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Patterns of distribution and dispersion of Silver Carp in an oxbow lake

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Oxbow lakes are highly productive waterbodies that host multiple life stages of many freshwater aquatic species. Oxbow lakes also provide habitat to Silver Carp (*Hypophthalmichthys molitrix*), which has enabled populations to grow and expand within the United States. Silver Carp are undesirable because they can compete for resources with native fishes. My goal was to identify patterns of distribution and dispersion of Silver Carp in Moon Lake, Mississippi, to assist and inform precise harvesting of fish. I implanted thirty-five adult Silver Carp with acoustic tags that I released into Moon Lake. I observed that Silver Carp were disproportionately found in locations where water depths ranged from 2.0-5.9 m during all seasons, despite the availability of locations with shallower and deeper water. Silver Carp did aggregate in the wintertime (December-February) in comparison to all other seasons. This information about depth distributions and seasonal aggregations can inform removal programs.

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CHAPTER I

PATTERNS OF DISTRIBUTION AND DISPERSION OF SILVER CARP

IN AN OXBOW LAKE

Introduction

Species introductions into foreign environs have occurred since the beginning of human civilization. As human societies change over time, so do our cultural values, scientific knowledge, and our perception of exotic species (Shackleton et al. 2019). There is a growing awareness that non-native species can harm biodiversity and industries, increasing the need for scientific research and management of non-native species (Doelle 2003). Researchers recognize that each invasive species carries disproportionate effects in ecological systems they annex (Clavero et al. 2009), yet researchers fail to prevent, manage, and extirpate invasive species that cause major disruptions.

Invasive carps collectively include four species, Silver Carp (*Hypophthalmichthys molitrix*), Bighead Carp (*H. nobilis*), Black Carp (*Mylopharyngodon piceus*), and Grass Carp (*Ctenopharyngodon idella*) (Cupp et al. 2021). Invasive carps are a nuisance to many aquatic systems in the United States because they cause physical, economic, and ecological damage to aquatic systems (Chick et al. 2020; Ivan et al. 2020). These species continue to expand and sustain populations across the United States including the Lower and Upper Mississippi, Missouri, and Ohio river basins. The species' distribution and population sizes increase their potential impact, which has created a need to limit their distributions and reduce their abundances.

Silver Carp have invaded new freshwater systems in more than 70 countries worldwide (Kolar et al. 2007; Lu et al. 2020). Their introduction into the United States occurred in the early 1970s, by escaping from an aquaculture facility in Arkansas (Freeze and Henderson 1982). Their plasticity in life history, prey item usage, habitat usage, their fast growth, and rapid dispersal have aided their establishment success outside of their native distribution in the Yangtze, Pearl, Red, and Amur rivers in Asia (Lu et al. 2020). Within their native range, Silver Carp use large rivers to spawn, but juvenile Silver Carp mature in floodplain lakes (Li et al. 1990; Lu et al. 2020). As the range of Silver Carp expands within river systems in the United States, they will likely extend their distribution into adjacent waterbodies like oxbow lakes.

A concern with Silver Carp in oxbow lakes is that they are effective filter feeders of phytoplankton and zooplankton (Cremer and Smitherman 1980; Pongruktham et al. 2010). Their ability to consume plankton could impact the natural abundance of plankton in lakes (Freedman et al. 2019). Plankton provide trophic support to native fish assemblages including Gizzard Shad (*Dorosoma cepedianum*), Bigmouth Buffalo (*Ictiobus cyprinellus*), and Paddlefish (*Polyodon spathula*) (Wang et al. 2018). Moreover, most native fish species depend on plankton through at least some stage of early life (Irons et al. 2007; Minder and Pyron 2018; Pendleton et al. 2017), thus changing plankton abundance could potentially alter fish assemblages in oxbow lakes (Sass et al. 2010). Another concern with Silver Carp is public safety; this species exhibits a behavior where it jumps out of the water when startled by boat traffic, which could potentially strike and injure boaters.

There is a strong desire to remove Silver Carp and protect waterbodies that offer valuable recreation, fisheries, or refuge for native species. Resources are being allocated to manage Silver Carp and mitigate their associated physical, ecological, and economic effects. For example, the Asian Carp Regional Coordinating Committee spent over US$ 66 million in 2021 to prevent invasive carps from entering the Great Lakes (ACRCC 2021). Silver Carp occur in large concentrations within the Lower Mississippi River Alluvial Valley, an extensive region reaching from the confluence of the Mississippi and Ohio River to the Gulf of Mexico. The region has widespread backwaters and oxbow lakes connected by natural and artificial channels to the region's rivers and streams (Pongruktham et al. 2010). Miranda et al. (2017) reported nearly 1,500 oxbow lakes are present in the Lower Mississippi River Alluvial Valley. Most oxbow lakes host diverse native aquatic species that conceivably could be impacted by Silver Carp. As Silver Carp continue to invade aquatic systems, these rich ecosystems need protection through management actions.

Silver Carp populations that are confined to oxbow lakes cannot reproduce due to insufficient water velocities to suspend eggs, meaning Silver Carp in oxbow lakes can only increase populations through immigration. Consequently, fishery managers use fish removals to reduce densities. Physical removal methods like commercial fishing use, gill nets, or techniques that use multiple gear types (Modified Unified Method; Chapman 2020) can be used to control established populations. The increased removal efficiency of Common Carp (*Cyprinus carpio*) during specific seasons and locations in lakes has been demonstrated by Penne and Pierce (2008) and Bajer et al. (2011). By collecting data about Silver Carp seasonal distributions and aggregation patterns within oxbow lakes, I could also increase removal efficiency.

The goal of my study was to research patterns of distribution and dispersion of Silver Carp in Moon Lake for the purpose of designing removal programs and informing precision harvesting by commercial fishers. My specific objectives were to use acoustic telemetry to characterize the seasonal distribution, habitat selection, and aggregation of adult Silver Carp. Cyprinids can have varying degrees of aggregation (Penne and Pierce 2008; Hundt et al. 2022), habitat selection (Calkins et al. 2012; Pretchel et al. 2018), and use of water depths (DeGrandchamp et al. 2008; Pretchel et al. 2018) across space and time, so I created three testable predictions: (1) Silver Carp will use lake areas with similar water depths in Moon Lake across seasons, (2) Silver Carp will use areas with water depths in proportion to their availability, and (3) Silver Carp will aggregate and disperse seasonally.

Methods

Study Area

Moon Lake is a 947-ha oxbow lake in northwestern Mississippi (Figure 1) located in an agricultural watershed (Hoover et al. 2015; Knight et al. 2015). Moon Lake hydrologic connections include Phillips Bayou, which serves as an inflow and Yazoo Pass, which provides inflow and outflow. Land use in the Moon Lake watershed is primarily cotton and soybean agricultural fields (Mississippi Department of Environmental Quality 2003; Knight et al. 2015). This hypereutrophic lake is shallow with a maximum depth of 10 m with the deepest areas on the eastern side of the lake. Oxbow lake depth, watershed land use, and riparian land use are highly correlated with lake primary productivity (Miranda et al. 2014) creating suitable trophic conditions for filter-feeding fishes like Silver Carp and Paddlefish. Moon Lake supports popular recreational fisheries for Largemouth Bass (*Micropterus salmoides*), Blue Catfish (*Ictalurus furcatus*), and crappies (*Pomoxis* spp.) as well as opportunities for recreational boating (e.g., water skiing, wakeboarding, tubing, kayaking). The concentrations of Silver Carp and their jumping behavior are a nuisance and create a potential safety risk to recreationists.

Acoustic telemetry to characterize Silver Carp distributions

I collected Silver Carp in Moon Lake and then tagged them with acoustic telemetry tags to evaluate potential seasonal habitat selection and aggregations using active acoustic telemetry methods. Thirty-five Silver Carp were captured, tagged, and released in Moon Lake between January 8, 2021, and May 31, 2021. I collected thirty Silver Carp using gill nets with the help of a commercial fisher. The commercial fisher used 305-m gill nets with a bar measure mesh size of 108 mm. I collected five Silver Carp with experimental gill nets measuring 90-m long with three 30-m panels of 76 mm, 101 mm, and 127 mm mesh size. All gill nets were fished perpendicular to the shoreline in water depths ranging from 3.5-5.5 m.

I screened captured Silver Carp for physical impairments, cuts, abscesses, or other openings that could reduce post-release survival after I implanted them with an acoustic tag (VEMCO, Halifax, NS, Canada V16 4X). I placed screened Silver Carp into a 95-L tote filled with lake water and fish were chemically immobilized with a Tricaine dosage ranging from 15-55 mg/L of water (FAU IACUC 2018). If Silver Carp maintained equilibrium within the tank after 5 minutes, I added Tricaine in 10 mg/L increments. I recorded total length of fish to the nearest millimeter and determined the sex of each fish. Male Silver Carp were identified by the presence of ridges along the first ray of the pectoral fin, whereas females lacked such ridges (Wolf et al. 2018). Once an anesthetized Silver Carp lost equilibrium, it was placed dorsal side down into a rayon gurney with a hose placed into its mouth to circulate water over its gills. I removed scales from a 3-5 cm section between the pelvic and anal fin, on the ventral side of the fish, and used a scalpel to make a 2-3 cm incision parallel to the lateral line (Coulter and Goforth

2013). An acoustic tag with a low acoustic sound setting (152 dB re 1 µPa @ 1 m) was sterilized in a 70% ethanol solution and immediately inserted into the body cavity. Tags, scissors, forceps, sutures, and scalpels were placed into a 70% ethanol solution before and after surgery to minimize infection risk. A size 0 or size 2 synthetic suture (Ethicon, Tokyo, Japan) was used to close the incision with a simple interrupted suture. Tagged Silver Carps were allowed to recover in a net pen in Moon Lake and monitored for restored equilibrium and impairments that may reduce survival. Silver Carp had their caudal fins clipped on the top and bottom of the fin so the commercial fisherman assisting with capture could identify and release tagged fish if captured. Three Silver Carp showed signs of excessive post-surgery distress and were euthanized. The acoustic tags were removed, sterilized, and reused.

Monitoring Movements

I began monitoring movements of tagged Silver Carp with gated acoustic receivers starting January 6, 2021 and active tracking starting May 5, 2021. All seasons were sampled once except spring which was sampled in 2021 and 2022. I placed a gated VEMCO receiver (VR2Tx) array positioned in a staggered configuration at the entrance/exit of Phillips Bayou and Yazoo Pass to monitor Silver Carp moving into and out of Moon Lake. Tagged Silver Carp locations, not depth, within Moon Lake were determined by active tracking along a single transect with an omnidirectional hydrophone (VEMCO VH 110) attached to a receiver (VEMCO VR 100) to evaluate (1) if Silver Carp are present in locations with similar water depths across seasons, (2) whether Silver Carp disproportionally select areas with certain water depths, and (3) if Silver Carp aggregate and disperse seasonally. The transect wrapped around the lake covering all accessible waters deeper than 0.6 m. The transects were spaced 122 m apart (Figure 2) based on read range tests conducted on Whites Creek Lake, Mississippi (Table 1). The transect would, on average, take 6.5 hours to track Moon Lake. Tracking speeds varied from 8-11.25 km/h. When I detected a tagged Silver Carp on the transect, the boat was placed in neutral to allow the hydrophone to collect the signal again. This was done to reduce noise and compensate for other conditions such as wind, waves, fish noises, or other boat engines that could affect the read range of the receiver. If a tagged Silver Carp was located within 5 m of where it was located on the previous two sampling occasions, it was deemed to be dead and removed from the study. The tag number and location were recorded on a Garmin GPSMAP 66s GPS (Garmin International, Kansas City, MO) along with gain level and decibels. Gain level is the number of decibels that a VR 100 is using to detect acoustic tags. The GPS is accurate within 15 m. After locating an individual, active tracking resumed along the transect. Active tracking occurred approximately every four weeks from May to October 2021, approximately every six weeks from November 2021 to January 2022, and every eight weeks from February to May 2022. I recorded the lake depths of the areas used by Silver Carp based on the latitudinal and longitudinal coordinates overlayed onto a raster image of Moon Lake to evaluate if Silver Carp used areas of water depths in relation to their availability. For the first season, I used the values of the raster image for water depths while a HOBO water temperature and pressure logger collected metrics for the first season as a baseline to compare to subsequent seasons. For subsequent seasons, I averaged pressure values collected from the HOBO water temperature and pressure logger and subtracted that from the averaged pressure values of the first season. The difference of the pressure (pounds per square inch, PSI) was converted to depth (m) as 0.70324*PSI and was then added to the raster image values for the respective season.

Data Analyses

Analyses were conducted to test each of the three predictions with an alpha level of 0.05: (1) Silver Carp will use lake areas with similar water depths in Moon Lake across seasons, (2) Silver Carp will use lake areas with water depths in proportion to the availability of water depths, and (3) Silver Carp will aggregate and disperse seasonally. For prediction 1, I applied a Fisher's exact test to test if Silver Carp were distributed over similar areas of water depths across different seasons. Fisher's exact test was used because sample sizes across seasons varied, and observations were occasionally low. Seasons evaluated were spring (March - May), summer (June - August), fall (September - November), and winter (December - February); depth classes were 0-1.9 m, 2-3.9 m, 4-5.9 m, and 6-7.9 m. I did not pinpoint the exact position of Silver Carp within the vertical water column, so depth classes represent the maximum depth for the water column class that Silver Carp occupied. For example, Silver Carp could be in the top 2 m of the 6-7.9 m depth class. Therefore, depth classes refer to classes of the depth of the lake floor, not the depth of the Silver Carp in the water column.

For prediction 2, I conducted a chi-square test of independence to test if Silver Carp selected depth classes in proportion to availability (i.e., at random) or whether Silver Carp used areas with water depths in proportion to availability of water depths. The chi-square test compared the available distribution of lake areas with given water depths in the lake with the distribution of such water depths used by Silver Carp. The depth classes established with prediction 1 were applied in this test.

For prediction 3, I used Nearest Neighbor Distances to evaluate Silver Carp seasonal aggregations. Nearest Neighbor Distances were calculated using the "gDistance" command (rgeos package, Bivand and Rundel 2021). The "gDistance" command uses Hausdorff distance to determine the nearest point around another set of points. This allows the function to determine distances, in meters, around landforms such as Alcorn Island or the shoreline of Moon Lake. The square-root of distances was used to create a normal distribution of distances. I then used a linear regression model to relate square-root distances to seasons and estimate Least-squares means that accounted for unbalanced seasonal samples. A pairwise comparison with a post-hoc Tukey test was used to determine if square-root distances among fish differed among seasons. All statistical analyses were completed in R (R Core Development Team v. 4.1.1)

Results

Overall, 35 tagged adult Silver Carp were released into Moon Lake. Adult Silver Carp averaged 828 mm in total length with a standard deviation of 31 mm. Sexes of adult Silver Carp were 54% (19) male, 43% (15) female, and 3% (1) was released before it was sexed. Over 11 sampling events, I sampled 67.25 hours observing an average of 6.5 fish per sampling event (Table 2).

In total, I recorded 71 detections of 23 of the 35 Silver Carp over a span of 367 days (Table 2). I determined four of the remaining 12 Silver Carp were dead and therefore, were removed from the analysis. Thus, eight Silver Carp were never relocated on acoustic receivers or active tracking efforts after release into Moon Lake. Of the 23 detected Silver Carp, nine were detected leaving Moon Lake on two acoustic receivers acting as a gate to monitor location. Of the nine Silver Carp that left Moon Lake, six eventually returned to the lake and the remaining three were never detected again.

Overall, 79% of the fish occupied lake areas with a water column ranging from 2.0-5.9 m maximum depth (Table 3). This estimate varied seasonally from 69% to 100%. Nevertheless, the water depths of areas used by Silver Carp were not significantly different according to a Fisher's Exact Test (P = 0.19).

Considering Silver Carp used areas in Moon Lake with similar water depths over all seasons, I combined seasons to test if the areas of water depths selected by Silver Carp were different than the available areas of water depths in Moon Lake (Table 4). Results suggest that Silver Carp disproportionally selected lake areas with 2.0-5.9 m water depths more than other lake areas with shallower or deeper water depths (χ^2 = 11.0, P = 0.03). Overall, Silver Carp tended to use areas with mid-range water depths with maximum depths of 2-3.9 m in greater proportions that what was available, occupied 4-5.9 m depths in proportion to availability, and avoided water 8-9.9 m deep and shallow water 0-1.9 m deep (Figure 3). Thus, Silver Carp disproportionately selected areas with intermediate depths, thereby avoiding lake areas with extreme water depths.

The Nearest Neighbor Distances analysis indicated that Silver Carp aggregate seasonally. Square-root transformed Least-squares mean distances among carps were greatest in the summer of 2021 and smallest in the winter of 2021 (Table 5). Silver Carp sampled per season ranged from 7-31 and was the highest in winter of 2021. The linear model indicated at least one of the seasonal mean distances were different (F = 9.0, P < 0.01). Pairwise comparisons with post-hoc Tukey test indicated no significant differences between most seasons but that distances were significantly shorter in the winter of 2021 compared to all other seasons (P < 0.02; Table 6). These results indicate that Silver Carp aggregated in winter but spread out more in other seasons.

In summary, I observed that Silver Carp in Moon Lake were disproportionately found in areas with water depths ranging from 2-5.9 m during all seasons despite the availability of areas with water depths ranging from 0-10 m. Silver Carp appeared to be found closer together in the wintertime compared to other seasons. These results indicate that Silver Carp are using areas in Moon Lake non-randomly over space and time.

Discussion

I evaluated macrohabitat use and aggregation of adult Silver Carp in a large oxbow lake in the Mississippi Alluvial Valley. Although researchers have studied habitat use of invasive carps (Coulter et al 2017; Prechtel et al. 2018), few studies have addressed aggregation of Silver Carp or other invasive carps (DeGrandchamp et al. 2008; Ghosal et al. 2016). Further, most studies have focused on invasive carp movements in the Upper Mississippi River drainage and in rivers whereas my study fills a knowledge gap by examining invasive carp in the Lower Mississippi River region and in oxbow lakes. The purpose of this study was to inform removal efforts of Silver Carp, which is one of the few management options available to control abundances. Results of this study indicate that 1) Silver Carp use lake areas with similar water depths across seasons, 2) Silver Carp disproportionally select areas with water depths ranging from 2-5.9 m, and 3) Silver Carp aggregate during the wintertime more than other seasons. These results can facilitate greater harvest efficiency by focusing removal efforts spatially and temporally.

My results indicate that Silver Carp use lake areas with similar depths in open-water macrohabitats of oxbow lakes year-round instead of exhibiting seasonal differences in areas of lake depth use. DeGrandchamp et al. (2008) also reported no differences in areas of waterbody depth used by Silver Carp between summer and spring. My findings that Silver Carp use areas with similar lake depths seasonally contrast with findings that indicate Common Carp use areas with different depths seasonally. For example, Otis and Weber (1982) and Penne and Pierce (2008) found that Common Carp selected areas with shallow depths (about 1 m) in summer but moved into areas with deeper depths (up to 4 m) to overwinter in natural lakes of the upper Midwest. Although Common Carp are in the same family as Silver Carp (*Cyprinidae*) and achieve similar body sizes, there are several ecological differences between these carp species. Common Carp are a detritivore and can spawn in lentic waters, whereas Silver Carp are pelagic filter feeders that require lotic waters to spawn. These ecological differences highlight the need for different management methods for both Common and Silver Carps.

Despite there being no clear seasonal patterns in lake depth areas used by Silver Carp, Silver Carp disproportionately selected lake areas with certain water depths in Moon Lake. Fish disproportionally occupied lake areas with water depths varying from 2-5.9 m and appeared to avoid shallower and deeper waters. Other studies in large-river systems determined that Silver Carp and Bighead Carp used areas with depths like those found in my study. For example, DeGrandchamp et al. (2008) found that Silver Carp can occur in areas of depths > 8 m, but generally avoided areas with depths > 4 m. Moreover, Glubzinski et al. (2021) reported that water depth was the best predictor of the fine-scale distribution of Silver Carp. MacNamara et al. (2018) reported that Silver Carp and Bighead Carp occurred in areas with 2.5–3.5 m depths in the main channel of the Illinois River and 1–2 m depths in backwaters.

In an experimental tank study, Ghosal et al. (2016) observed juvenile Silver Carp forming groups of 2-3 fish, while juvenile Bighead Carp aggregated into a single group, and suggested Bighead Carp and Silver Carp aggregate to enhance their feeding efforts and avoid predation. My field study observed that Silver Carp aggregate in winter but disperse throughout the rest of the year. Similarly, Miranda et al. (in press) reported winter aggregations of invasive carps in large reservoirs in the Tennessee and Cumberland rivers. Although research on Silver Carp aggregation behavior is limited, Penne and Pierce (2008) reported winter aggregations of adult

Common Carp in water 2-4 m deep in a natural lake. Their literature review indicated that Common Carp winter aggregations were due to low temperature, ice cover, or both because studies from warmer regions lacking ice cover had not documented winter aggregations. My study, albeit with Silver Carp, suggests other variables may be in play as water in Moon Lake remains ice-free throughout the year. I speculate aggregations may be an adaptive behavior for controlling metabolic activity (Parker 1973), avoiding predators (Smith 1997), improving hydrodynamic efficiency (Partridge et al. 1983), or identifying location of conspecifics before spawning (Johnsen and Hasler 1977), but additional research is needed.

Winter habitat selection and aggregation patterns indicate telemetry-guided techniques could be an effective management approach to locate Silver Carp aggregations (Bajer et al. 2011). For example, Bajer et al. (2011) tracked and targeted a few tagged Common Carp moving in water 1.5 m deep, resulting in removing 94% of the entire population. Hessler et al. (2021) used acoustic and radio telemetry tags to locate Grass Carp in a reservoir and its tributaries, which increased catch per effort threefold in the winter. Although, Hessler et al. (2021) determined that Grass Carp were not aggregating, the aided effort of acoustic and radio telemetry still increased efficiency.

Techniques other than radio-tagged fish have been investigated to locate or concentrate fish for removals. Ridgway et al. (2020) used an electrified butterfly trawl net to catch Silver Carp in large reservoirs and a large river. Results of Ridgway et al. (2020) suggest that catch per unit effort (CPUE) was higher in fall and that location, season, interactions between location and season, depth, and habitat, and sample time all influenced CPUE. Chapman (2020) addresses the Modified Unified Method of collecting Bighead and Silver carps. The method requires block nets and electrofishing boats equipped with underwater speakers to move carp from one net to the next in wintertime. This concentrates the fish while sonar is used to precisely locate the school for targeted capture efforts using a seine. This method is adapted from Chinese commercial fishermen who used a similar method without underwater speakers and sonar to remove up to 85% of the Bighead and Silver carp from ponds (Chapman 2020). Many methods to remove non-native cyprinids have been applied with variable success and have illustrated the need to understand habitat use and aggregation patterns across time and physical space.

This study had at least two shortfalls. First, the experimental unit (i.e., the lake) was not replicated, precluding generalizations about oxbow lakes, although providing useful information about Moon Lake and a starting point for developing hypotheses to test elsewhere. Second, it was difficult to sample extreme shallow waters (<2 m) that emulated a floodplain adjacent to a river when water levels were high. The presence of cypress trees and their knees along with dense sediment limited navigation and access to potential locations for Silver Carp. Waters were sampled as closely to cypress trees as possible, although my diminished ability to sample these shallow areas could have limited observations of Silver Carp. Conversely, waters beyond the cypress trees lines are protected from wind, allowing tags sound to carry farther or reverberate off trees to receivers, facilitating detection. I used tags with a low acoustic setting, which increased the amount of water that needed to be covered whenever sampling occurred and increased the chance that some other noise would mask or disrupt the acoustic signal from the tag.

Understanding the spatial and temporal distribution of Silver Carp is critical to designing harvesting plans in Moon Lake and the hundreds of similar lakes that occur in the Mississippi Alluvial Valley. My study indicated that Silver Carp exhibit distinct seasonal and spatial distributions within Moon Lake. The observed patterns can facilitate efficient harvesting with no or limited overlap with the recreational activities supported at oxbow lakes. Fish removal through harvesting with gill nets, or other procedures summarized by Cupp et al. (2021), during the winter and in open water is likely to yield the highest harvest rates and population reductions without interfering with recreational activities which are mostly limited to warmer seasons. Additionally, recreational fishing is typically associated with shallow nearshore water locations. Removals targeted to winter in areas with moderate depths could reduce the bycatch of nearshore species. However, open-water species such as Paddlefish could still be vulnerable to bycatch.

Tables

Table 1 Read range test of an acoustic receiver, VR-100 and VH-110 hydrophone, on Whites Creek Lake, Mississippi. Detections are denoted by an “X”, while a detection that was missed is denoted by an “-“. The V16 acoustic tag was submerged for one set of pings. I had another VR-100 receiver and VH-110 hydrophone directly adjacent to the tag to determine when it had completed a cycle of pings.

Read range (m)	25	50	75	100	125	150	175	200	225	250
Detected	X	X	X	X	X	X	X	-	-	-

Table 2 Detections of individual adult Silver Carp (*Hypophthalmichthys molitrix*) across 11 sampling trips covering five seasons at Moon Lake, Mississippi between 2021-2022. A single "X" denotes one detection while two "X" represents two detections.

Fish ID	Spring 2021		Summer 2021			Fall 2021		Winter 2021			Spring 2022
	5/5	5/31	6/25	7/30	8/24	9/71	10/7	12/12	1/23	1/30	5/7
52129								X	X	X	
52130											X
52131		X	X			X			X	X	
52139		X	X					X	X	X	X
52144										X	
52148											XX
52149									X	X	
52151											X
52154								X			X
52155			X	X				X	X	X	X
52158		X						X		X	X
52160	X						XX		X	X	X
52163		X						X	X	X	
52165											X
52166	X						X		X	X	X
52192		X									
52194				X			X		X	X	X
52196											X
52199			X								
52203						X	X			X	
52204		X		X					X	X	X
52206											X
52210			X		X			X		X	X

Table 3 Seasonal counts of 23 Silver Carps (*Hypophthalmichthys molitrix*) across lake area depth classes in Moon Lake, Mississippi, 2021–2022.

Depth class (m)	2021 Spring	2021 Summer	2021 Fall	2021 Winter	2022 Spring
0-1.9	1	0	0	8	4
2-3.9	4	8	3	13	6
4-5.9	2	1	4	10	5
6-7.9	1	0	0	0	1

Table 4 Seasonally adjusted combined counts of depths selected by 23 Silver Carps (*Hypophthalmichthys molitrix*) versus available depths in Moon Lake, Mississippi, in 2021-2022. Moon Lake was subdivided into 60,604 27.6 m^2 square grids. The locations of selected depths coincide with locations of acoustically tracked Silver Carp.

Depth class (m)	Used frequency	Available frequency
0-1.9	13	13,955
2-3.9	34	29,850
4-5.9	22	10,853
6-7.9	2	5,875
8-10	0	71

Table 5 Least squares means (LSMeans) for square-root transformed distances among Silver Carp (*Hypophthalmichthys molitrix*) and their nearest three neighbors grouped by season in 2021-2022 in Moon Lake, Mississippi. SE is the standard error; SD is the standard deviation; df is the degrees of freedom; Lower CL is the lower 95% confidence interval; Upper CL is the upper 95% confidence level.

Season	LSMeans	SE	SD	df	Lower CL	Upper CL
2021 Fall	29.3	3.45	10.40	66	22.4	36.1
2021 Spring	29.9	3.22	6.09	66	23.5	36.4
2021 Summer	33.1	3.04	10.98	66	27.0	39.1
2021 Winter	17.1	1.64	9.03	66	13.9	20.4
2022 Spring	28.6	2.28	8.84	66	24.0	33.1

Table 6 Pairwise comparison results of aggregations between all seasons for Silver Carp (*Hypophthalmichthys molitrix*) in Moon Lake, Mississippi. Estimate is the adjusted coefficients to describe the linear pattern of the model; SE is the standard error; df is the degrees of freedom; P value is the probability that a season means could be observed from the probability distribution of the other season it is being compared to if the null hypothesis is true; t ratio is the estimate divided by the standard error.

Contrast	Estimate	SE	df	t ratio	P value
2021 Fall - 2021 Spring	-0.68	4.72	66	-0.14	1.00
2021 Fall - 2021 Summer	-3.80	4.59	66	-0.83	0.92
2021 Fall - 2021 Winter	12.13	3.81	66	3.18	0.02
2021 Fall - 2022 Spring	0.67	4.13	66	0.16	1.00
2021 Spring - 2021 Summer	-3.13	4.43	66	-0.71	0.95
2021 Spring - 2021 Winter	12.80	3.62	66	3.54	0.01
2021 Spring - 2022 Spring	1.35	3.95	66	0.34	1.00
2021 Summer - 2021 Winter	15.93	3.45	66	4.62	0.00
2021 Summer - 2022 Spring	4.47	3.80	66	1.18	0.76
2021 Winter - 2022 Spring	-11.46	2.81	66	-4.08	0.00

Figures

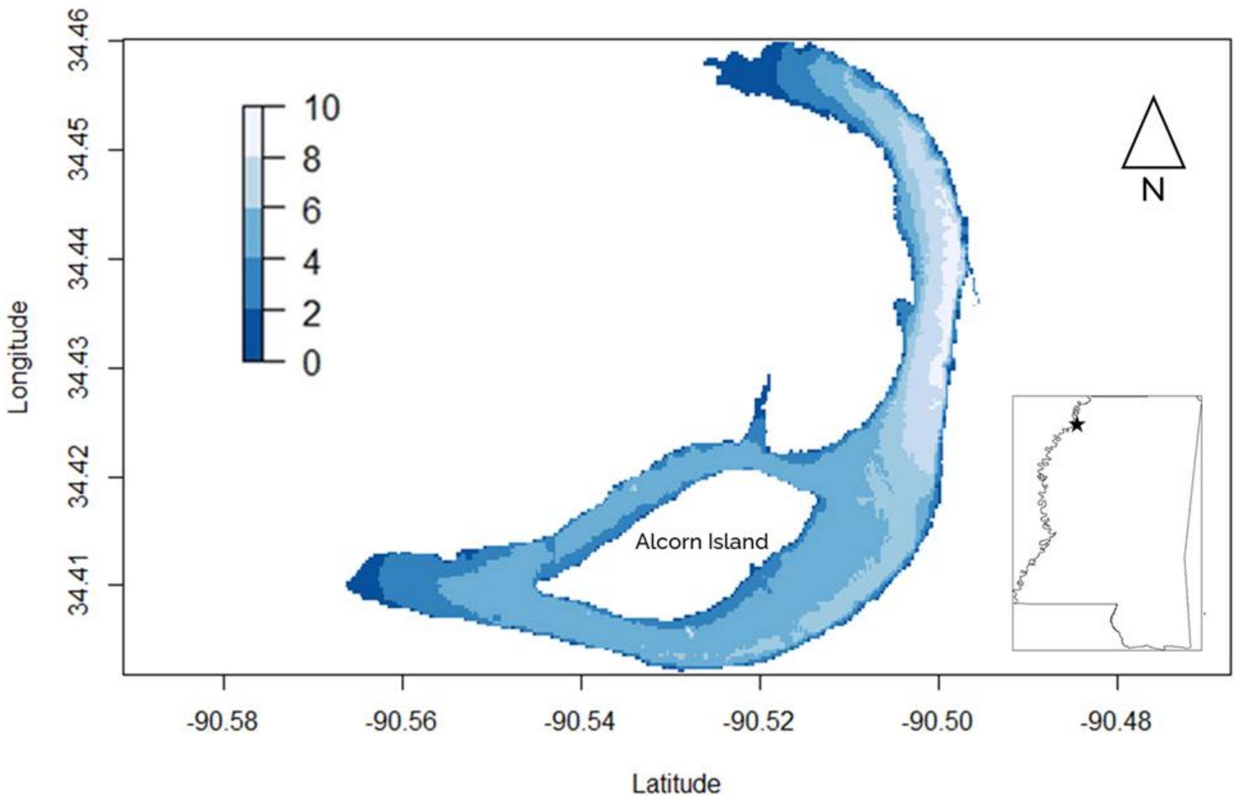

Figure 1 Depths contours (m) for Moon Lake, Mississippi, where Silver Carp (*Hypophthalmichthys molitrix*) were tracked seasonally in 2021–2022.

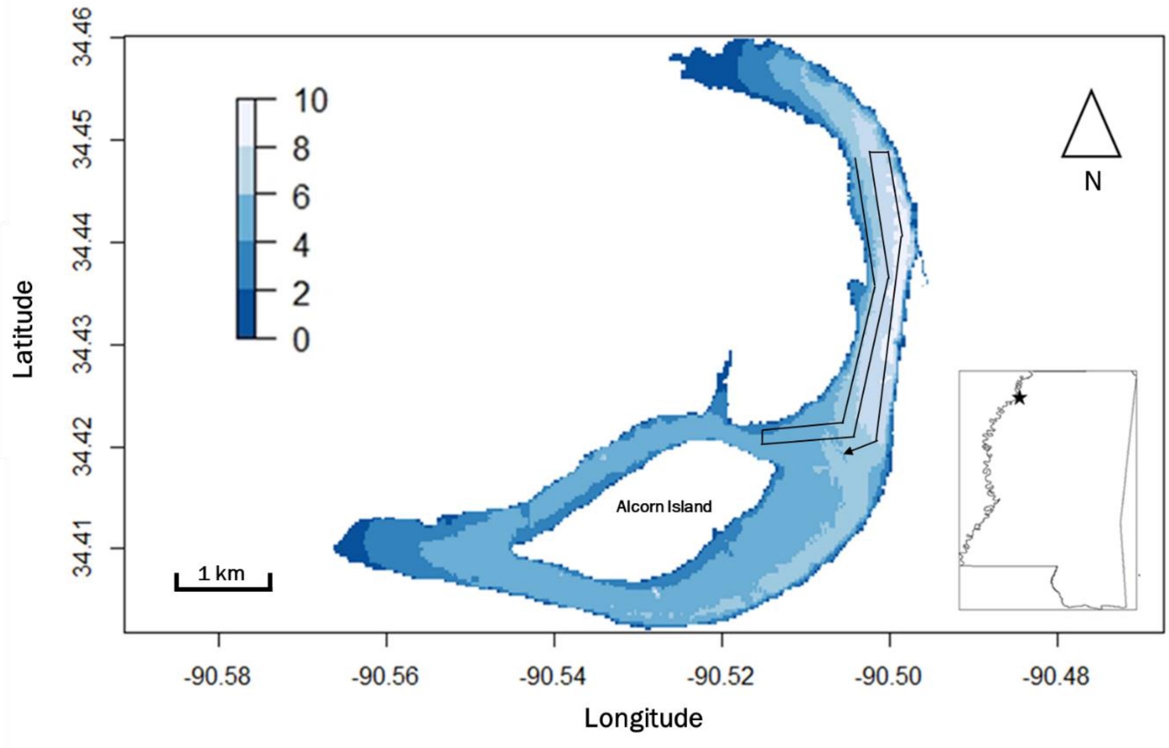

Figure 2 A continuous transect was used to find Silver Carp (*Hypophthalmichthys molitrix*) in Moon Lake, Mississippi, 2021–2022. The transect would take an approximately 180° turn and continue along 122 m away, parallel, in the opposite direction. The black arrow and lines on Moon Lake illustrate an example of the continuous transect which on average took 5.5 hours.

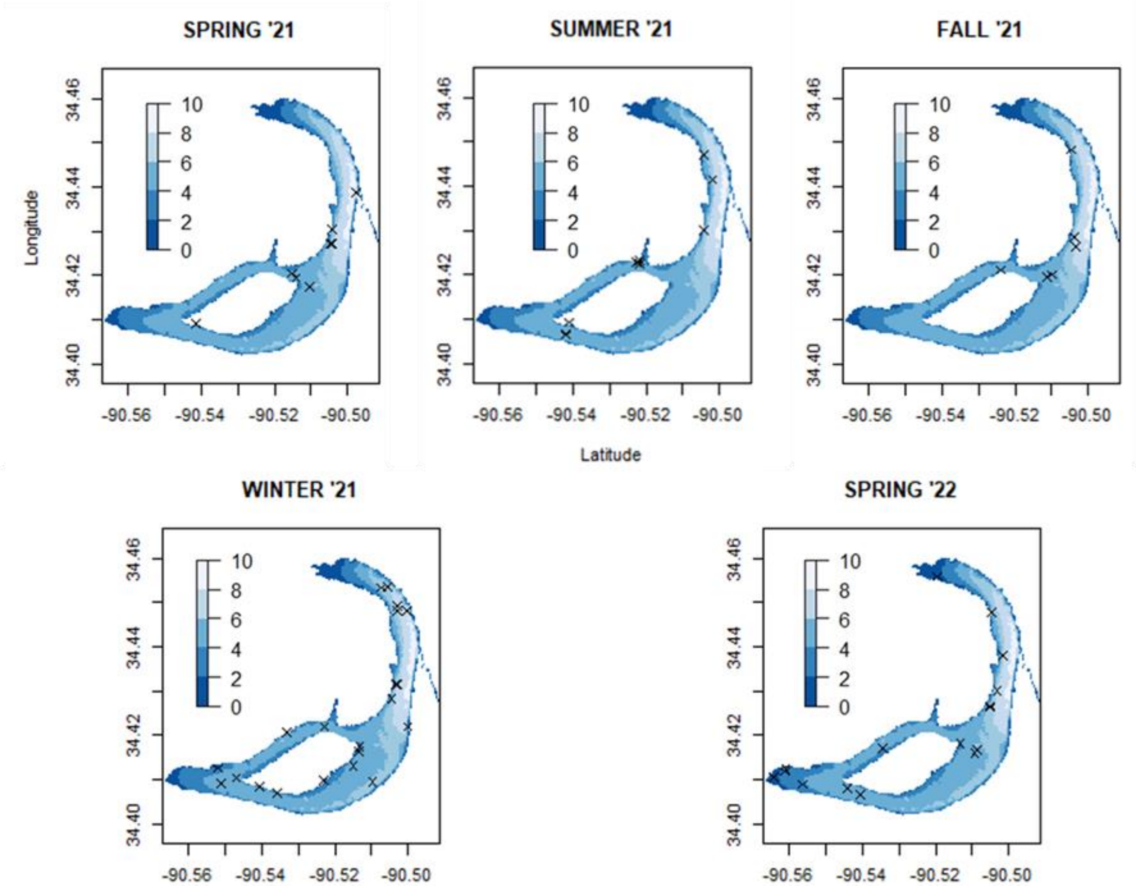

Figure 3 Depth chart of Moon Lake, Mississippi, with locations (x) of Silver Carp (*Hypophthalmichthys molitrix*) during each season in 2021-2022.

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