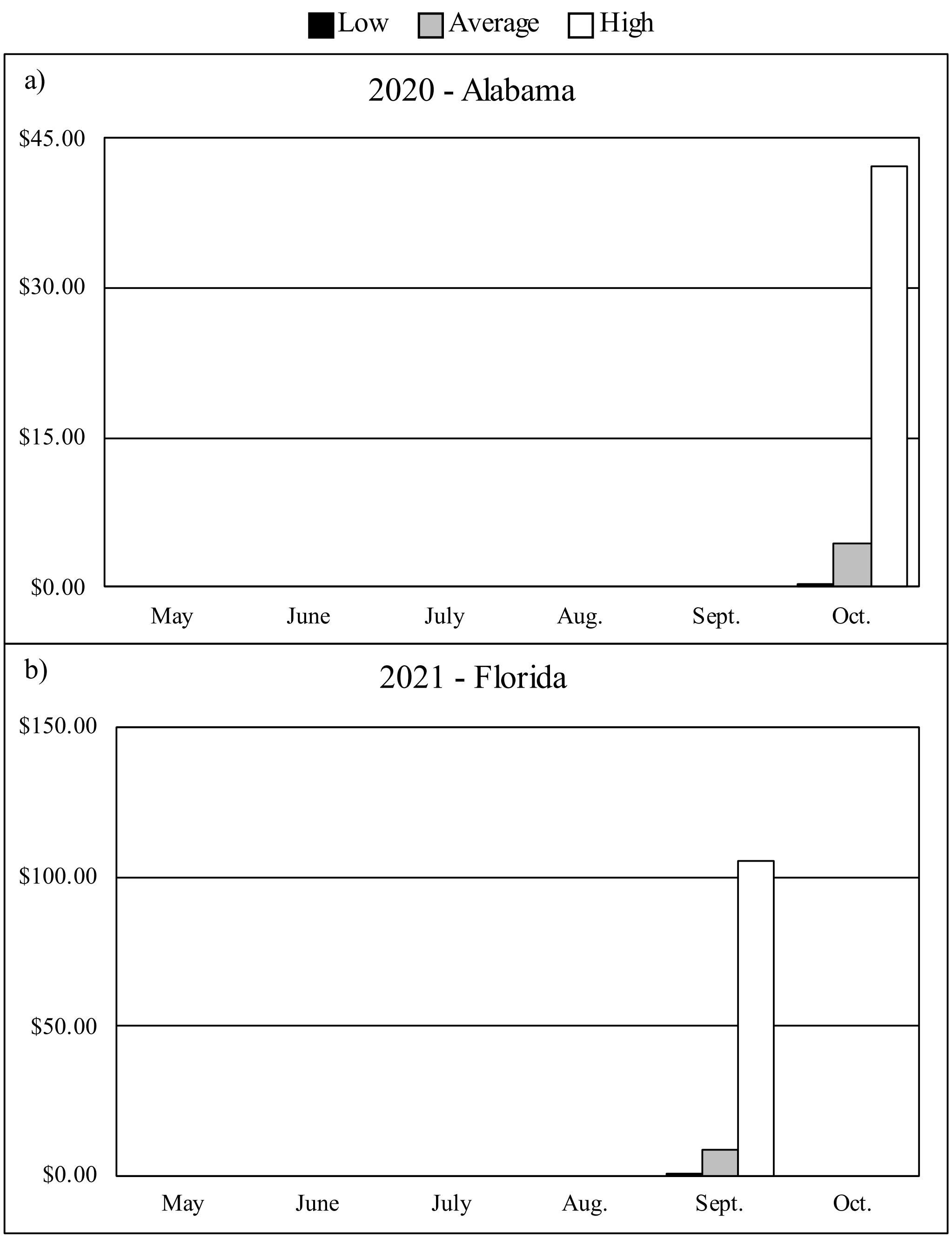


Figure 3.8 Potential low, average, and high financial losses due to Little Blue Heron shrimp consumption throughout the production season at the Gulf County, Florida, USA, study site, 2020 (Table 3.7).