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HABITAT USE AND DIEL MOVEMENTS OF SILVER CARP Hypophthalmichthys molitrix IN TWO SOUTHEASTERN RESERVOIRS

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Background

Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix*, collectively called bigheaded carp, are native to Eastern Asia and have been widely introduced to 88 countries (Kolar et al. 2005). They are both members of the Xenocyprididae family, which includes Bighead Carp, Grass Carp *Ctenopharyngodon idella*, Black Carp *Mylopharyngodon piceus*, and Silver Carp in the U. S. The first documented introduction of bigheaded carp was from China to Taiwan before the 18th century (Froese and Pauly 2004; Kolar et al. 2005).

Bigheaded carp were introduced to North America many years later. They were primarily used as a biological control for improving water clarity in aquaculture (Kolar et al. 2005). For example, bigheaded carp were intentionally introduced into the U. S. in 1973 in Arkansas by a private fish farmer (Henderson 1976; Freeze and Henderson 1982). They were utilized as a biological control in sewage lagoons and aquacultural ponds to reduce overabundant phytoplankton populations (Freeze and Henderson 1982).

In January of 1980, a commercial fishers caught several Silver Carp while fishing Crooked Creek, located in northeastern Arkansas. Crooked Creek flowed through two private hatcheries that were propagating bigheaded carp, and the escapement into Crooked Creek likely occurred due to flooding events (Freeze and Henderson 1982). From Crooked Creek, bigheaded carp likely egressed into the Bayou Meto River and then into the Arkansas River, which is a major tributary of the Mississippi River. By 1982, bigheaded carp had reached the Mississippi River and established a thriving population (Kolar et al. 2005).

In 1974, shortly after the arrival of bigheaded carp within Arkansas, Arkansas Game and Fish Commission began propagating them to determine if they posed a threat to the state's aquatic ecosystem or would be a beneficial addition to fish production ponds (Henderson 1976; 1978; Freeze and Henderson 1982). Once Arkansas Game and Fish Commission realized three private fish hatcheries were propagating bigheaded carp too, they quickly enacted regulations preventing the stocking or release of bigheaded carp into public waters and required vendors to register with the Commission (Freeze and Henderson 1982).

After the report of Silver Carp in Crooked Creek in 1980, the Arkansas Commercial Fishers's Association was asked to report and save specimens of bigheaded carp. Arkansas Game and Fish Commission personnel accompanied at least four commercial fishermen in all four major river systems in the state to observe and record the number of bigheaded carp specimens caught (Freeze and Henderson 1982). In the same year, the Arkansas River was sectioned off into sampling sections which were gill netted with three standard sets per month from September through May and once per month from June through August (Freeze and Henderson 1982). By 1981, gill netting was reduced to once a month by section. Due to the concern that bigheaded carp might have a negative effect, rotenone and shoreline seining were also enacted from June through August of 1981. Enough rotenone to treat 0.5 hectares was released in each river section each month but failed in kill any bigheaded carp (Freeze and Henderson 1982). With the failed attempt to contain the invasion into public waters, researchers began examining what potential ecological problems these bigheaded carp may incur in U. S. waters.

Current Status of the Invasion

Bigheaded carp have proven to be resilient and capable of spreading quickly because they are very fecund, with few predators impeding the establishment of their populations. Bigheaded carp are deep-bodied with rapid growth rates that allow them to quickly evade the gape-limitation of most native U. S. predators. Silver Carp can grow to > 300 mm within one year (Williamson and Garvey 2005; Lebeda 2020), and one female, given favorable conditions, such as abundant food resources and favorable temperatures, can contain up to 5,400,000 eggs (Kamilov and Salikhov 1996; Kolar et al. 2005). Bigheaded carp are aggregatory pelagic potamodromous broadcast spawners (Li et al. 2013; Whitledge et al. 2019) and can spawn multiple times within a season, usually while the hydrograph limb is ascending, and water temperatures are exceeding 17 °C (Krykhtin and Gorbach 1981; Deters et al. 2013; Li et al. 2013; Larson et el. 2017; Whitledge et al. 2019). Upon fertilization of the eggs during spawning, the eggs drift downstream before hatching. Once hatched, they will continue to drift until their gas bladder inflates, which allows them to swim to nearby nursery areas such as backwaters with low flow (George and Chapman 2013; Whitledge et al. 2019). Downstream drift distance coupled with warming water temperature strongly correlate with egg and larval development timing (Kolar et al. 2007; Murphy and Jackson 2013; Whitledge et al. 2019). River fragmentation has reduced the rkm distances of free-flowing habitat required for many species in their embryonic state to complete ontogenetic development (Braaten et al. 2012). If a free drifting egg or embryo settles out of the water column, it can be buried by detritus and die due to anoxic conditions.

Due to their fast growth rate and high fecundity bigheaded carp spread rapidly throughout North America. Since 1972 Silver Carp have been detected in 23 states within the U.S. and

Puerto Rico (Nico et al. 2022). They have established populations in the three largest river basins in North America: the Mississippi, Ohio, and Missouri (Kammerer 1990; Conover et al. 2007; Altenritter et al. 2022). Bigheaded carp have spread throughout long stretches of these major rivers, suggesting they can navigate through locks and dams. Recently, the Tennessee Wildlife Resources Agency confirmed that Silver Carp had reached Chickamauga Reservoir, the third of the nine reservoirs impounded on the Tennessee River (TWRA 2020). Hence, with Kentucky Reservoir being the 9th and last reservoir of the Tennessee River. Within Illinois, bigheaded carp reproduction is limited in the upper Illinois River and was last observed in 2015 (ACRCC 2020; Altenritter et al. 2022) but is sporadically successful in the lower Illinois River (Gibson-Reinemer et al. 2017; Altenritter et al. 2022). Coincidentally, the first documented age-0 Silver Carp specimens in Kentucky Reservoir were also collected in 2015 (Lebeda 2020).

Researchers are concerned Silver Carp may move from their established populations in large rivers into other water bodies, such as the Great Lakes. Murphy and Jackson (2013) used a cumulative thermal unit model for assessing the potential establishment of bigheaded carp within tributaries of the Great Lakes and found that under certain conditions, less than 25 km proved adequate for transporting eggs until hatched. All four major tributaries of the Great Lakes, the Sandusky, Maumee, Milwaukee, and St. Joseph Rivers, contain at least 25 rkm of free-flowing habitat to make embryo development and survival successful (George and Chapman 2013). Bigheaded carp environmental DNA (eDNA) has been detected above the electric barriers implemented to keep bigheaded carp out of the Great Lakes. Bigheaded carp eDNA has been sampled from Lake Calumet, the Little Calumet River, the North Shore Channel, the Chicago River (USACE 2012; Nico et al. 2022), and Maumee Bay, Lake Erie (Jerde et al. 2013; Nico et al. 2022). However, no physical detections of bigheaded carp have been made in these locations.

Certain reaches and tributaries of the Mississippi River Basin's biomass are dominated by bigheaded carp (Upper Mississippi River Restoration Program Long Term Resource Monitoring data at https://www.umesc.usgs.gov/ltrmp.html; Sass et al. 2010; Whitledge et al. 2019), where they are suspected of affecting native fish assemblages and plankton populations (Sass et al. 2014; Whitledge et al. 2019). Bigheaded carp are planktivores (Pflieger 1997; Nico et al. 2022), requiring a food source of larval fish and mussels. Their consumption of plankton can potentially cause severe damage to native invertebrates and young of the year, who feed on plankton at some point in their larval development (Kolar et al. 2005). Most directly they will compete with native planktivorous fishes (Laird and Page 1996; Nico et al. 2009), such as the Paddlefish *Polydon spathula*, Gizzard Shad *Dorosoma cepedianum*, and the Bigmouth Buffalo *Ictiobus cyprinellus*. Studies have confirmed diet overlap with native planktivorous species (Sampson et al. 2009) and there is direct interspecific competition between Silver Carp and native planktivores (Irons et al. 2007; Lebeda 2017). Evidence from both mesocosm and field studies suggest that if plankton becomes limited, interspecific competition will likely occur. For example, a mesocosm study found evidence that bigheaded carp reduced the growth rates of juvenile Paddlefish (Schrank et al. 2011). A second mesocosm study by Fletcher et al. (2019) showed Bluegill *Lepomis macrochirus* growth was reduced from 58%-87% when reared with juvenile Bighead Carp, relative to the control without a competitor. Further, post-bigheaded carp invasion in the Illinois River resulted in a decrease in the relative weight of Gizzard Shad by 5% and Bigmouth Buffalo by 7% and led to declines in the abundance of both species (Irons et al. 2007; Pendleton et al. 2017; Altenritter et al. 2022).

Bigheaded carp may also affect economies near large rivers and lakes, such as recreational boating and sport fishing. Bigheaded carp often jump out of the water more than 1 meter when boat engine vibrations and noises approach them. This behavior might be used by bigheaded carp to avoid predators (Perea 2002). Silver Carp can reach weights up to nearly 50 kg (Billard 1997; Kolar et al. 2005) and lengths of 1.2 m (Kamilov and Salikhov 1996; Kolar et al. 2005). Collisions between humans and jumping Silver Carp have led to injuries including black eyes, broken bones, back injuries, cuts, and concussions (Kolar et al. 2005). Silver Carp damage to personal property includes broken radios, generators, depth finders, windows, fishing equipment, lights, and antennae (Kolar et al. 2005). Bigheaded carp will typically breach the surface when the motor is closest to them, leaving a following boat or water skier at a higher risk of injury (pers. obs., Kolar et al. 2005).

Technologies Considered for Prevention

Multiple state, federal, and private agencies are working together to eradicate, manage, and prevent the spread of these bigheaded carp. However, one of the greatest challenges of fisheries management is implementing an effective and economical control mechanism that can block the passage of invasive fishes (Popper and Carlson 1998; Taylor et al. 2005). Silver Carp only cross into Kentucky Reservoir and Barkley Reservoir, the two reservoirs under study in this thesis, by using the locks when barges transit the dam (T. Spier, pers. com.). One method to prevent the spread of bigheaded carp would be to stop bigheaded carp from navigating through the natural bottleneck created by these locks. However, this also limits the movement of native species who need to navigate through these dams for seasonal migrations and to retain genetic diversity among populations.

A technology that has proven effective in altering fish movements is known as the hybrid Sound Projector Array (SPA) driven BioAcoustic Fish Fence (BAFF) system (Maes et al. 2004; Taylor et al. 2005). The SPA driven BAFF functions include an air bubble curtain with pneumatically generated sound signals randomly selected from predetermined frequency ranges (Taylor et al. 2005). The sounds/chirps generated are trapped in the air bubble curtain creating a barrier used to deter fish away from unwanted areas. Using a mesocosm study including bigheaded carp and the SPA driven BAFF, Taylor et al. (2005) found that it was 95% effective in prohibiting bigheaded carp from crossing the sound/bubble barrier. This was the first study in which the SPA driven BAFF was tested as a cross-channel movement barrier.

Species in the Xenocyprididae family, such as bigheaded carp, have special hearing abilities due to their Weberian ossicles (modified vertebrae that enhance hearing) (Tavolga 1971; Taylor et el. 2005). This acute hearing ability allows bigheaded carp to detect sounds at further distances and a wider range of sound frequencies compared to other fish species which lack these structures (Fay and Popper 1999; Taylor et al. 2005). The SPA driven BAFF can be tailored to the sensitivities of bigheaded carp, which have a detection frequency of 50 – 2000 Hz (compared to fishes without, which have detection frequencies of 50 – 600 Hz) (Popper and Carlson 1998; Taylor et al. 2005). The SPA driven BAFF could provide opportunities for native species with less sensitive auditory capabilities to swim through such a barrier (Taylor et al. 2005). In 2019, the SPA driven BAFF was implemented at the lock and dam below Barkley Reservoir, and a study is currently underway to test the effect of this barrier on both Silver Carp and native species.

Another method for stopping the spread of bigheaded carp uses electric barriers deployed in the Chicago Sanitary and Ship Canal in northeastern Illinois (Dettmers et al. 2005). In 1848, this canal was constructed, connecting the Illinois River to lower Lake Michigan. Bigheaded carp have a well-established population in the Illinois River and have exhibited substantial population growth in recent decades (Koel et al. 2000; DeGrandchamp et al. 2008). The strength of the electric field increases from the outside inward, giving fish a chance to detect the field and turn around before becoming stunned (Dettmers et al. 2005). Electric barriers, when calibrated correctly, have proven effective in blocking passage for a variety of fish species (Dettmers et al. 2005). However, initial testing of the Chicago barrier suggested that steel hulled barges can cast an ‘electric shadow’ that reduces the electric current around their hulls. This allows fish to travel deep into the electric barrier; some fish traveling alongside a barge were never fully immobilized (Dettmers et al. 2005). Although Silver Carp eDNA has been found upstream of the barrier, I was unable to find any published or anecdotal evidence of a live Silver Carp captured within the Great Lakes. One downside of the electric barrier method is that it can’t be adjusted to be species specific. In Lake Michigan this might be less problematic, as it was not naturally connected to the Mississippi Basin. However, if this method was implemented at every lock and dam, the financial cost would be extreme, and it would impede passage of native species.

Eradication Efforts

Once bigheaded carp become established in a large water body, eradicating the population would be expensive and logistically difficult (Qiyue and Cooke 2014). A goal of management via harvest is to limit the negative effects on native biodiversity and productivity while simultaneously suppressing bigheaded carp populations (Tsehaye et al. 2013; Altenritter et al. 2022). Potential eradication and control methods include physical barriers, fish poisons, mass removal, habitat alteration, or the addition of predators, pathogens, or parasites (USGS 2022).

The use of harvest practices have been tested within the Illinois River (Altenritter et al. 2022). Despite data suggesting an increase in bigheaded carp population within the Illinois River (Chick and Pegg 2001; Sass et al. 2010; Irons et al. 2011), Tsehaye et al. (2013) argued that it may be possible to collapse the bigheaded carp population within the Illinois River if commercial fishing efforts were expanded and combined with economic incentives to capture a wider range of bigheaded carp sizes. Intensive harvesting reduced densities of bigheaded carp by 93% within the upper Illinois River near the invasion front and limited their replenishment abilities from adjacent habitats (MacNamara et al. 2016; ACRCC 2017; Altenritter et al. 2022). These efforts may be undermined since the movement of more bigheaded carp from the lower Illinois River replaced those removed from the upper Illinois River (MacNamara et al. 2016; Altenritter et al. 2022). In September 2019, harvest was expanded farther downstream to limit replenishment to the upper Illinois River (ACRCC 2020; Altenritter et al. 2022).

Economic Demand

If revenue could be generated from the abundant bigheaded carp resource, it would help to offset the costs of suppression. Bigheaded carp are some of the most productive fishes in freshwater aquaculture (Li et al. 2021). In China, bigheaded carp have been farm-raised for human consumption for 8,000 years and can be fried, steamed, boiled, baked, or processed into surimi which can be processed as fish tofu, fish balls, fish sausage, and fish cakes (Cao et al. 2019; Pourashouri et al. 2020; Wu et al. 2020; Li et al. 2021). Byproducts from fish processing can be sold as low-value products such as animal feed and fertilizer. Other products obtained from fish byproduct includes fish oil, collagen, fishbone powder, fish jelly, gelatin, minced fish products, calcium supplements, bioactive peptides, leather, visceral digestive enzymes, food additives, bioactive compounds, medical materials, chondroitin sulfate, and other nutraceutical products (Li et al. 2021).

Despite their product versatility, bigheaded carp are underutilized within the U. S. where they are not welcomed as table fair (Li et al. 2021). One disadvantage is that bigheaded carp contain more epineural and epipleural (intermuscular) bones compared to most fishes that are processed for human consumption in the U. S. This poses a financial disincentive for processing companies (Li et al. 2021). Americans' misconceptions and prejudices towards bigheaded carp as a viable food source remain a tough obstacle to overcome (Li et al. 2021). Li et al. (2021) suggests the negative news coverage that bigheaded carp have received in the U. S. has led to a negative connotation towards these species as a food source. If this misconception could be overcome, bigheaded carp would have great potential to be a low-fat and high-protein food source for human consumption within the U. S. (Keevin and Garvey 2019; Li et al. 2021). Establishing a market may reduce bigheaded carp numbers in waters, while providing local communities with more jobs and generate significant economic value (Li et al. 2021).

Several companies along the Mississippi River do exist that harvest bigheaded carp commercially, such as Moon River Foods, Inc. located in Mississippi, and Two Rivers Fisheries, located in Kentucky. Unfortunately, after exporting bigheaded carp to China and paying the high cost of U. S. labor, these industries are earning a lower profit (Li et al. 2021). Currently, in the U. S., most products produced from bigheaded carp are limited to prepared and frozen products (Li et al. 2021). If fish byproducts could be further developed by U. S. enterprises, the value-added output of bigheaded carp would rise, and profits would increase as the demand for fishmeal is extremely high. Products that would not only be consumed in the U. S. but also exported to other countries would create greater economic revenue for enterprises within the U.S. fish processing industry (Li et al. 2021).

Bigheaded carp have the potential to be problematic for U. S. waters, and their long-term cascading effects throughout the aquatic food web are poorly understood. Limited data exist concerning bigheaded carp behavioral ecology within U. S. reservoirs. Therefore, a need for more research on bigheaded carp within U. S. reservoirs exists to fill knowledge gaps and to aid commercial fishers. Currently, a multi-year study of seasonal bigheaded carp movements is being conducted by the Kentucky Department of Fish and Wildlife Resources and Murray State University. In this thesis, I describe my research, which focuses on the short-term movement and macrohabitat use of Silver Carp within two such reservoirs, Kentucky Reservoir and Barkley Reservoir.

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Chapter II

Diel Movements of Silver Carp *Hypophthalmichthys molitrix* in Kentucky Reservoir and Barkley Reservoir

ABSTRACT

Bigheaded carp have spread rampantly throughout the Mississippi watershed and continue to spread by navigating through rivers, locks, and dams. The long-term effects these species will have on our ecosystems and natural resources is unknown. Their movements, behavior, and general seasonal patterns are well studied within rivers. However, their movements and behavior within reservoirs is poorly understood due to their initial numbers within reservoirs being lower than in rivers. To address this gap, I investigated the distribution and movement rates of Silver Carp within two reservoirs, Kentucky Reservoir and Barkley Reservoir, and possible correlative variables, including wind, temperature, residency, sex, and relative exposure index. I hypothesized that wind would have the greatest influence on Silver Carp movement rates and location, thru its effect on the distribution and abundance of food resources. Over 13 months, I collected movement rates on 30 individual Silver Carp; twenty-two of these Silver Carp were tracked for 24-hours. To my knowledge, these 24-hour tracking data are the first to be collected for this species within a reservoir. I determined that Silver Carp movement rates increased in waters of warmer temperatures ($F_{1,28} = 6.8$, $p = 0.01$, $N = 30$). Within Barkley Reservoir, swim rates did increase with mean wind speed ($F_{1,4} = 12.5$, $p = 0.02$, $R^2 = 0.76$). *However, this result will need further conformation, due to my low sample size (n = 6) within Barkley Reservoir, and no significant differences detected within Kentucky Reservoir. Data collected from the Hancock Biological Station confirms seasonal variation of phytoplankton but is distributed evenly among macrohabitats. It is possible Silver Carp are swimming at random considering their food source is abundant and evenly distributed.*

INTRODUCTION

Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix*, collectively referred to as bigheaded carp, are native to Eastern Asia and have been widely introduced to 88 countries (Kolar et al. 2005), primarily for use in aquaculture (Kolar et al. 2005).). They are both members of the Xenocyprididae family, which includes Bighead Carp, Grass Carp *Ctenopharyngodon idella,* Black Carp *Mylopharyngodon piceus,* and Silver Carp in the U. S. The first documented introduction of bigheaded carp was from China to Taiwan before the 18th century (Froese and Pauly 2004; Kolar et al. 2005). Bigheaded carp were intentionally introduced into the U. S. much later, in 1973, within the state of Arkansas by private fish farmers (Henderson 1976; Freeze and Henderson 1982). They were utilized as a biological control in sewage lagoons and aquacultural ponds to reduce overabundant phytoplankton populations (Freeze and Henderson 1982), which improves water clarity. The growth rate and fecundity of bigheaded carp have allowed them to spread rapidly throughout North America. Since 1973 Silver Carp have been detected in 23 states within the U.S. and Puerto Rico (Nico et al. 2022). They have established populations in the three largest river basins in North America: the Mississippi, Ohio, and Missouri (Kammerer 1990; Conover et al. 2007; Altenritter et al. 2022). Bigheaded carp have spread throughout long stretches of these major rivers, which suggests they can navigate through locks and dams. In such rivers, the Silver

Within these large river basins, Silver Carp movements have been well studied (Tumolo and Flinn 2017). Fish movements can generally be classified into two categories: broadscale migrations and fine-scale routine movements (Diana 1995; Coulter et al. 2016). At a broad scale, carp movement in large rivers is influenced by environmental variables such as river stage (DeGrandchamp et al. 2008), flow (Calkins et al. 2012), and temperature (Coulter et al. 2016).

In their native range, rises in river stage and current velocity are associated with spawning migrations (Krykhtin and Gorbach 1981; Abdusamadov 1987; DeGrandchamp et al. 2008). Warming water temperature influences the onset of Silver Carp spawning (Abdusamadov 1987; Kocovsky et al. 2012; Coulter et al. 2016), as Silver Carp are potadromous and typically spawn at water temperatures between 21 – 26 °C (Verigin et al. 1978; Krykhtin and Gorbach 1981; Abdusamadov 1987; Jennings 1988; DeGrandchamp 2006). DeGrandchamp et al. (2008) discovered Silver Carp peak movement was more closely linked to river stage than water temperature.

Finer scale routine movements (i.e., movements over a 24-hour period), are influenced by extrinsic factors such as food availability (Hill and Grossman 1993; Coulter et al. 2016), foraging (Clough and Ladle 1997; Coulter et al. 2016), and competition (Swan and Palmer 2000; Gilliam and Fraser 2001; Kahler et al. 2001; Fraser et al. 2006; Coulter et al. 2016). Often animal location can be tightly linked to their food supply. Silver Carp are a ram suspension planktivorous filter-feeding species. Therefore, a planktivorous species may need to move to find areas with higher plankton abundance. Fish routine movements can also be influenced by intrinsic factors, such as body size (Gowan and Fausch 1996; Skalski and Gilliam 2000; Roberts and Angermeier 2007; Coulter et al. 2016), morphology, sex (Hanson et al. 2007; Coulter et al. 2016), and maturity (Hutchings and Gerber 2002; Croft et al. 2003; Albanese et al. 2004; Petty and Grossman 2007; Coulter et al. 2016).

The first reservoirs in the U.S. to be invaded by Silver Carp were Kentucky Reservoir and Barkley Reservoir in 2004. Recently, the Tennessee Wildlife Resources Agency confirmed Silver Carp had reached Chickamauga Reservoir (third from the top), which is the third of the nine reservoirs impounded on the Tennessee River (TWRA 2020); as such, we know the carp can invade riverine impoundments via their locks and dams. These reservoirs represent unique environments for this species that deserve further investigation. For example, Coulter et al. (2016) concluded that spring flows resulted in upstream movements and in the fall, downstream movements were observed in Silver Carp within the Wabash River in Indiana. Unlike their behavior in large rivers, the Silver Carp tend to move downstream in spring, and their movement rates are different among different subpopulations (T. Spier, pers. com.).

Bukaveckas et al. (2002) has also hypothesized that greater transparency within Kentucky Reservoir allows for higher net phytoplankton production than free-flowing rivers. Within Kentucky Reservoir the mechanisms regulating autotrophic and heterotrophic activity also differ from free-flowing rivers (Buckaveckas et al. 2002). A diet study conducted by Tumolo and Flinn (2017) confirmed Silver Carp within Kentucky Reservoir were feeding primarily on phytoplankton. Of 83 Silver Carp, gut contents contained 63.5% phytoplankton, 33.8% zooplankton, and 2.7% intermediate. Phytoplankton composition was 86.9% little green balls (referring to coccoid alga that are difficult to distinguish as green algae or cyanobacteria), 8% diatom, 4.1% cyanobacteria, and 1% green algae. Zooplankton composition was 54.7% copepoda, 23.3% cladocera, and 22% rotifera.

Studying the behavior of invasive species at their leading edge is critical to managing the spread of such invaders (Williamson and Garvey 2005). Information about the diel movements could be utilized by commercial fishers to fish during times of higher activity rates and would fill knowledge gaps for managers and scientists. I used ultrasonic telemetry to study the routine diel movements of Silver Carp in Kentucky Reservoir and Barkley Reservoir, in relation to sex, wind speed and direction, water temperature, and discharge. I hypothesize that diel movements are primary controlled by food resources. The Hancock Biological Station’s multi-decade sampling efforts suggest that zooplankton and chlorophyll a is abundant and mostly evenly distributed throughout the reservoir. Phytoplankton density and community within Kentucky Reservoir varies seasonally, but on a given day, little variability has been observed (Bukaveckas et al. 2002). A study by Nakayama et al. (2018) confirmed wind influences fish movements, such as Eurasian Perch *Perca fluviatilis*. Thus, if food resources control routine movements, I expect fish movement to be located in areas with plankton aggregations.

METHODS

Study Area

I studied individual Silver Carp from populations within Kentucky Reservoir and Barkley Reservoir. Both are mainstem reservoirs, with Kentucky Reservoir being the last and largest reservoir on the Tennessee River and Barkley Reservoir being the last and largest reservoir on the Cumberland River. Both were constructed for power generation, navigation, flood control, and recreation. The lower portion of both reservoirs is considered lacustrine due to the relatively stable water levels, which only fluctuate by 1.5 meters from winter to summer pool, and the static temperatures (KDFWR 2016). However, as with many mainstem reservoirs, both water bodies retain some riverine characteristics, such as constant flow. But, unlike large rivers, the flow in these reservoirs can be decoupled from the water levels.

Constructed in 1944, Kentucky Reservoir is the largest reservoir within the eastern U.S. It spans 298 river kilometers, beginning in Tennessee at Pickwick Dam and flowing north to Kentucky Dam near Grand Rivers, Kentucky. Its surface area at maximum capacity is nearly

65,000 hectares (Kerns et al. 2009; Tennessee Valley Authority 2016; Lebeda 2020). Kentucky Reservoir is classified as mesotrophic (M. Flinn, pers. comm.) to eutrophic (Kerns et al. 2009; KDFWR 2016; Lebeda 2020). The lacustrine, northern portion of the reservoir consists of 0.01% canal (connecting Kentucky Reservoir to Barkley Reservoir), 4.10% cove (inlets along the main body of the reservoir > 5 ha but < 100 ha), 23.3% major cove (inlets > 100 ha), 59.2% side-channel (shallower areas flanking the thalweg in the main channel), and 12.3% thalweg (Ridgway and Bettoli 2017; Lebeda 2020). Secchi depths within Kentucky Reservoir vary seasonally and range from 0.6 – 1.4 m (Lebeda et al. 2022). The discharge varies by season; over the duration of my study average weekly discharge was 1,893 cms, ranging from 571 – 2394 cms (data shared by the U. S. Army Corps of Engineers). Chlorophyll a abundances also vary seasonally, but averaged 12 – 16 mg/L in Kentucky Reservoir (data shared by Hancock Biological Station).

Barkley Reservoir was constructed in 1966 and is 189.9 km long. It starts at Cheatham Dam in Tennessee, flows north to Barkley Dam near Grand Rivers Kentucky, and has a maximum surface area of 23,490 ha (Jarret and King 1991). Like Kentucky Reservoir, Barkley Reservoir also consists of a lacustrine downstream portion and consists of 0.2% canal, 10.1% cove, 28% major cove, 55.2% side channel, and 6.5% thalweg (Ridgway and Bettoli 2017; KDFWR 2020). Barkley Reservoir mean weekly discharged ranged from 432 – 1233 cms. Chlorophyll a abundance was not sampled for Barkley Reservoir.

These reservoirs each have their own characteristics, but since a canal connects them near their dams they share some characteristics, such as water elevation; fish can also move freely between each system. Altogether, Kentucky Reservoir and Barkley Reservoir represent unique ecosystems which are quite different than the large rivers that Silver Carp initially invaded.

My study was completed on the lower 67 km of Kentucky Reservoir (from Kentucky Dam to the Highway 79 bridge near Paris, Tennessee). In Barkley Reservoir, my sample area consisted of the lower 50 km between Barkley Dam and Devil's Elbow bay near the Highway 80 bridge (Figure 2-1). More effort was expended on Kentucky Reservoir due to its proximity to the Hancock Biological Station, which is where the boats used for this study were stored or docked.

Field Sampling

Before this study, over 2,000 Silver Carp were implanted with InnovaSea V16 ultrasonic transmitters in waters connected to or including Kentucky Reservoir and Barkley Reservoir by over eight agencies and institutions (i.e., Kentucky Department of Fish and Wildlife Resources (KDFWR), Tennessee Wildlife Resources Agency, Mississippi Department of Wildlife, Fisheries and Parks, U. S. Fish and Wildlife Service, U. S. Geological Survey, Murray State University, Tennessee Technological University, among others). These tags had varying battery life, decibel output, and ping intervals. Different subpopulations of Silver Carp are known to behave differently (T. Spier, pers. comm.). As such, all tagged fish were assigned a residency status based on their tagging location. For example, a fish tagged in Pickwick Reservoir or at the Pickwick tailwaters was classified as "non-resident far". Fish tagged within Kentucky Reservoir and Barkley Reservoir were assigned as "residents" and fish tagged in the tailwaters of Kentucky Reservoir and Barkley Reservoir were called "non-resident near".

Two trials of field testing were performed to determine how precisely tagged Silver Carp could be located via a directional hydrophone. A test tag was attached to a small float tethered to an anchor sunk in a known location. The float held the tag off the substrate as if it were a tagged fish suspended in the water column at a depth of 1-2 meters. Once the test tag was hidden, the researchers, without knowledge of the tag's location, attempted to find the tag with a VEMCO VR100 receiver and boat-mounted VH110 directional hydrophone. The receiver was set to "near" and gain was set to 0 to enhance precision. As the hydrophone drew closer to the tag, the intensity of signal in decibels was recorded at several locations near the test tag. The location of the test tag was considered to be where the receiver read 85-105 dB via the precision settings. The estimate of the tag's location was compared to the actual location and provided insight into how accurately I would be able to locate a tagged fish. The mean distance (± SE) between the estimated and actual tag location based on the two trials was 47.2 ± 21.8 m. These measurements suggested that a signal intensity greater than 85 decibels using the precision settings is necessary to achieve this level of accuracy. Note that this level of accuracy is possible for an immobile tag, but a tagged fish might be startled by the boat; thus, I estimate my ability to locate tagged fish would be between 50 – 100 m of the actual fish location (Figure 2-2).

Beginning in May 2021, an attempt was made to track at least one Silver Carp each week through August 2022. When attempting to locate a 24-hour fish, we picked a direction in that was thought to have tagged Silver Carp from previous tracking run days and started stopping every km in areas theorized to have tagged Silver Carp nearby. Some days we travelled in a north or south direction and searched randomly until locating a tagged Silver Carp. To locate a tagged Silver Carp, the omni-directional hydrophone was deployed and left in the water for at least 2 minutes with the VR100 settings adjusted to "far" and the gain adjusted from 36-42 (search settings). These search settings permitted a detection range of roughly 0.8 km (Webber 2014; T. Spier pers. comm.). If no tags were detected, the boat was moved approximately 1 km, and the process was repeated until a live Silver Carp was found. Next, the directional hydrophone was utilized on the precision settings to obtain a precise location of the fish. If the Silver Carp did not appear to be moving, the existing tracking data from the stationary receivers was referenced to investigate if the fish had not recently moved. If so, the Silver Carp was assumed to have shed the tag or died, and a different carp was located.

If the Silver Carp was alive, I followed that Silver Carp and used the directional hydrophone to locate the fish approximately every hour for 24 hours. I only recorded Silver Carp locations if I could obtain a decibel reading ≥ 80 with the precision settings. Although a dB reading ≥ 85 is ideal, such readings were difficult to obtain when the fish was moving. Tracking the same fish twice was avoided unless more than one month elapsed between tracking dates. During the first year, I normally did not track Silver Carp from 23:00 until 5:00 the following morning. The following year, I tracked the fish for 24 hours per individual. Once a fish had been precisely located within 50 – 100 m, I recorded coordinates, date, time, wind direction, and wind speed. Wind speed was measured with a Pro Anemometer BT-100 held above the head while the boat was anchored. I used a compass to measure wind direction. Daily surface water temperature in °C was obtained from the Hancock Biological Station website (https://www.murraystate.edu/qacd/cos/hbs/hbs.htm) and was used for reservoir temperature. Reservoir daily mean discharge and elevation for each reservoir was obtained from the Tennessee Valley Authority (TVA).

<u>Statistical Analysis</u>

For all Silver Carp locations during a 24-hour period, I determined the distance between successive locations as the shortest distance the fish could swim while remaining in the water (i.e., the “swim distance”, not necessarily the straight line distance). A land/water raster was created in QGIS version 3.22.3 (QGIS development team 2018). I used this raster in R to calculate the swim distance between successive locations and then divided this distance by the time between locations to estimate the swim rate in meters per second. Additionally, a signal intensity map was created to exhibit results from field testing while attempting to locate the test tag.

I used a variety of techniques to investigate factors that might influence movement rates in fish, such as water temperature, sex, flow, and wind. Movement rates were averaged for each fish on each sample date. For the individual Silver Carp that were tracked twice, each Silver Carp’s movement rate was averaged across sample dates so that the Silver Carp could be utilized as the unit of measurement. Statistical analysis was performed using program R and R studio 4.1.2 (R version 4.1.2, RStudio Team 2021). A Kruskal-Wallis test was used to investigate the relationship between sex and movement rate, and residency and movement rates. A paired t-test was used to investigate the relationship between reservoirs and movement rates. A linear regression was used to compare movement rates based on each ’s average weekly discharge and average surface temperature.

Since movement rates of fish can vary over a 24-hour period, I investigated diel movement patterns and considered “Sunrise” to be the period 1 hour before sunrise until 1 hour after sunrise, while “Sunset” was a similar duration around sunset. “Day” and “Night” were the appropriate periods between sunrise and sunset. The R package suncalc (Thieurmel et al. 2019) was used to determine sunrise and sunset for each date. Movement rates were then averaged by fish and by the time of day. A repeated measures ANOVA was completed to determine if the movement rate differed based on the time of day.

I studied the influence of wind on fish location by comparing the positions of the fish to random locations within three different sized buffers. I used the land/water raster in R to measure fetch at 45-degree intervals for each fish location. Then, I used the wind data from each fish location to determine which fetch value represented the actual wind at the time for that location, with a mesh size of 100 m within the fetch map. Finally, I multiplied the proper fetch by the wind speed to calculate the Relative Exposure Index (REI) at each fish location in m^2/s (Rohweder et al. 2008), which measures the wind energy at a location. I buffered each Silver Carp location based on the distance traveled between successive locations of the Silver Carp to determine the area of which each Silver Carp could potentially have swum. These buffers were clipped to remove any area that was on land, and a random point was chosen within each buffer for REI calculation. A paired t-test was used to compare the mean REI of the random point location to the actual REI of each Silver Carp location. These analyses were used to investigate if Silver Carp were selecting for or against areas of the reservoir with higher or lower REI values.

Similar calculations were performed at larger scales to determine if this relationship was scale-dependent. The average speed was calculated for each Silver Carp during each sample, and this average speed was used to calculate the theoretical distance a fish could swim in 24 hours. A buffer of this size was created around each fish location, and the buffer was clipped to remove all non-water area. The REI was calculated at a random location within this buffer to be compared as before. Finally, REI at a random location anywhere within the reservoir was paired with each fish location and also compared. Similar calculations were performed at each scale to compare the average total fetch at random locations to the positions at which a fish was located.

I used the adehabitatHR package in R to calculate Silver Carp daily home range for each 24-hour Silver Carp sample (Calenge 2006), which is an integrative measure of movement used to further analyze the surface area of water preferred. A kernel density raster with the default "href" bandwidth was created for all Silver Carp locations in a sample. Then a daily home range polygon was created from this raster based on an occupancy level of 80%. Each daily home range polygon was then clipped to remove any portions which were not in the water, and the area of each daily home range was determined for the remaining portion of the polygon. I used a Kruskal Wallis test to investigate if the median daily home range size differed among Silver Carp sex, residency, and reservoir. For all analyses, an alpha value of 0.05 was used to determine statistically significant p-values.

RESULTS

I spent 498 hours tracking on Kentucky Reservoir and 183 hours on Barkley Reservoir (Table 2-1). I tracked 24 individual Silver Carp in Kentucky Reservoir and 6 in Barkley Reservoir. Full 24-hour data was limited to 18 individual Silver Carp in Kentucky Reservoir, and partial days were spent on six others. One Silver Carp was tracked twice in Kentucky Reservoir. In Barkley Reservoir, full 24-hour data was limited to 4 individual Silver Carp, and partial days were spent on two others. One Silver Carp was tracked twice in Barkley Reservoir. I tracked Silver Carp at water temperatures ranging from 10 °C – 32 °C. It should be noted that a regional drought occurred during the summer of 2022. During my study, the reservoirs were gradually raised to summer pool (109.4m) starting on April 1 and were held at summer pool from May 1 to July 1. Then they were gradually drawn down to winter pool (107.8m) (TVA 2016).

Movement Rates

Of the 30 Silver Carp, 14 were female, 11 were males, and 5 were of unknown sex. Length and weight were recorded prior to tag implantation; however, since fish grow over time the length and weight of Silver Carp during the years of this study was unknown, and therefore size of fish was not used for analyses. Most Silver Carp tagged were at least 400 mm in total length.

Mean swimming speed was calculated for each fish during each sample. For fish sampled more than once, the mean was calculated for each sample and then averaged across all samples. Mean swimming speeds ranged from 0.02 – 0.32 m/s. A Kruskal-Wallis test suggested median swimming speed across all fish was not significantly different among sexes (Chi-squared = 1.3, df = 2, p = 0.5) (Figure 2-3). Swimming speed was also not significantly different among residencies (Chi-squared = 2.6, df = 2, p = 0.2) (Figure 2-4). Similarly, a t-test suggested mean swimming speed was not different among reservoirs ($t_{11.3} = 0.9$, $p = 0.3$) (Figure 2-5). An ANOVA with all three independent variables (sex, residency, reservoir) still did not show any relationship with mean swimming speed ($F_{5,24} = 1.4$, $p = 0.2$).

Linear regression showed that discharge did not have a significant influence on mean swimming speed in Kentucky Reservoir ($F_{1,22} = 0.08$, $p = 0.7$, $R^2 = 0.003$) (Figure 2-6), or Barkley Reservoir ($F_{1,4} = 2.9$, $p = 0.1$, $R^2 = 0.4$) (Figure 2-6). Although a canal connects these impoundments, discharge varies between them because they have different watersheds and different morphologies. However, their temperatures are tightly linked. Linear regression showed that Silver Carp movement rates increased with water temperature when data from both reservoirs were combined ($F_{1,28}$ = 6.8, p = 0.01, R^2 = 0.2) (Figure 2-7). An individual Silver Carp made a 27 km trek upstream in a 24-hour-period and was considered an outlier. This relationship was retained after removing one outlier ($F_{1,27}$ = 7.9, p = 0.008, R^2 = 0.23) (Figure 2-8).

A repeated-measures ANOVA suggested mean swimming speed was not different among time of day ($F_{3,39}$ = 1.9, p = 0.1, N = 14) (Figure 2-9). The repeated measures analysis requires a balanced design, but not all fish were located within every time period. Therefore, I could only use 14 of our 22 Silver Carp for the time period analysis.

A linear regression suggested mean swimming speed was not influenced by wind speed in Kentucky Reservoir ($F_{1,21}$ = 3.8, p = 0.06, N = 23) (Figure 2-10). However, mean swimming speed increased significantly with wind speed in Barkley Reservoir ($F_{1,4}$ = 12.5, p = 0.02, N = 6) (Figure 2-10). A paired t-test suggested that the wind energy (as measured by REI) was not different between Silver Carp locations and a local random location in Kentucky Reservoir (t_{16} = -0.5, p = 0.6) (Figure 2-11). A paired t-test suggested that the wind energy (as measured by REI) was not different between Silver Carp locations and a local random location in Barkley Reservoir (t_3 = -1.3, p = 0.3) (Figure 2-11). Looking at a larger scale, a paired t-test suggested that the wind energy (as measured by REI) was not different between Silver Carp locations and a nearby random location in Kentucky Reservoir (t_{16} = -0.5, p = 0.6) (Figure 2-12) and in Barkley Reservoir (t_3 = -1.3, p = 0.3) (Figure 2-12). A paired t-test suggested that the wind energy (as measured by REI) was not different between Silver Carp locations and an entire reservoir random location in Kentucky Reservoir (t_{16} = -0.5, p = 0.6) (Figure 2-13) and in Barkley Reservoir (t_3 = -1.3, p = 0.3) (Figure 2-13).

Although wind energy did not appear to influence Silver Carp location, perhaps the Silver Carp were choosing locations based on the overall windiness of an area. For example, perhaps

Silver Carp prefer areas of the reservoir that receive more wind more frequently, such as shoreline or coves that are on the receiving end of the predominate winds. A paired t-test suggested that the mean fetch was not different between Silver Carp locations and a local random location in Kentucky Reservoir ($t_{16} = -0.5$, $p = 0.6$) (Figure 2-14) and in Barkley Reservoir ($t_3 = -1.3$, $p = 0.3$) (Figure 2-14). Similarly, the mean fetch was not different between Silver Carp locations and a nearby random location in Kentucky Reservoir ($t_{16} = -0.5$, $p = 0.6$) (Figure 2-15) and in Barkley Reservoir ($t_3 = -1.3$, $p = 0.3$) (Figure 2-15). Finally, a paired t-test suggested that the mean fetch was not different between Silver Carp locations and an entire reservoir random location in Kentucky Reservoir ($t_{16} = -0.5$, $p = 0.6$) (Figure 2-16) and in Barkley Reservoir ($t_3 = -1.3$, $p = 0.3$) (Figure 2-16).

One Silver Carp contained a tag that also recorded its depth. This fish was tracked on May 10th-11th, 2022, in Little Bear cove on Kentucky Reservoir. The depth range in Little Bear cove is 0 – 12 m, and its average depth is 2.12 m. This carp spent most of the day in the top 1 m of water (Figure 2-17).

Silver Carp daily home range ranges ranged from 4 – 9019 ha with an average size of 832 ha. A Kruskal-Wallis test suggested median daily home range size was not significantly different between sexes (Chi-squared = 1.1, df = 2, p = 0.5) (Figure 2-18), or residency (Chi-squared = 3.1, df = 2, p = 0.2) (Figure 2-19). A Welch's t test suggested mean daily home range size was not significantly different between reservoirs ($t_{8.4} = 0.4$, $p = 0.6$) (Figure 2-20). When the daily home range was compared between sex, residency, and reservoir, no significant differences were detected (Figure 2-18, 2-19, and 2-20).

DISCUSSION

Silver Carp have continued to spread and are a growing problem in the U.S. Multiple studies have confirmed invasive species effects have caused drastic reductions in native fish populations (Irons et al. 2007; Lebeda et al. 2022). Most of the research within the U. S. has been in large rivers (Peters et al. 2006; Irons et al. 2007; DeGrandchamp et al. 2008; Coulter et al. 2016; Altenritter et al. 2022), but these fish have also entered reservoir systems with different environmental conditions. The VR2W network in Kentucky Reservoir has documented unique largescale migrations downstream in spring (T. Spier, pers. comm.), but we lack information on the fine scale routine movements of individuals. Some 24-hour tracking has been conducted on bigheaded carp (Coulter et al. 2016), but this tracking was not over several seasons or as intensive. To my knowledge, this was the first research on diel movement patterns of Silver Carp within reservoirs in the U. S. DeGrandchamp (2006) confirmed Silver Carp within the Illinois River had an average swim rate of 10.6 km/d. Coulter et al. (2016) confirmed Silver Carp in the Wabash River, Indiana had average swim rates of 4.4 km/d. My Silver Carp within these reservoirs had average swim rates of 8.3 km/d.

This study was the first to collect diel tracking data on 30 different Silver Carp within a reservoir. Similar to the results of the large-scale movement study on the same populations in Kentucky Reservoir (T. Spier, pers. comm.) I found no influence of sex on swimming rate (Figure 2-3). This was contrary to Coulter et al. (2016), who found that female Silver Carp had a lower movement probability compared to males. They hypothesized their movement probability was linked to sex-biased dispersal or physiological processes, such as energy conservation for gonadal development. Differences in sex dispersal distances have been documented for other invasive fish species (Marentette et al. 2011; Coulter et al. 2016). My analysis did not suggest differences in swim rates between sex. However, since nearly all Silver Carp in this study were adults and they are a schooling species, it is unclear if this is occurring within these reservoirs.

Previously, the VR2W network documented that residency status influences activity within these reservoirs; for broadscale movements, the nonresident far Silver Carp are more active than the residents (T. Spier, pers. comm.). My study also showed that the nonresident-far Silver Carp had the highest mean routine movement swimming speed, but these data were not significantly different (Figure 2-4), perhaps a bigger sample size is required.

No differences were documented in the swimming rate between the reservoirs (Figure 2-5). While each reservoir has a unique discharge, I also found no relationship between daily discharge rates and swimming speed in either reservoir (Figure 2-6), which were expected as routine movements are influenced by flow (Taylor and Cooke 2012; Coulter et al. 2016). This is contrary to large-scale movements within these reservoirs, which have been related to changes in discharge. For example, activity can increase when the river stage is ascending or descending (T. Spier, pers. comm.). Seasonal fluctuation in the hydrograph influences river fish movements up and down the river (Manion 1977; Reynolds 1983; Lucas and Batley 1996; Coulter et al. 2016). DeGrandchamp et al. (2008) have documented adult bigheaded carp moving long distances during high-flow periods.

Water temperature is tightly linked between the reservoirs, so I combined data from both reservoirs for analyzing the effect of temperature on activity. Mean daily activity increased significantly with water temperature (Figure 2-7 and 2-8). An increase in temperature is positively correlated with an increase in movement rates of bigheaded carp (Coulter et al. 2016). My results are consistent with other studies suggesting that increasing water temperatures can increase other fish movements (Beamish 1970). At water temperatures below 15°C, Silver Carp appetite is reduced, and below 8-10°C, feeding nearly ceases (FAO 1980; Tripathi 1989; Kolar et al. 2005), which in turn could influence movement. I anticipated Silver Carp swim rates would increase with warming water temperatures above 15 – 16 °C due to what has been previously observed from the VR2W data (T. Spier, pers. comm.)

I suspect from my movement rate by time period analysis, it is possible that activity level may change throughout the day. These data suggest an increase in activity towards sundown, but not at a level of statistical significance (Figure 2-9). Ridgeway et al. (2020) documented that CPUE for Silver Carp increased at night, and I found the greatest swimming speed to be around sunset. Perhaps Silver Carp at the young of the year stage feel more comfortable moving around during darker time periods which enables them to avoid predation, and these character traits have been passed on and retained into adulthood even when no natural predators are present.

An animal's location is often closely related to the availability of food, which for these fish is phytoplankton and zooplankton. Since, phytoplankton biomass and composition within a shallow productive reservoir can be influenced by wind (Carrick et al. 1993), I tested whether wind would be useful for predicting the activity level of Silver Carp. While wind speed had no effect on activity level in Kentucky Reservoir, activity level increased with wind speed on Barkley Reservoir (Figure 2-10). Perhaps this is due to Barkley Reservoir being a relatively smaller shallower reservoir than Kentucky Reservoir, or this could be an artifact of a smaller sample size within Barkley Reservoir. Further analysis will be required to determine if wind is important to Silver Carp activity in Barkley Reservoir. For example, I did not analyze if fish were moving with or against the wind.

It is more likely that wind influences the general location of fish, not their activity level, as wind concentrates plankton in areas creating high food density hot spots. I compared REI at each fish location to a random location. The smallest scale I studied used random local locations (within a few hundred meters of each fish location), the middle scale used nearby random locations (within a few km of each fish location), and the largest scale used random locations from the entire reservoir. However, the wind energy at each fish location was not different from the wind energy at random locations, no matter what the scale (Figure 2-11, 2-12, and 2-13).

Although REI is a useful index of wind energy, it may not be appropriate because it is based on wind conditions while tracking the fish, but the fish might have chosen a particular location under different wind conditions. Instead, do fish generally use windier areas of the reservoir? To analyze general “windiness”, I used total fetch, which uses fetch in all directions, not just the direction of wind on the sample date. However, the total fetch of fish locations was not significantly different from random points, no matter the scale (Figure 2-14, 2-15, and 2-16).

Other tracking studies often use locations to estimate home range size (Kurz and Marchinton 1972; Bryars et al. 2012). To estimate home range, it is more appropriate to collect location data over a longer time than just 24 hours, but the daily home range can be used to provide an estimate of the area size needed for daily activity. I used the kernel density technique to estimate the daily home range size for each of my 22 Silver Carp. All Silver Carp seem to have the same general requirements for their daily activities with the average daily home range size being 832 ha. These reservoirs consist of heterogenous morphology. Throughout my sampling areas, Silver Carp have access to all different macrohabitat types in these reservoirs. So no significant differences are not surprising considering can get out of wind in coves, find deeper water, access ledges, all within the average daily home range size.

Although no obvious patterns were detected within my analysis, it may be due to a small sample size. Collecting diel activity data requires locating individual fish several times per day, is time consuming, and limits the number of fish that can be included in the analyzes. A study of this nature will likely not reveal any patterns until the fish are observed for several seasons.

Some factors which I studied show promise for revealing patterns in Silver Carp activity. For example, water temperature seemed to influence carp activity. However, surface water temperature during the spring and fall varies between wind protected coves and the thalweg (Pers. obs.), so mapping local surface temperatures and comparing those temperatures to fish locations may reveal patterns. Much anecdotal evidence suggests that these fish become more active at night (Ridgway et al. 2020), and I feel that an increased sample size will likely reveal a statistically significant effect of time of day on activity. Daily home range estimates can be improved with methods that acknowledge the shoreline barrier; better home range estimates can then be compared among more factors, such as temperature and season.

Similarly, to Coulter et al. 2016, my study confirmed an increase in temperature is correlated with an increase in movement rates. Although some species movement rates vary by sex (Hanson et al. 2007), this was not evident in my study. Nakayama et al. 2018 confirmed wind to influence movement rates of Eurasian Perch, within Barkley Reservoir, this was evident, but not within Kentucky Reservoir. Weekly discharge did not suggest an increase in movement rate, contrary to DeGrandchamp et al. 2008 and Calkins et al. 2012. The diel activity of Silver Carp is important to understand to properly manage, and perhaps eradicate, this invasive species. For example, the factors which influence carp movement can be exploited by commercial fishers to enhance their harvest. Silver Carp most likely do not swim at random, and future studies which build upon my research should be able to help us determine which factors are most important to this species' behavior.

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Tables and Figures

Table 2-1. Total 24-hour tracking effort by season and reservoir.

		Days tracked	Total hours tracked
Kentucky	Combined	25	498
	Spring	3	59
	Summer	18	358
	Fall	4	72
Barkley	Combined	9	183
	Spring	1	25
	Summer	5	105
	Fall	3	53

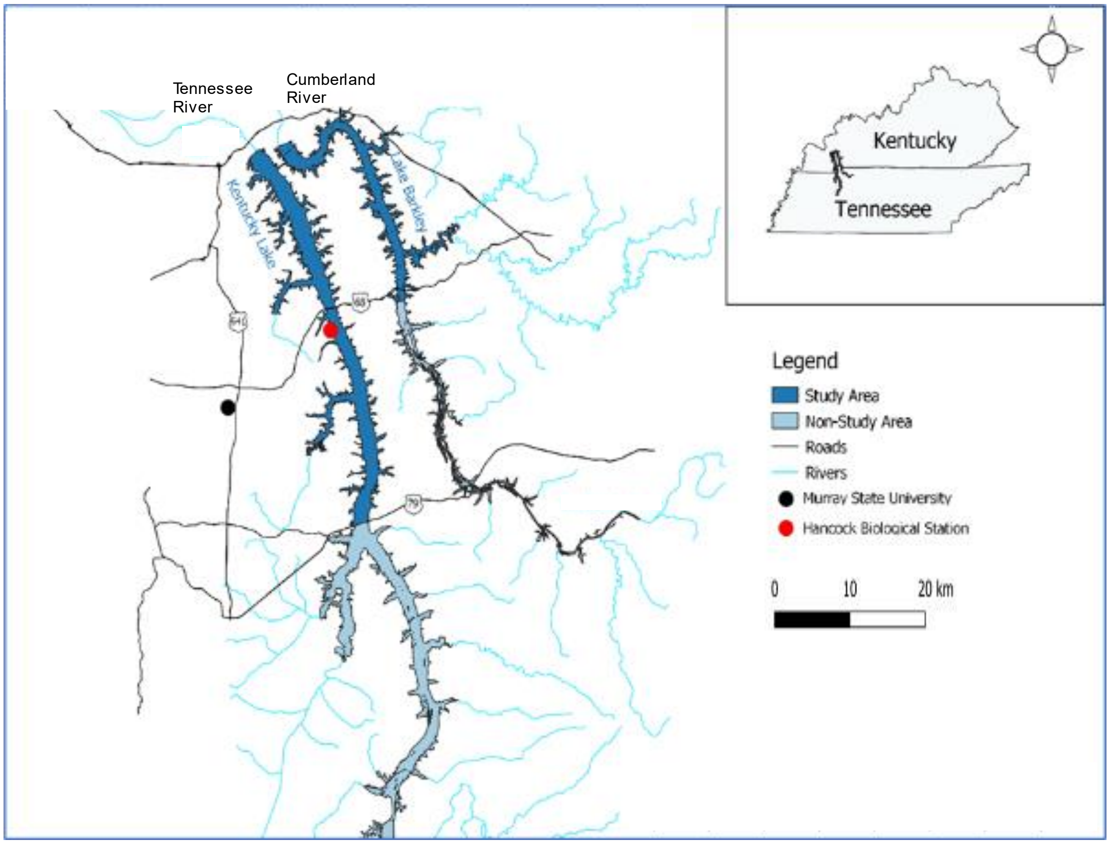


Figure 1-1. Map of Kentucky Reservoir and Barkley Reservoir. The darker blue represents study areas within these reservoirs.

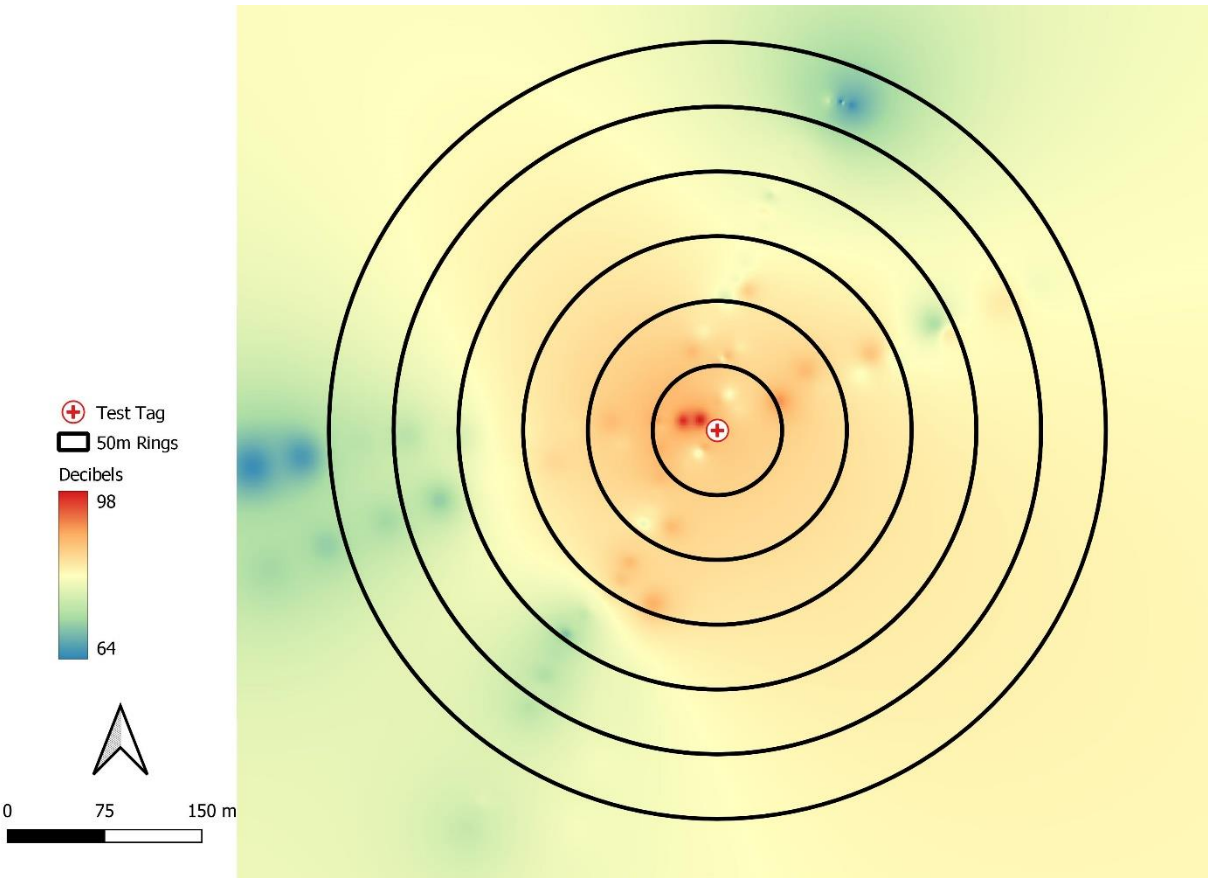


Figure 1-2. Signal intensity (decibels) compared to distance from the test tag. Rings are plotted at 50 m intervals.

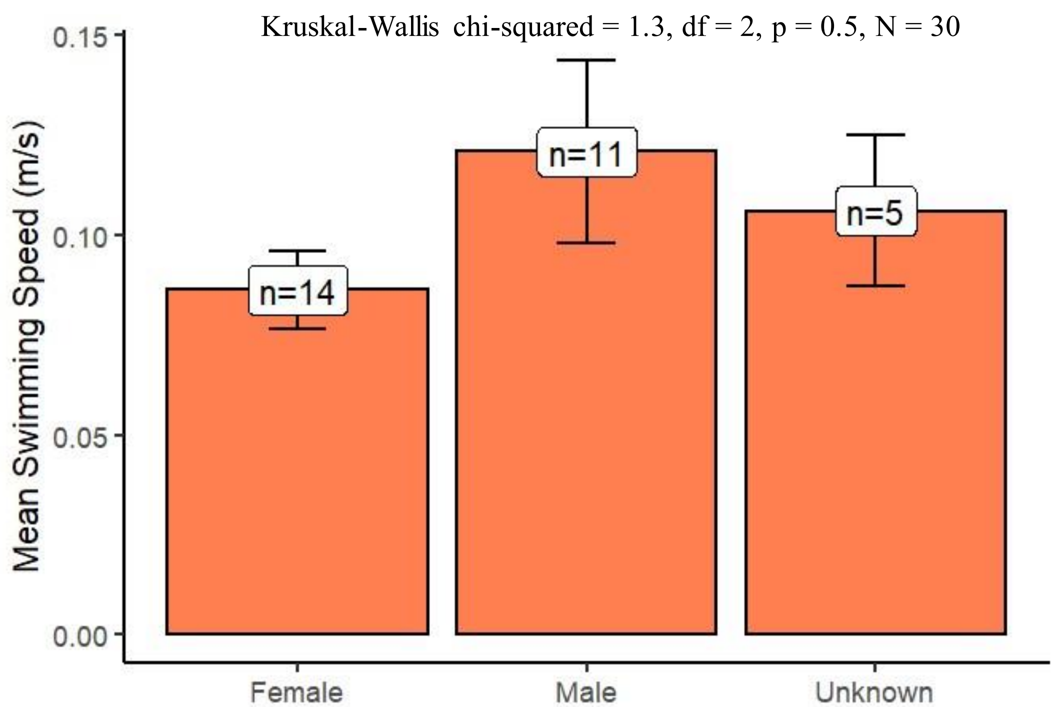


Figure 1-3. Mean Silver Carp swimming speed (± SE) among female (n = 14), male (n = 11), and unknown sex (n= 5) within Kentucky Reservoir and Barkley Reservoir. A Kruskal-Wallis test suggested that swimming speed was not significantly different among sex.

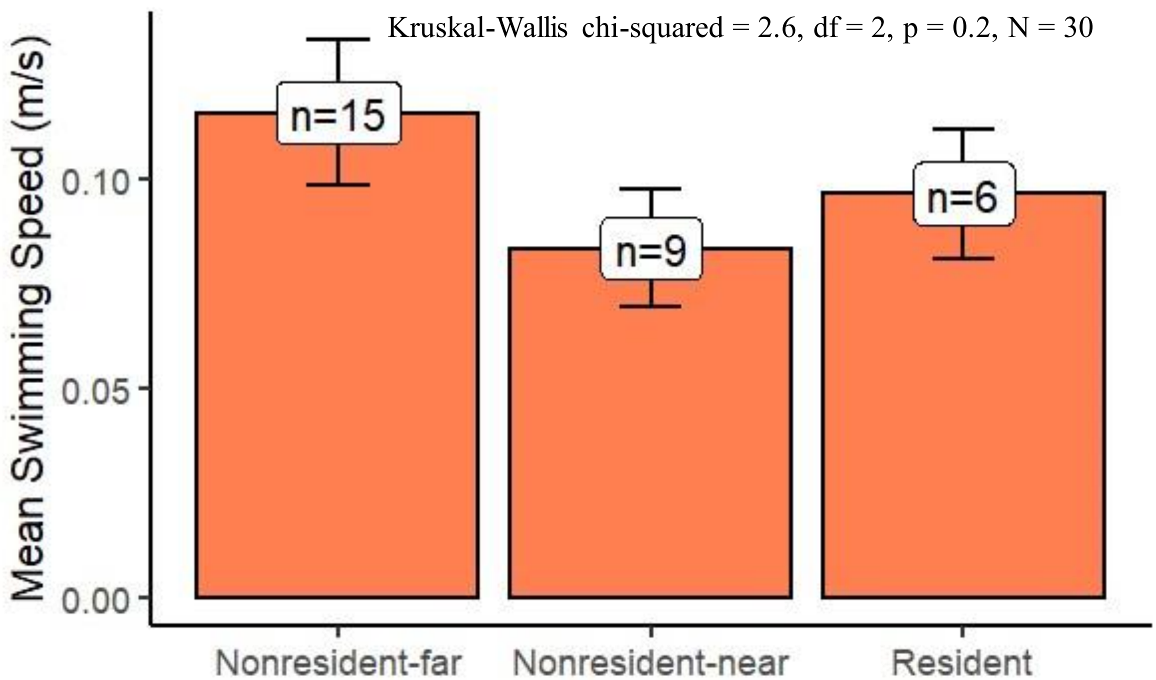


Figure 1-4. Mean Silver Carp swimming speed (± SE) among residency status within Kentucky Reservoir and Barkley Reservoir. A Kruskal-Wallis test suggested that swimming speed was not significantly different among residencies. Nonresident-far fish were tagged at Reservoir Pickwick tailwaters or in Pickwick Reservoir. Nonresident-near fish were tagged below either Kentucky Reservoir or Barkley Reservoir tailwaters, and resident fish were tagged in Barkley Reservoir or Kentucky Reservoir.

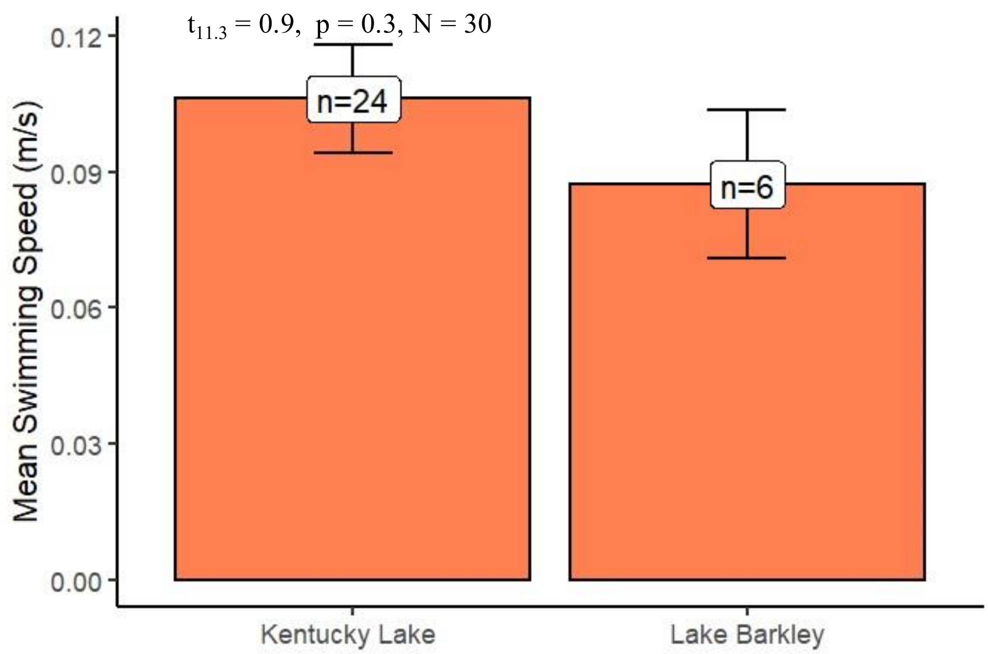
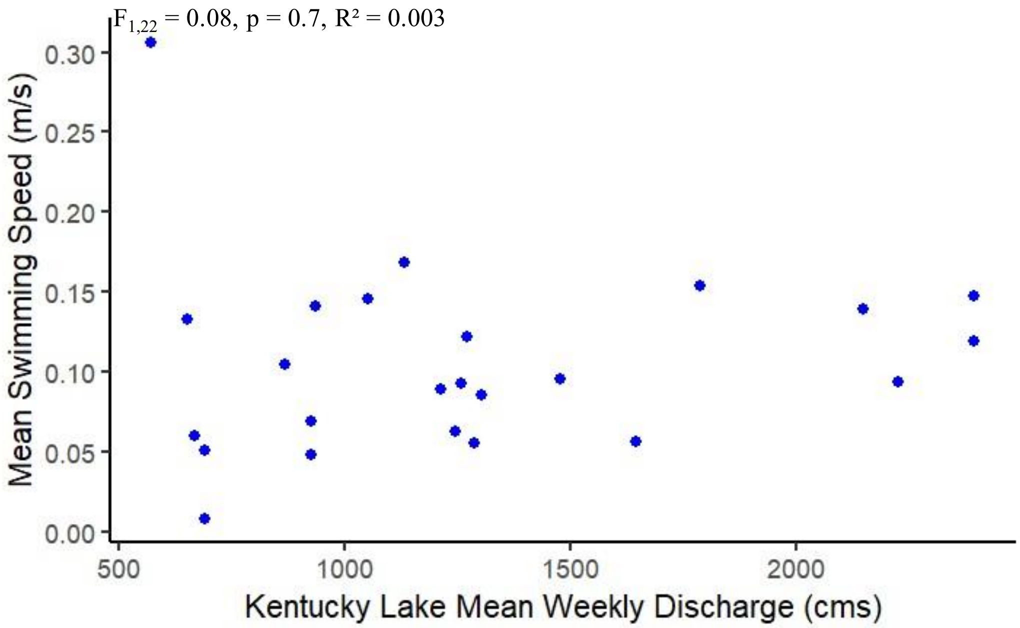


Figure 1-5. Mean Silver Carp swimming speed (± SE) between Kentucky Reservoir and Barkley Reservoir. A Welch's t-test suggested that swimming speed was not significantly different between reservoirs.



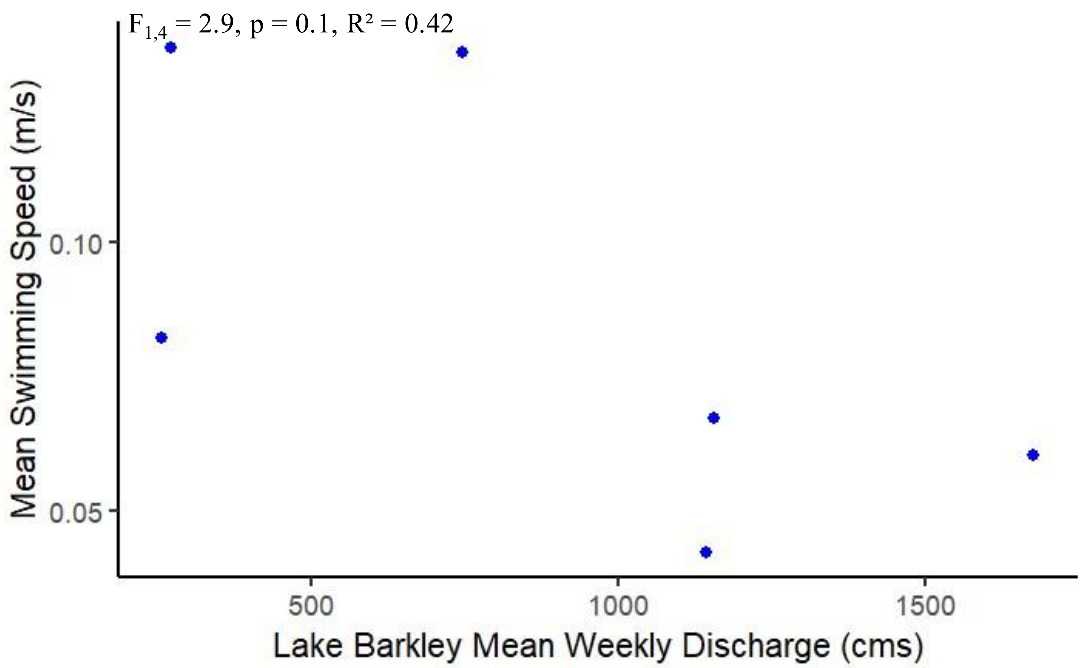


Figure 1-6. Scatterplot comparing mean swimming speed of Silver Carp to weekly discharge within Kentucky Reservoir and Barkley Reservoir. A linear regression suggested that swimming speed was not influenced by discharge for either reservoir.

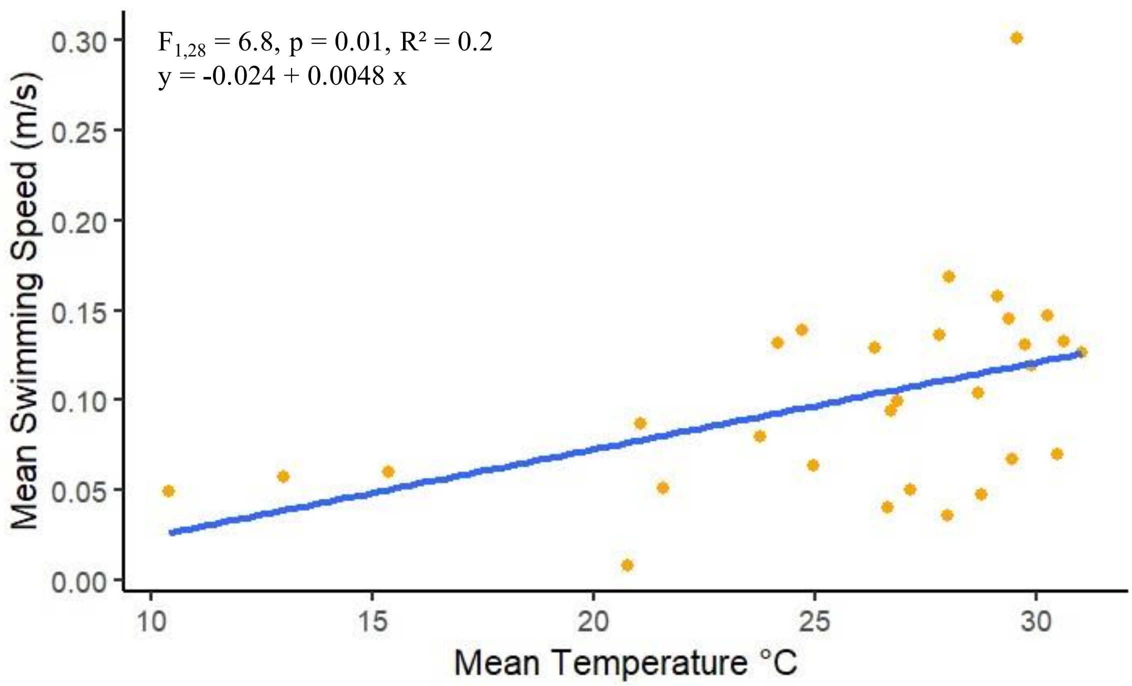


Figure 1-7. Scatterplot comparing swim rates of Silver Carp to surface temperature within both reservoirs. A linear regression suggested that temperature had a significant, positive effect on swim rates.

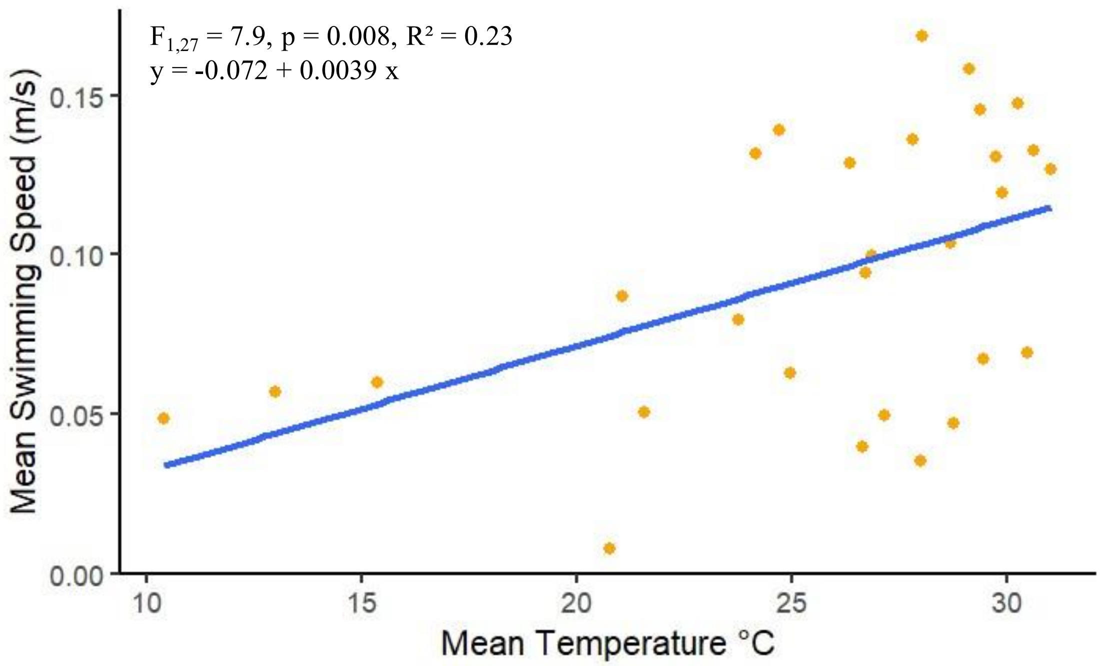


Figure 1-8. Scatterplot comparing swim rates of Silver Carp to surface temperature within both reservoirs. A linear regression suggested that temperature had a significant, positive effect on swim rates. (Outlier removed)

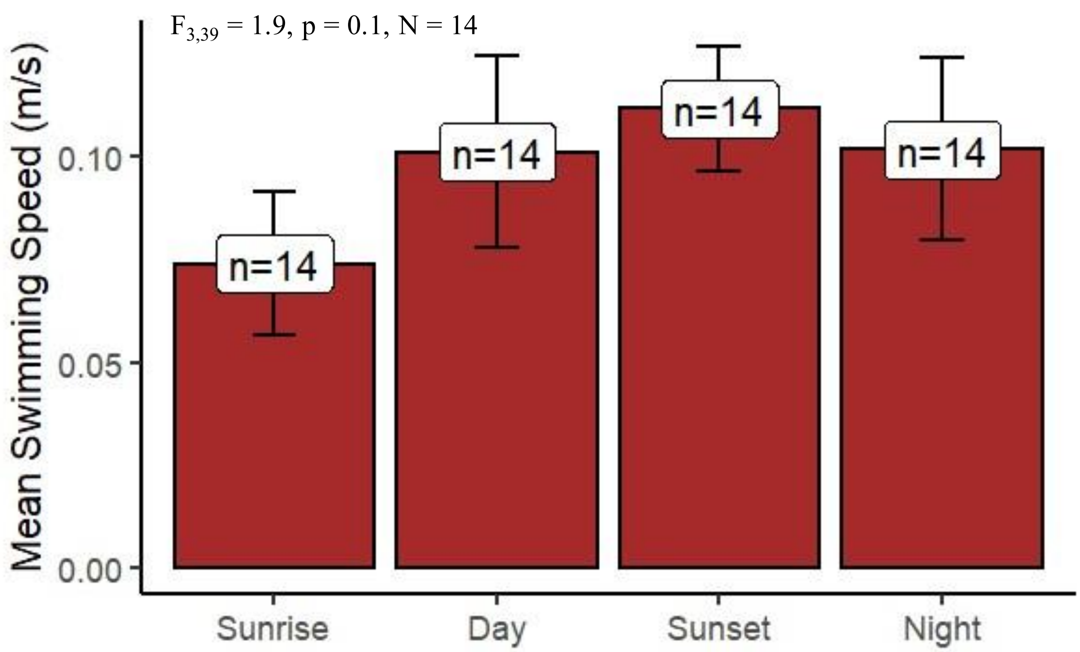
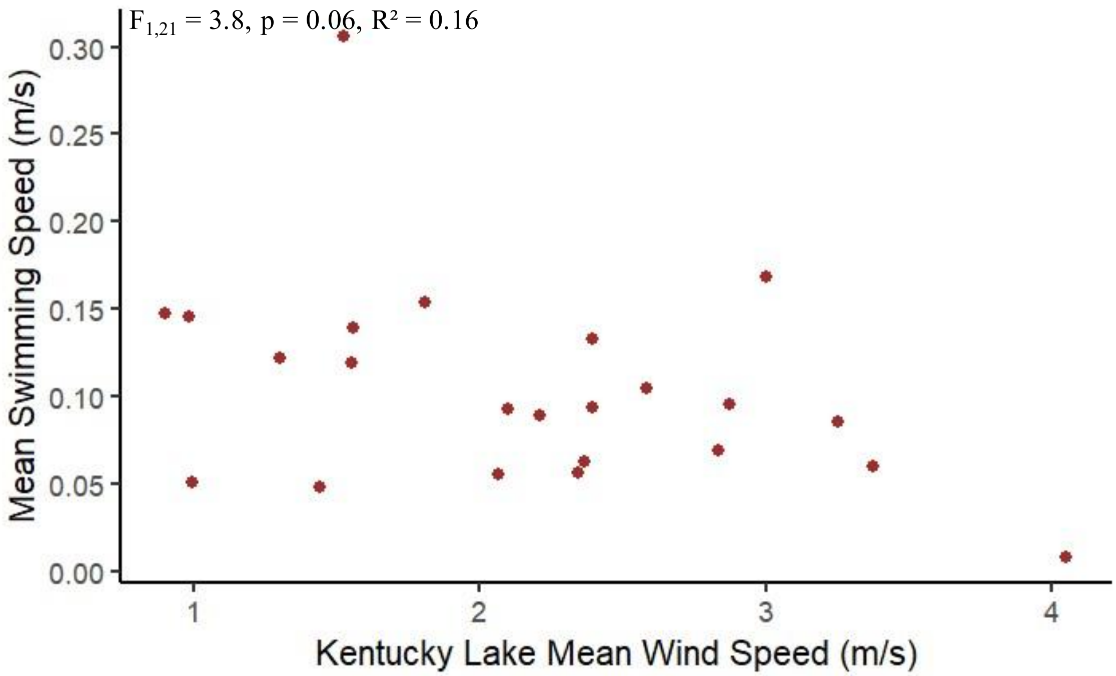


Figure 1-9. Mean (±SE) Silver Carp swim rate throughout the day. Sunrise and sunset are the period 1 hour on either side of sunrise or sunset. A repeated-measures ANOVA suggested that swimming speed was not significantly different among time periods.



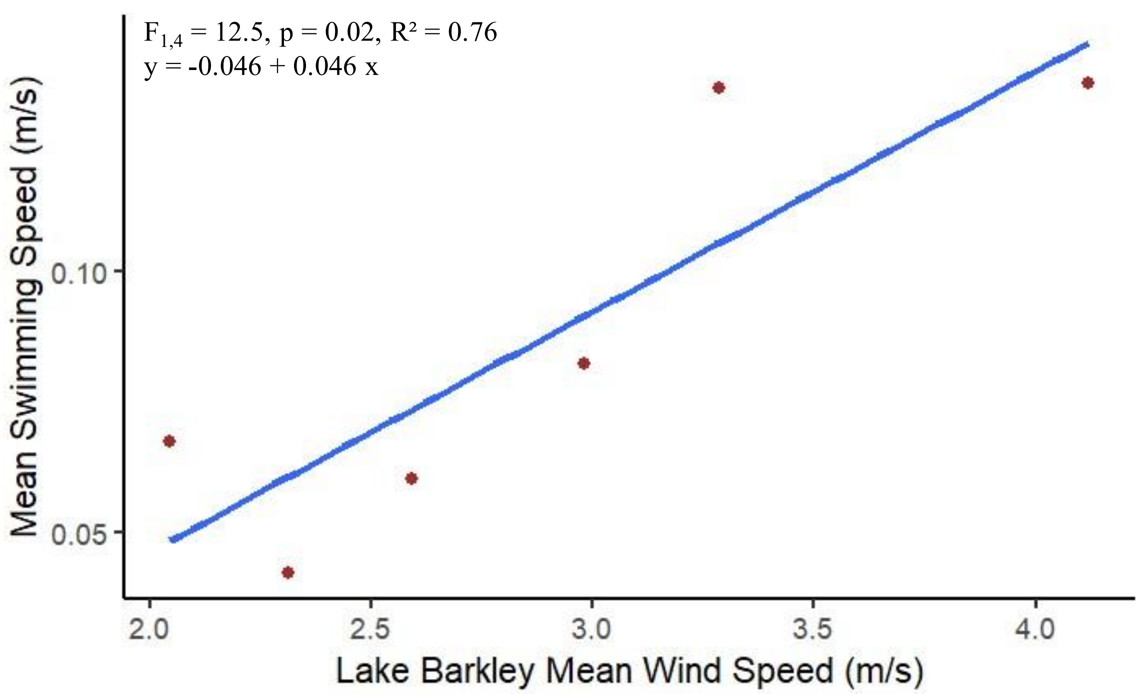


Figure 1-10. Scatterplot comparing swim rates of Silver Carp within Kentucky Reservoir and Barkley Reservoir. A linear regression suggested that wind did not have an effect on swim rates in Kentucky Reservoir, but wind did have an effect on swim rates in Barkley Reservoir.

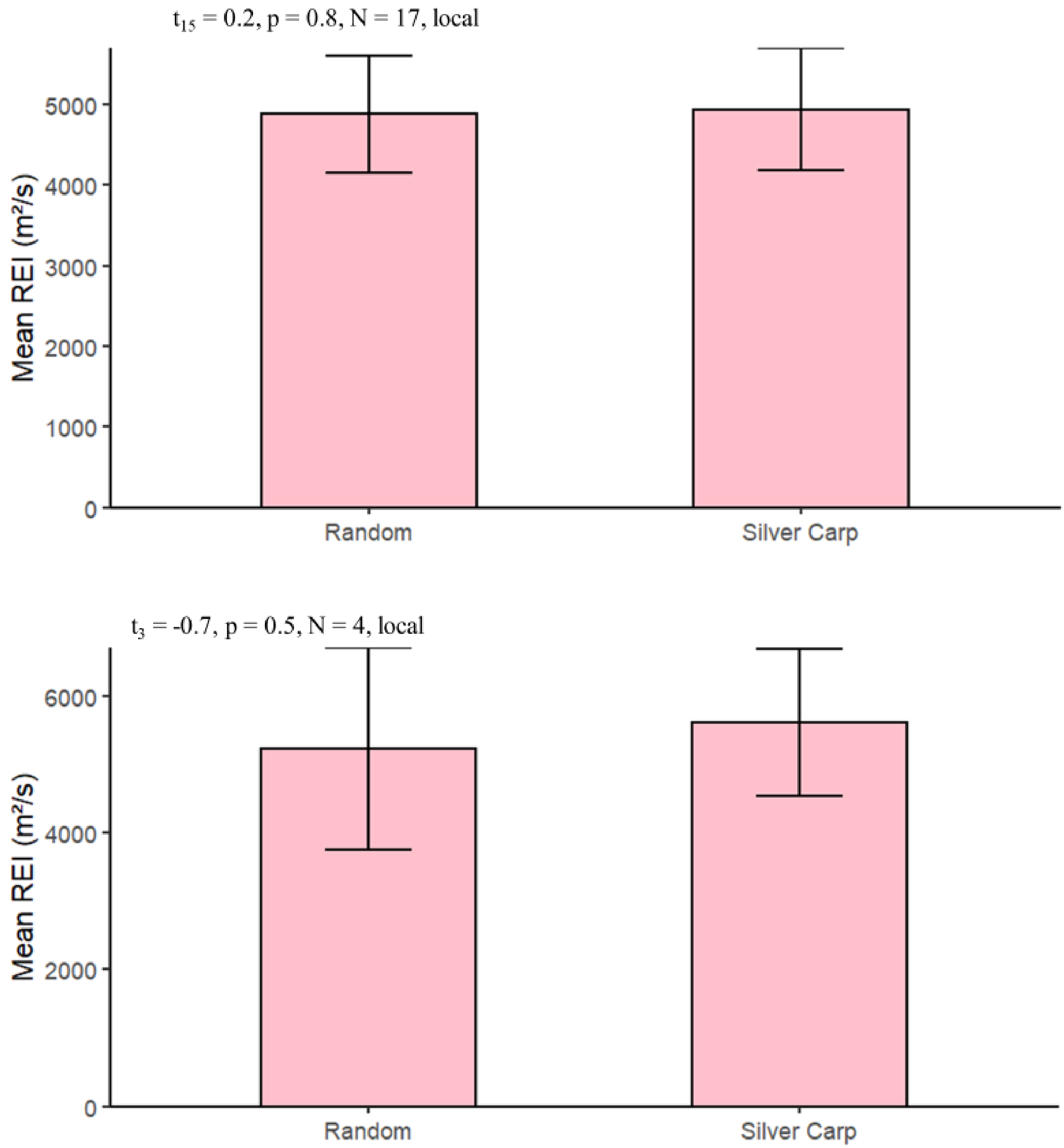


Figure 1-11. Mean (±SE) relative exposure index (REI) for local random locations and Silver Carp locations in Kentucky Reservoir (top) and Barkley Reservoir (bottom). A paired t-test suggested that mean REI was not significantly different between groups for either reservoir.

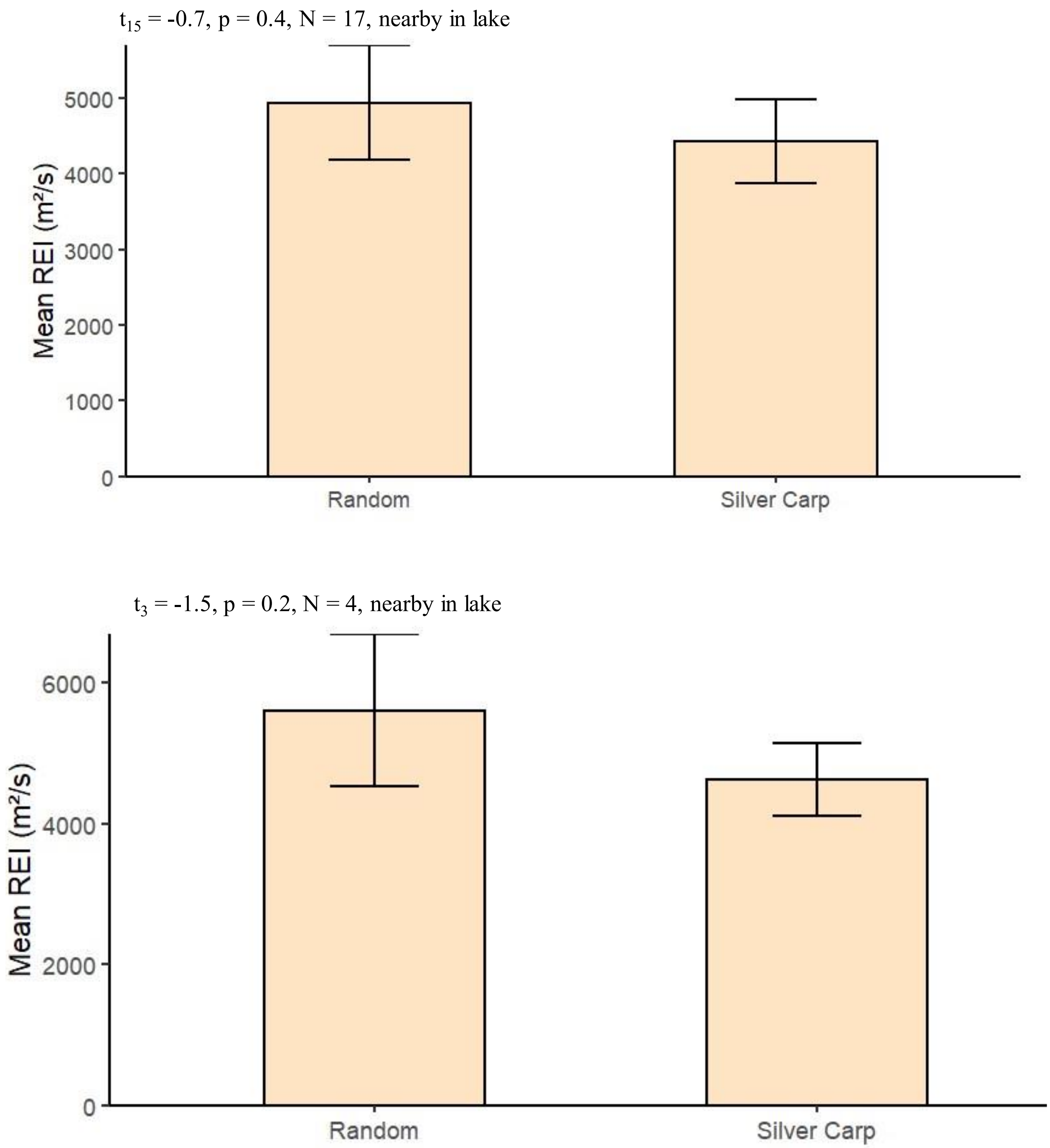


Figure 1-12. Mean (±SE) relative exposure index (REI) for nearby random locations and Silver Carp locations in Kentucky Reservoir (top) and Barkley Reservoir (bottom). A paired t-test suggested that mean REI was not significantly different between groups for either reservoir.

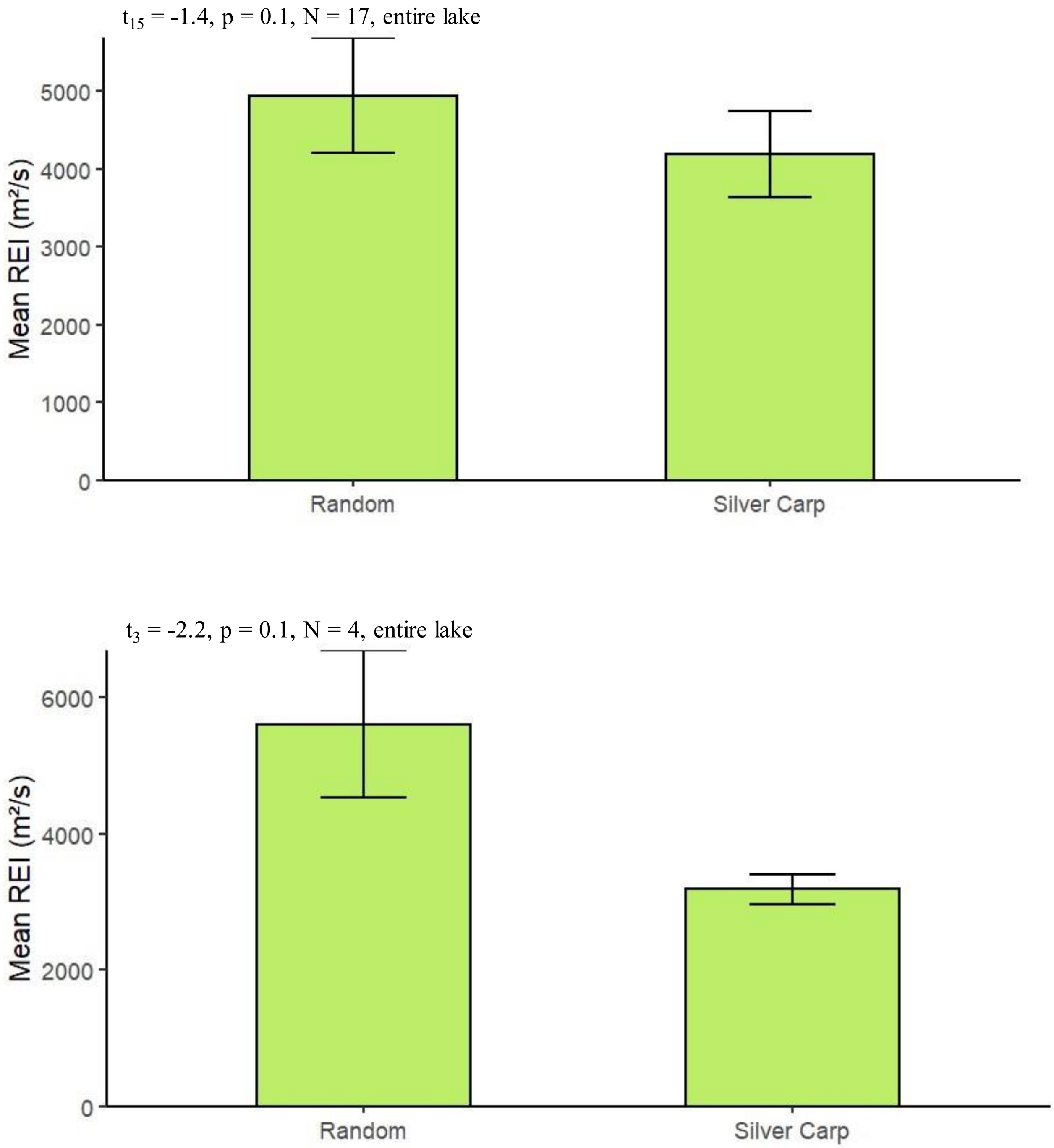
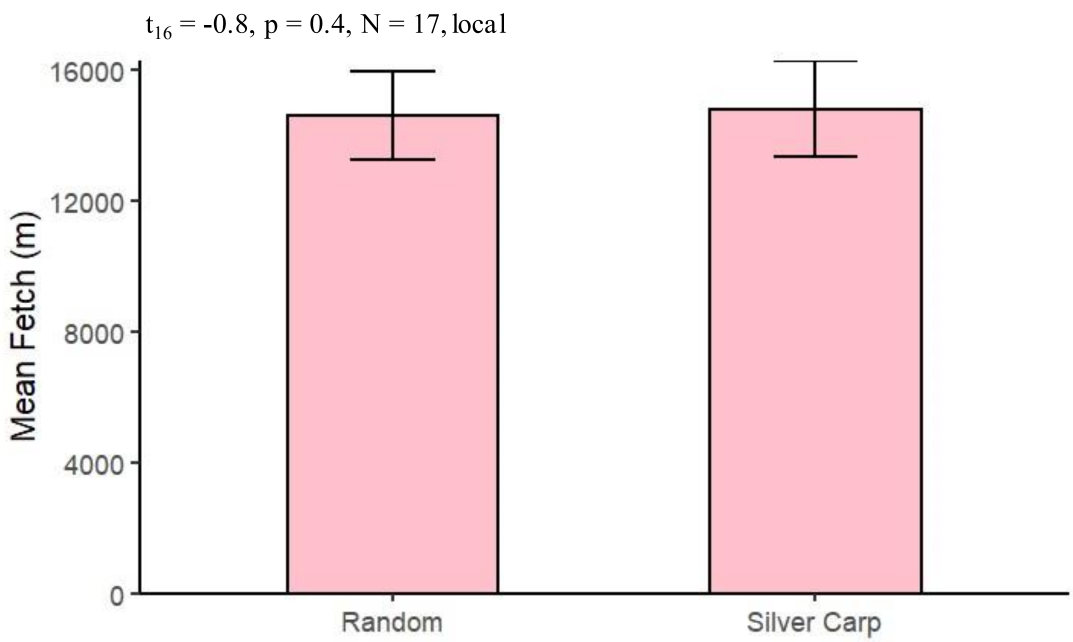


Figure 1-13. Mean (±SE) relative exposure index (REI) for entire reservoir random locations and Silver Carp locations in Kentucky Reservoir (top) and Barkley Reservoir (bottom). A paired t-test suggested that mean REI was not significantly different between groups for either reservoir.



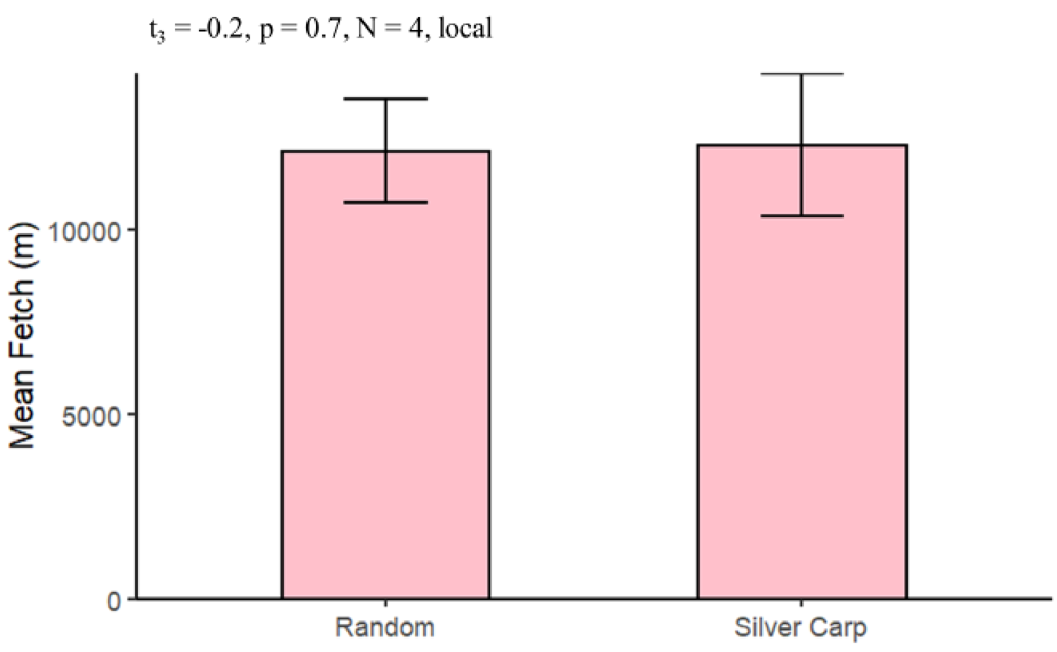
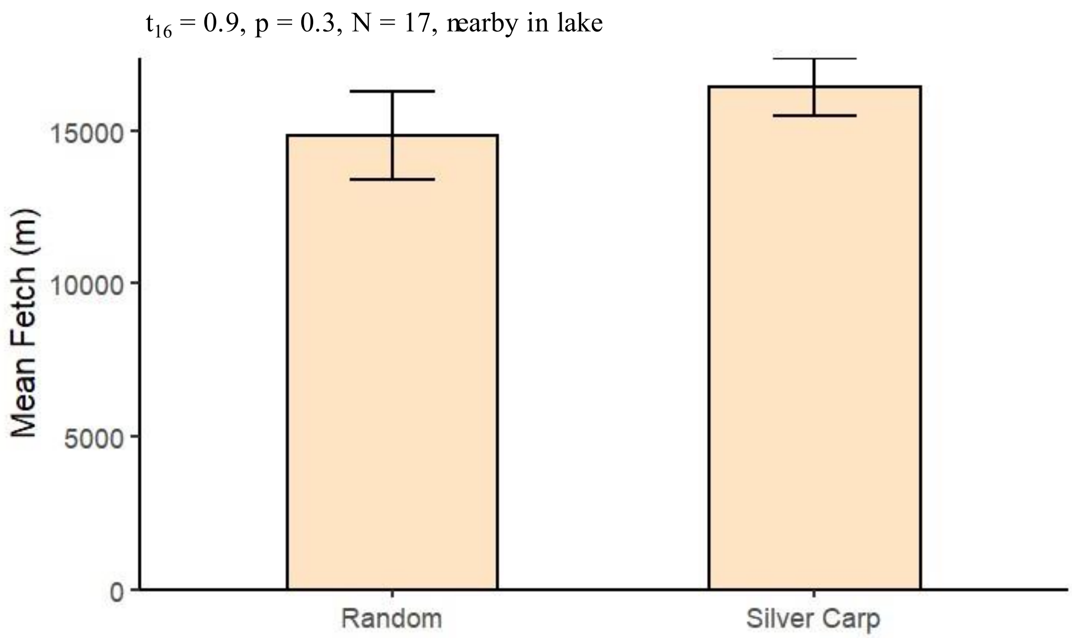


Figure 1-14. Mean (±SE) fetch for local random locations and Silver Carp locations in Kentucky Reservoir (top) and Barkley Reservoir (bottom). A paired t-test suggested that mean fetch was not significantly different between groups for either reservoir.



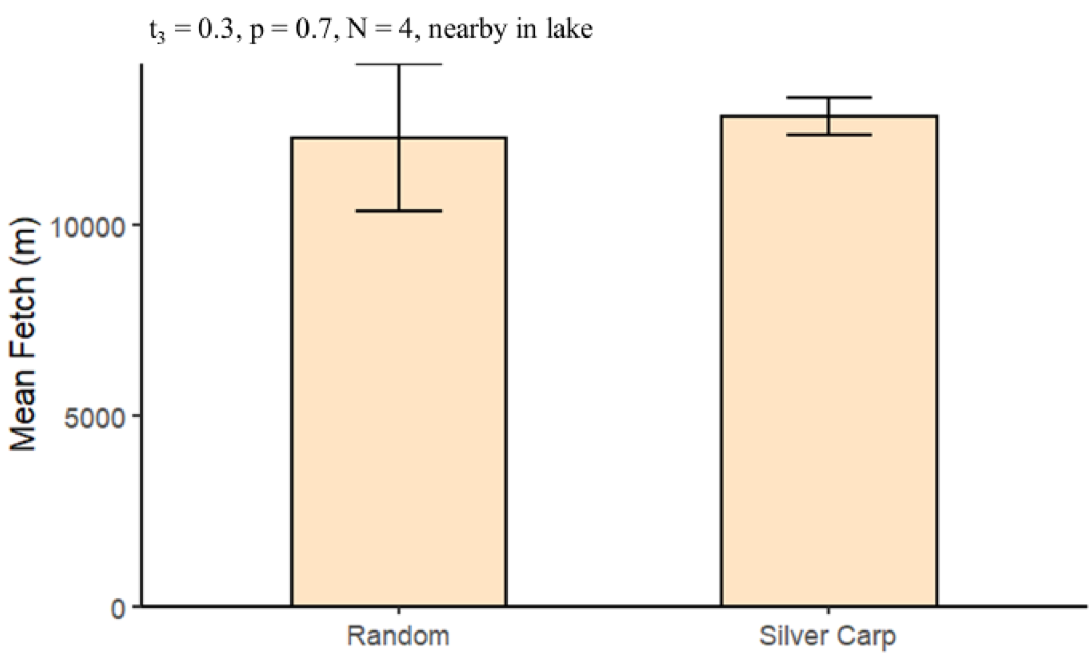


Figure 1-15. Mean (±SE) fetch for nearby random locations and Silver Carp locations in Kentucky Reservoir (top) and Barkley Reservoir (bottom). A paired t-test suggested that mean fetch was not significantly different between groups for either reservoir.

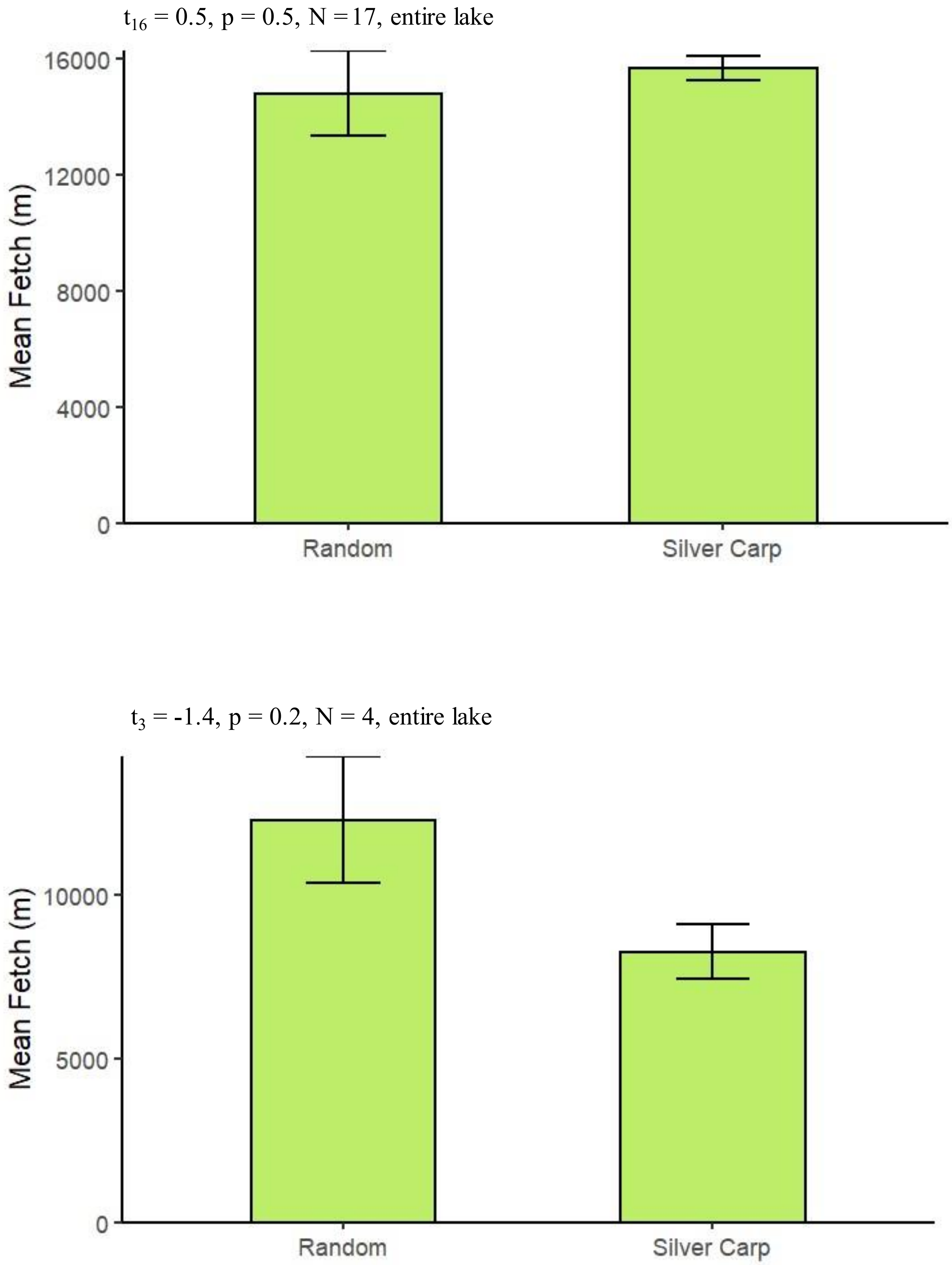


Figure 1-16. Mean (±SE) fetch for entire reservoir random locations and Silver Carp locations in Kentucky Reservoir (top) and Barkley Reservoir (bottom). A paired t-test suggested that mean fetch was not significantly different between groups for either reservoir.

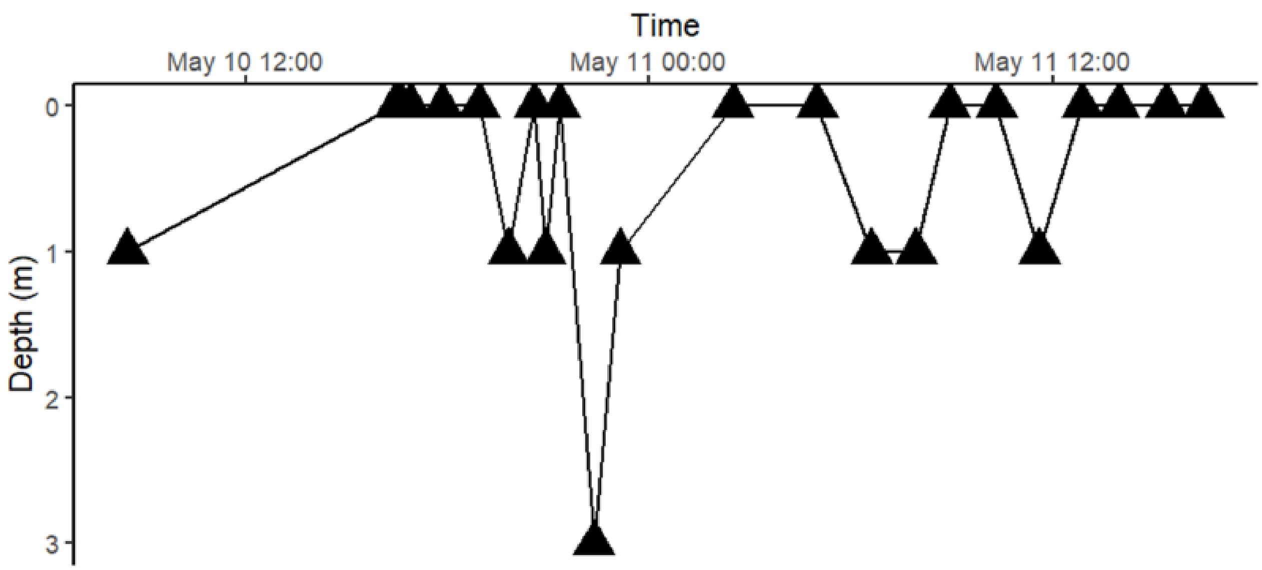


Figure 1-17. Depths utilized over a 24-hour period by a single Silver Carp in Little Bear cove on Kentucky Reservoir.

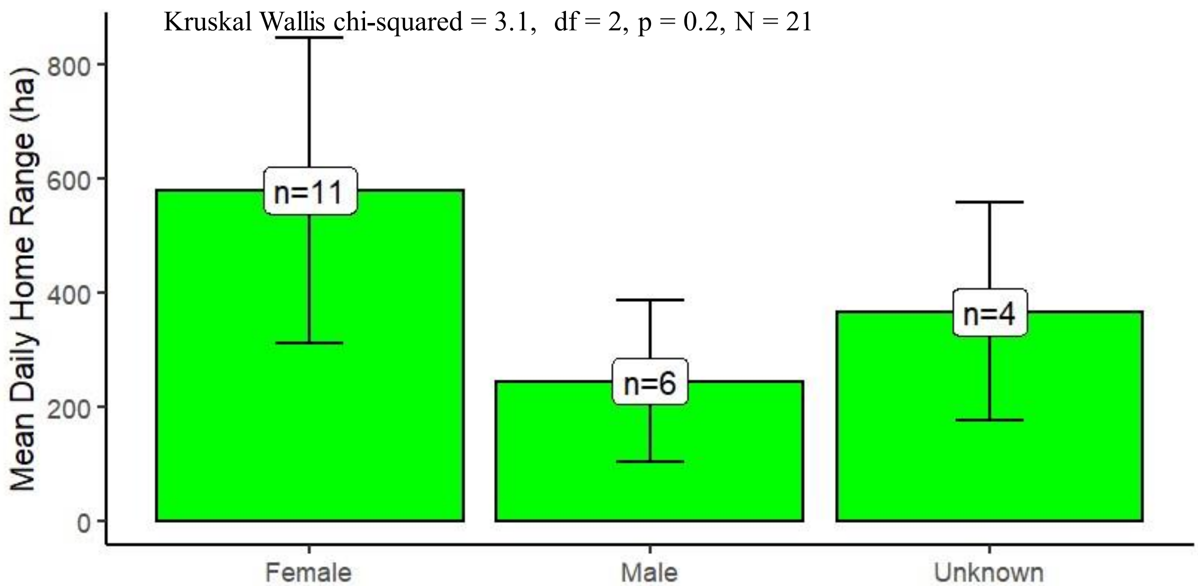


Figure 1-18. Mean Silver Carp daily home range (± SE) among sex. A Kruskal-Wallis test suggested that daily home range size was not significantly different among sexes.

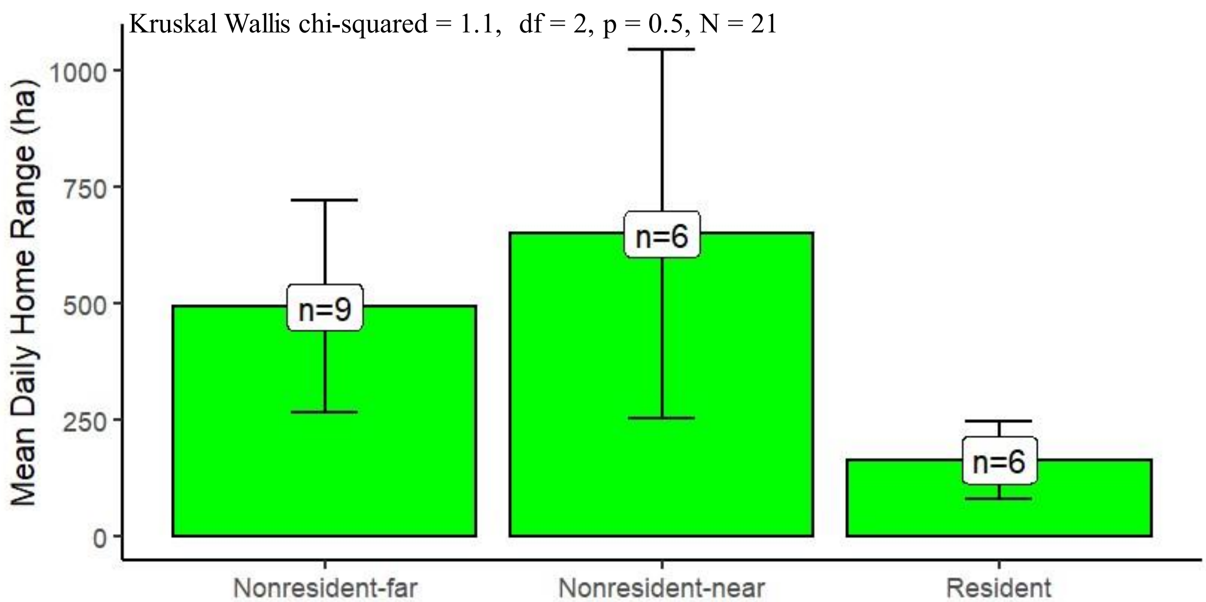


Figure 1-19. Mean Silver Carp daily home range (± SE) among residencies. A Kruskal-Wallis test suggested that daily home range size was not significantly different among residencies. All tagged fish were assigned a residency status based on their tagging location. For example, a fish tagged in Pickwick reservoir or at the Pickwick tailwaters was classified as "non-resident far". Fish tagged within Kentucky Reservoir and Barkley Reservoir were assigned as "residents" and fish tagged in the tailwaters of Kentucky Reservoir and Barkley Reservoir were called "non-resident near".

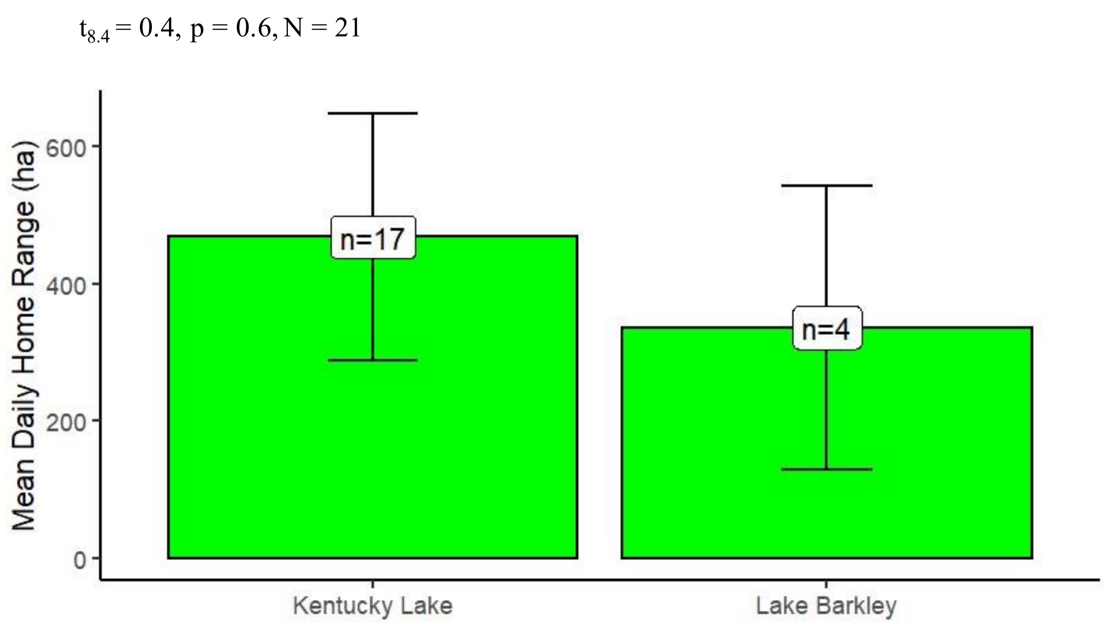


Figure 1-20. Mean Silver Carp daily home range (± SE) in Kentucky Reservoir and Barkley Reservoir. A Welch's t test suggested that daily home range size was not significantly different between reservoirs.

Macrohabitat Use of Silver Carp *Hypophthalmichthys molitrix* in Kentucky Reservoir and Barkley Reservoir

ABSTRACT

To date, bigheaded carp have invaded many pools and reservoirs within the U. S. waters. These species have proven resilience and can dominate the fish biomass given favorable conditions. Reservoirs provide steppingstones for them to continue their invasion throughout the U. S. waters. A commercial market for these species exists, but most of the effort is concentrated within rivers instead of reservoirs. Limited data exist on the habitat use of Silver Carp within reservoirs. This tracking study was tailored to partially fill the existing knowledge gaps concerning reservoir macrohabitat use of Silver Carp and to inform commercial fishermen of their daily patterns or macrohabitat usage. Our data seems to suggest that Silver Carp use these macrohabitats evenly throughout the year, regardless of water temperature. Additionally, our data suggested that on days with mean average wind speeds greater than 3 (m/s), Silver Carp favored coves (less than 5 ha) over the thalweg of the reservoirs. These data could provide a recommended macrohabitat for commercial fisherman with a place to begin side scanning for Silver Carp given these conditions.

INTRODUCTION

Bighead Carp *Hypophthalmichthys nobilis* and Silver Carp *H. molitrix*, collectively referred to as bigheaded carp, are native to Eastern Asia and have been widely introduced to 88 countries (Kolar et al. 2005). Since bigheaded carp feed on plankton (Tumalo and Flinn 2017), they could potentially cause severe damage to native species because plankton are a required food source by larval fish (Lebeda et al. 2022), zooplankton, and native mussels (Laird and Page 1996; Nico et al. 2022). Alterations of the aquatic food web might not be the only negative impact of bigheaded carp. Many economies based near large rivers and lakes depend upon recreational boating and sport fishing. However, bigheaded carp often jump out of the water more than 1 meter when boat engine vibrations and noises approach them, which makes them a danger to boaters. This behavior might be a method used by bigheaded carp to avoid predators (Perea 2002). Silver Carp can reach weights up to nearly 50 kg (Billard 1997; Kolar et al. 2005) and lengths of 1.2 m (Kamilov and Salikhov 1996; Kolar et al. 2005), and collisions between humans and jumping Silver Carp have led to injuries including black eyes, broken bones, back injuries, cuts, and concussions (Kolar et al. 2005). Silver Carp damage to personal property includes broken radios, generators, depth finders, windows, fishing equipment, lights, and antennae (Kolar et al. 2005).

Once bigheaded carp become established in a large water body, eradication of those populations has shown to be logistically challenging and expensive (Qiyue and Cooke 2014). However, the Silver Carp are a recent invader to Kentucky Reservoir and Barkley Reservoir, and thus their population in these reservoirs might still be manageable. Silver Carp do not seem to reproduce often in these reservoirs, and they must move through the locks in each dam to get into the reservoirs. Thus, if an effective barrier can be designed at the locks, and if natural and fishing mortality continue to act upon this population, this invasive species might one day be eradicated from the reservoirs, assuming no additional spawning occurs within these reservoirs or in reaches upstream.

Previous research has focused on the habitat use of Silver Carp in large rivers (DeGrandchamp 2006; Calkins et al. 2012). DeGrandchamp (2006) suggested Silver Carp select for and against macrohabitats by season within the Illinois River. Calkins et al. (2012) studied habitat use within the Upper Mississippi River and suggested Silver Carp preferred areas with lower flows than the main thalweg, but preferred areas with some flow over backwater habitats where phytoplankton abundances were suspected to be higher but contained no flow. Kentucky Reservoir and Barkley Reservoir are unique environments since they are connected and the farthest downstream and largest reservoirs on the Tennessee and Cumberland rivers. To my knowledge, no studies have concentrated on tracking Silver Carp within large reservoirs. The information gained from such research could be exploited by commercial fishers to enhance the harvest and potential eradication of Silver Carp in Kentucky Reservoir and Barkley Reservoir.

Often animal location can be tightly linked to food supply; therefore, Silver Carp location should not be random within these reservoirs. Silver Carp are a ram suspension planktivorous filter feeding species. Therefore, a planktivorous species may need to move to find areas with higher plankton abundance. A diet study conducted by Tumalo and Flinn (2017) confirmed Silver Carp within Kentucky Reservoir primarily were feeding on phytoplankton. A total of 83 Silver Carp gut contents were identified and summarized as 63.5% phytoplankton, 33.8% zooplankton, and 2.7% were intermediate. Phytoplankton composition was 86.9% little green ball (i.e., coccoid alga that is difficult to distinguish as green algae or cyanobacteria), 8% diatom, 4.1% cyanobacteria, and 1% green algae. Zooplankton composition was 54.7% copepoda, 23.3% cladocera, and 22% rotifera. The Hancock Biological Station's multi decade sampling efforts suggest that zooplankton and chlorophyll a is abundant and mostly evenly distributed throughout the reservoir, but seasonal variation is observed.

I hypothesized that wind intensity would influence Silver Carp macrohabitat use. I used ultrasonic tags to track Silver Carp in Kentucky Reservoir and Barkley Reservoir to better understand the macrohabitat use of this species. Few studies have analyzed the macrohabitat use of Silver Carp within a reservoir. My study was designed to fill these existing knowledge gaps and provide valuable information concerning macrohabitat use of Silver Carp that could be exploited by commercial fishers.

METHODS

Study Area

My research focused on the Silver Carp populations within Kentucky Reservoir and Barkley Reservoir. Both are mainstem reservoirs with Kentucky Reservoir being the last and largest reservoir on the Tennessee River and Barkley Reservoir being the last and largest reservoir on the Cumberland River. Constructed in 1944, Kentucky Reservoir is the largest reservoir within the eastern U.S. It spans 298 river kilometers, beginning in Tennessee at Pickwick Dam and flowing north to Kentucky Dam near Grand Rivers, Kentucky. Its surface area at maximum capacity is nearly 65,000 hectares (Kerns et al. 2009; Tennessee Valley Authority 2016; Lebeda 2020). Kentucky Reservoir is classified as mesotrophic (M. Flinn, pers. comm.) to eutrophic (Kerns et al. 2009; KDFWR 2016; Lebeda 2020). The lacustrine, northern portion of the reservoir consists of 0.01% canal (connecting Kentucky Reservoir to Barkley Reservoir), 4.10% cove (inlets along the main body of the reservoir > 5 ha but < 100 ha), 23.3% major cove (inlets > 100 ha), 59.2% side-channel (shallower areas flanking the thalweg in the main channel), and 12.3% thalweg (Ridgway and Bettoli 2017; Lebeda 2020). Secchi depths within Kentucky Reservoir vary seasonally and range from 0.6 – 1.4 m (Lebeda et al. 2022). The reservoir's discharge varies by season; average weekly discharge was 1,893 cms over the duration of my study (data shared by the U. S. Army Corps of Engineers). Chlorophyll a abundances also vary seasonally, but are on average 12 – 16 mg/L within Kentucky Reservoir (Hancock Biological Station data set). Kentucky Reservoir was constructed for power generation, navigation, flood control, and recreation.

Barkley Reservoir was constructed in 1966 and is 189.9 km long. It starts at Cheatham Dam in Tennessee, flows north to Barkley Dam near Grand Rivers Kentucky, and has a maximum surface area of 23,490 ha (Jarret and King 1991). Like Kentucky Reservoir, Barkley Reservoir also consists of a lacustrine downstream portion and consists of 0.2% canal (connecting Kentucky Reservoir to Barkley Reservoir), 10.1% cove (inlets along the main body of the reservoir > 5 ha but < 100 ha), 28% major cove (inlets > 100 ha), 55.2% side channel (shallower areas flanking the thalweg in the main channel), and 6.5% thalweg (Ridgway and Bettoli 2017; KDFWR 2020). Similar to Kentucky Reservoir, Barkley Reservoir was constructed for power generation, navigation, flood control, and recreation.

The lower portion of both reservoirs is considered lacustrine due to the relatively stable water levels, which only fluctuate by 1.5 meters from winter to summer pool (KDFWR 2016). However, as with many mainstem reservoirs, both water bodies retain some riverine characteristics, such as flow. But, unlike large rivers, the flow in these reservoirs can be decoupled from the water levels. These reservoirs each have their own characteristics, but since a canal connects them near their dams they share some characteristics, such as water elevation, and fish can move freely between each system. Altogether, Kentucky Reservoir and Barkley Reservoir represent unique ecosystems which are quite different than the large rivers which Silver Carp initially invaded. These reservoirs are different from rivers since the water levels are drawn down 1.5 m to winter pool winter and raised 1.5 m for summer pool. These reservoirs contain more surface area than sections of river of the equivalent length in rkm. Unlike rivers, flows within these reservoirs are easier to regulate.

My study was completed on the lower 67 km of Kentucky Reservoir (from Kentucky Dam to the Highway 79 bridge near Paris, Tennessee). In Barkley Reservoir, my sample area consisted of the lower 50 km between Barkley Dam and Devil's Elbow bay near the Highway 80 bridge (Figure 2-1). More effort was expended on Kentucky Reservoir due to its proximity to the Hancock Biological Station.

Field Sampling

Prior to this study, the Kentucky Department of Fish and Wildlife Resources (KDFWR), Tennessee Wildlife Resources Agency, Mississippi Department of Wildlife, Fisheries and Parks, U. S. Fish and Wildlife Service, U. S. Geological Survey, Murray State University, Tennessee Technological University, and other agencies had implanted InnovaSea V16 ultrasonic transmitters in over 2,000 Silver Carp in waters connected to or including Kentucky Reservoir and Barkley Reservoir. These tags had varying battery life, decibel output, and ping intervals. All tagged fish were assigned a residency status based on their tagging location. For example, a

Silver Carp tagged in Pickwick reservoir or at the Pickwick tailwaters was classified as "non-resident far". Fish tagged within Kentucky Reservoir and Barkley Reservoir were assigned as "residents" and fish tagged in the tailwaters of Kentucky Reservoir and Barkley Reservoir were called "non-resident near".

Field testing was performed to determine how precisely tagged Silver Carp could be located via the directional hydrophone. A test tag was attached to a small float tethered to an anchor that was sunk in a known location. The float held the tag off the substrate as if it were a tagged fish suspended in the water column. Once the test tag was hidden within the reservoir, researchers without knowledge of the tag's location attempted to find the tag with a VEMCO VR100 receiver and boat-mounted VH110 directional hydrophone. The receiver was set to "near" and gain was set to 0 to enhance precision. As the hydrophone drew closer to the tag, the intensity of signal in decibels was recorded at several locations near the test tag. Location of the test tag was considered to be the location where the receiver read 85-105 dB via the precision settings. The estimate of the tag's location was compared to the actual location and provided insight to how closely I would be able to locate a tagged fish. The mean distance (± SE) between the estimated and actual tag location was 47.2 ± 21.8 m. These measurements suggested that a signal intensity greater than 85 decibels using the precision settings is necessary to achieve this level of accuracy. Note that this level of accuracy is possible for an immobile tag, but a tagged fish might be startled by the boat; thus, I estimate my ability to locate tagged fish would be between 50 – 100 m of the actual fish location (Figure 2-2).

Tracking runs usually began along one side of the reservoir and then returned along the other side. The boat was stopped every km and the omni directional hydrophone was deployed for at least 2 minutes with the VR100 settings adjusted to "far" and the gain adjusted to 36-42 (search settings). These search settings permitted a detection range of roughly 0.8 km (Webber 2014). If a partial detection was made, the tag ID would not be displayed, so additional time was spent until the VR100 was able to detect and identify the tag ID. Once a Silver Carp was located, the directional hydrophone was used with precision settings (Near and 0 gain) to obtain the location of the fish. Location coordinates were only recorded if a reading above 80 dB was obtained with the VR100 (most detections were made at 85 dB or above). Wind direction and wind speed were also recorded with a Pro Anemometer BT-100 held above the head and the boat anchored. Surface water temperature was obtained for each date from the Hancock Biological Station website (https://www.murraystate.edu/qacd/cos/hbs/hbs.htm). Bathymetric maps were supplied by Navionics (www.navionics.com) and used to determine depth for each location.

Statistical Analysis

Detection locations were summarized by the macrohabitat they were detected within, and then compared to the available habitat with a log-ratio chi-square analysis (Manly et al. 2007). For this analysis, each Silver Carp location was treated as a sample rather than averaging all locations of a single Silver Carp. If the null hypothesis of random habitat use was rejected, macrohabitat use was analyzed to determine which macrohabitats were selected for and against. Statistical analysis was performed using program R and R studio 4.1.2 (R version 4.1.2, RStudio Team 2021). I used a Kruskal Wallis with Dunn's post hoc test to investigate if mean water depth (m), mean wind speed (m/s), mean daily wind speed (m/s), and mean water temperature (°C) differed among Silver Carp macrohabitat use. For all analyses, an alpha value of 0.05 was used to determine statistically significant p-values.

RESULTS

Throughout the duration of tracking for this macrohabitat study, I spent over 383 hours tracking, which amounted to 66 days. The total individual detections were 3 Bighead Carp, 3 Freshwater Drum *Aplodinotus grunniens*, 4 Grass Carp *Ctenopharyngodon idella*, 6 Smallmouth Buffalo *Ictiobus bubalus*, 17 Paddlefish, 194 Silver Carp, and 9 tags that were unknown within our database. I recorded the macrohabitat used by 59 Silver Carp in Kentucky Reservoir and 67 Silver Carp in Barkley Reservoir over several seasons. Since my search radios was 1 km in circumference, I believe I searched habitats entirely. However, sections of the reservoirs were not searched evenly due to the vastness of the sample areas

<u>Macrohabitat Use</u>

Chi-square analysis of all tracking run data for Kentucky Reservoir suggested that Silver Carp used macrohabitats at random (Chi-square = 223.9, df = 268, p = 0.9) (Table 2-2). Similarly, carp did not demonstrate habitat selection during spring (Chi-square = 43.8, df = 76, p = 0.9), summer (Chi-square = 158.3, df = 192, p = 0.9), or fall (Chi-square = 29.1, df = 52, p = 0.9) (Table 2-2).

In Barkley Reservoir, the Chi-square analysis showed no overall macrohabitat selection (Chi-square = 190, df = 268, p = 0.9) (Table 2-3). As with Kentucky Reservoir, the carp did not show macrohabitat selection during spring (Chi-square = 42.2, df = 64, p = 0.9), summer (Chi-square = 149.1, df = 220, p = 0.9), fall (Chi-square = 14.4, df = 28, p = 0.9) or winter (Chi-square = 11.4, df = 20, p = 0.9) (Table 2-3).

Abiotic Analysis

The Silver Carp did not use different macrohabitats based on the local wind intensity (Chi-square = 6.4, df = 4, p = 0.1) (Figure 2-3), but a similar analysis based on mean daily wind speed suggested that Silver Carp favored the coves over the thalweg on days with higher winds (Chi-square = 10.7, df = 4, p = 0.03) (Figure 2-4). Mean water temperature was different among macrohabitats used, but a Dunn's test adjusted p-values was unable to pinpoint differences among groups (Chi-square = 11.3, df = 4, p = 0.02) (Figure 2-5).

DISCUSSION

Understanding the macrohabitat use of Silver Carp can be important to help direct management and removal efforts. Some habitat selection studies have been conducted on Silver Carp (Calkins et al. 2012), but this tracking was over a short period in a large river. Within the Upper Mississippi River around pool 26 Calkins et al. (2012) discovered Silver Carp distributions favored habitats with lower flows but were never located in areas with no flow (i.e., between rkm 306.5 and 354). To my knowledge, my study is the first research on macrohabitat selection of Silver Carp within reservoirs in the U. S.

I recorded the macrohabitat used by 59 Silver Carp in Kentucky Reservoir and 67 Silver Carp in Barkley Reservoir over four seasons. By comparing the macrohabitat used by these fish to the available macrohabitat, I was able to test if Silver Carp were selecting for or against certain macrohabitats. The macrohabitats I used were chosen based on logical partitions of these reservoirs. However, I was unable to detect any habitat selection within either reservoir (Table 2-2 and 2-3). Thus, Silver Carp seem to swim at random since food resources were not limiting, which is indicated by chlorophyll a abundance sampled on a routine basis throughout the reservoir by the Hancock Biological Station during my sample years with respect to these macrohabitats.

Wind direction and intensity can influence the macrohabitat selection of fish in reservoirs (Chapman and Mackay 1984). For example, Northern Pike *Esox lucius* used habitats that were further from shore on windier days (Chapman and Mackay 1984). I hypothesized that wind intensity would influence Silver Carp macrohabitat use. Wind intensity might influence many factors within a reservoir, but wind might be especially important for influencing plankton abundance (Carrick et al. 1993), and therefore, possibly Silver Carp location. However, the median wind speed recorded at each fish location was not significantly different among the macrohabitat types (Figure 2-4). But, the wind speed measured when each fish was located might not be the best measure of the effect of wind speed on macrohabitat use. For example, the overall wind intensity over a longer period might be a more appropriate index of the wind's influence on macrohabitat use. So, I also investigated the mean daily wind speed and its influence on habitat use. Silver Carp seemed to be found in coves on windier days (Figure 2-5), perhaps because the wind concentrates plankton in these coves, or perhaps the fish are more comfortable in coves on windy days because the more open waters are too rough. If Silver Carp do indeed use coves on windier days, this fact could be exploited by commercial fishermen. A block net set at the mouth of a cove could ensure the Silver Carp do not escape and would allow the commercial fisherman more time to deploy their gill nets. With the Silver Carp trapped in a cove it can make the Silver Carp more vulnerable to typical commercial fishing gear.

Temperature can also influence fish macrohabitat use (Linfield 1985; Winemiller and Jepsen 1988; Coulter et al. 2016). For example, areas with warmer temperatures during colder months of the year can attract fish. A warm rain in late winter or early spring will provide creeks with warmer water and fish at times will aggregate in areas where creeks with warmer water are flowing into the reservoirs. In my study, Silver Carp seemed to use the thalweg and side channels more often at higher temperatures (although post-hoc tests do not reveal a statistically significant difference in distribution). I hypothesize that these Silver Carp are favoring the thalweg when mean temperatures are at its highest because there is flow present there and the flow may contain a steady flow of plankton. A Silver Carp need only sustain its position within the thalweg and would be able to filter feed on the replenishing flow of phytoplankton. Maintaining position within flow while feeding may aid the Silver Carp in avoiding predation from arial predators during its younger months when it is vulnerable to arial predation. Perhaps this is a characteristic trait that Silver Carp maintain once they mature.

The Silver Carp in these reservoirs might be relating more to microhabitats within the macrohabitats that I studied. For example, gyres that flow into major coves might provide consistent replenishment of phytoplankton requiring less swimming effort by Silver Carp (M. Flinn, pers. com.). Perhaps young of the year Silver Carp prefer areas with flow providing a replenishment of food so they can remain stationary and monitor for aerial predators. These characteristic traits may be retained into adulthood even though aerial predators would no longer be a threat (M. Flinn, pers. com.).

Perhaps since the thalweg has more recreational and barge traffic, carp might avoid areas of this macrohabitat that have such traffic. Contrary to phytoplankton abundances varying daily within the thalweg of the Illinois and Mississippi rivers (DeGradnchamp 2006; Calkins et al.

2012), phytoplankton abundance within the thalweg of Kentucky reservoir does not differentiate daily (Buckaveckas et al. 2002). So, perhaps the cost analysis of remaining in the thalweg during higher flows is less beneficial.

Within Kentucky Reservoir and Barkley Reservoir there are shallow flats with ditches running through them that could theoretically channel flow. DeGrandchamp (2006) confirmed during the spring of 2004 and 2005, and the summer of 2005, bigheaded carp selected for channel border habitats in the Illinois River. Though my data did not show it at a level of significance, I strongly suspect Silver Carp are selecting for these channel border habitats within Kentucky and Barkley reservoir. Thus, future studies might consider concentrating efforts on teasing apart specific factors within macrohabitats that influence Silver Carp movement and habitat use.

Although wind proved significant in motivating Northern Pike to move to offshore habitats (Chapman and Mackay 1984), this had the opposite effect on Silver Carp. In contrast, although a sample size of seven, the opposite was observed for Silver Carp within these reservoirs. Silver Carp selected for coves over the thalweg on days with higher mean wind speeds. This provides valuable information for commercial fishers to exploit on days with higher sustained winds.

Conclusion

It is possible that these Silver Carp, since they have an abundance of evenly-distributed food and no natural predators, swim randomly throughout these reservoirs. Perhaps on occasion they will favor areas where they are not spooked by recreational boater traffic or may be found in protected areas with slightly warmer surface temperature where phytoplankton abundance may be higher in the spring or fall, but for the most part, I was unable to detect many patterns to their macrohabitat use. These fish might be reacting to other factors that are difficult to measure; for example, the Silver Carp are a schooling species, and travelling in a school might be more important to an individual carp than any other factors which I measured in this study.

To my knowledge, this is the first Silver Carp tracking study to have been performed on a reservoir within the U.S. These data provide a baseline for future studies on this species within reservoirs. It is our hope that these data will be helpful for future studies within reservoirs on this invasive species.

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Tables and Figures

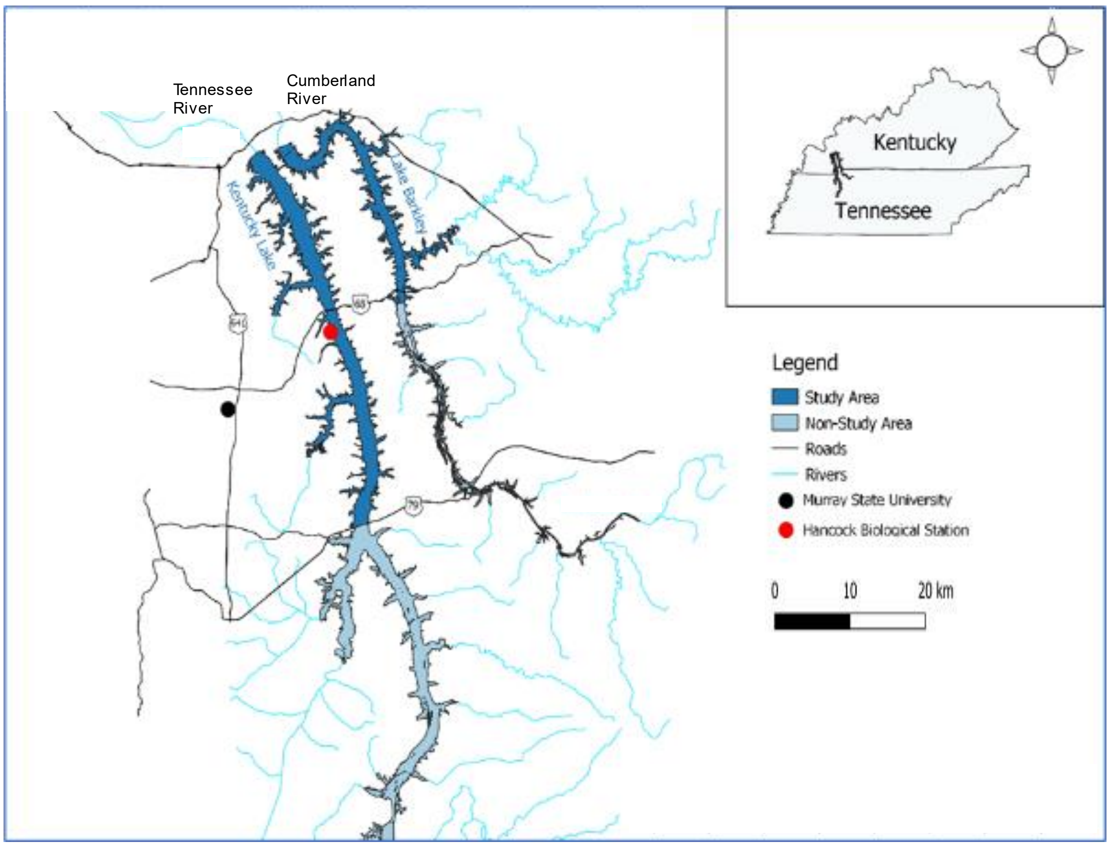

Figure 2-1. Map of Kentucky Reservoir and Barkley Reservoir. The darker blue represents study areas within these reservoirs.

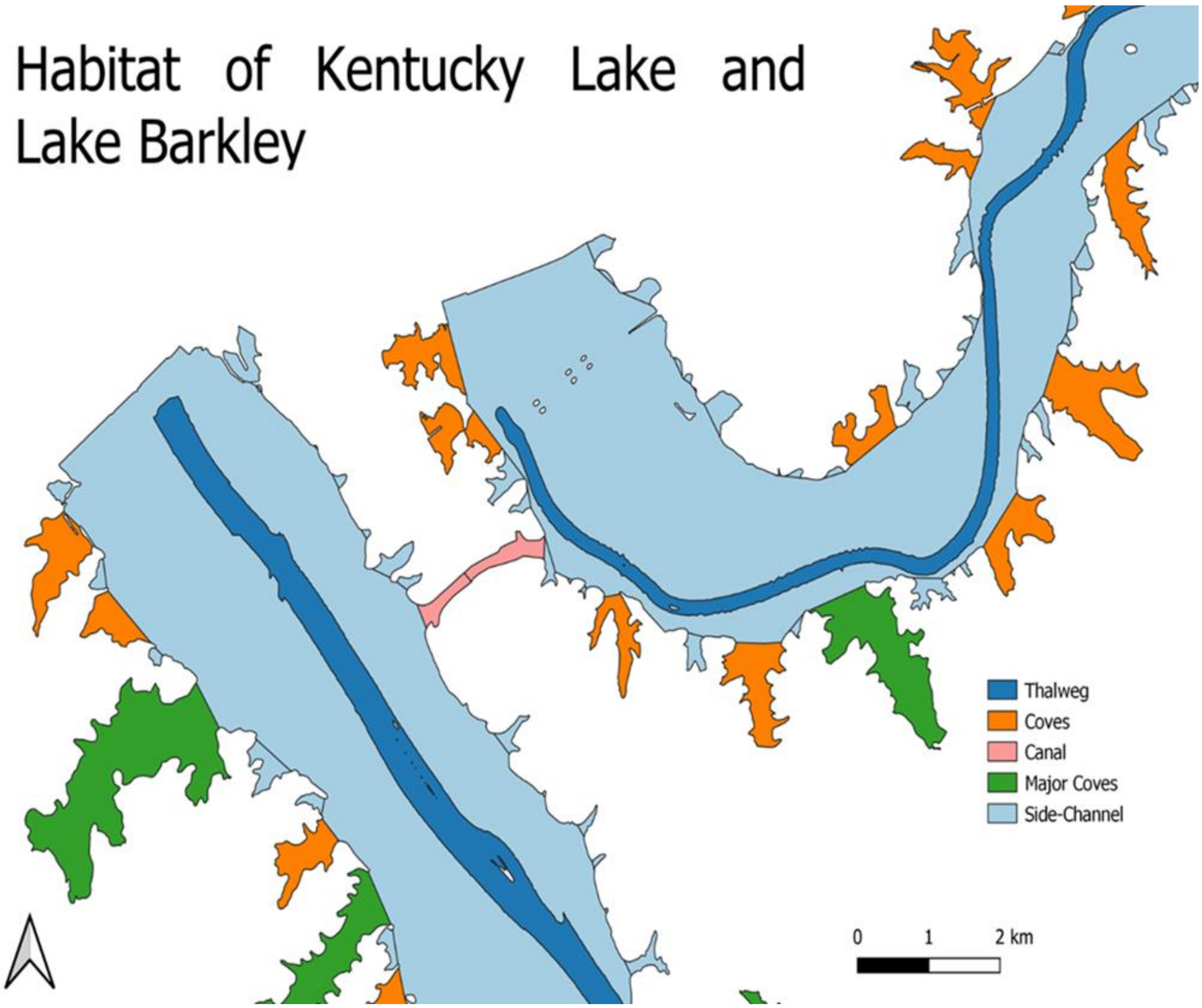

Figure 2-2. Example of the 5 macrohabitat types evaluated within each lake. Each reservoir's thalweg was evaluated as being > 20m of depth. Coves were > 5 ha but less than 100 ha, and major coves were > 100 ha. The side-channel included the remaining areas of the reservoir, excluding the canal between Kentucky Reservoir and Barkley Reservoir.

Table 2-1. Results of Silver Carp tracking run effort.

		Days tracked	Total hours tracked
Kentucky	Combined	43	258
	Spring	11	58
	Summer	25	172
	Fall	6	26
	Winter	1	2
Barkley	Combined	23	125
	Spring	4	21
	Summer	16	82
	Fall	2	15
	Winter	1	7

Table 2-2. Summary of Silver Carp use compared to available macrohabitat in Kentucky Reservoir.

Kentucky Lake						
	% Available	% Used All Seasons	% Used Spring	% Used Summer	% Used Fall	% Used Winter
Canal	0.01%	1.37%	0%	1.9%	0%	0%
Cove	5.10%	2.06%	4.17%	0.95%	6.25%	0%
Major Cove	23.3%	13.01%	29.17%	5.71%	31.25%	100%
Side Channel	59.2%	73.29%	58.33%	79.04%	62.5%	0%
Thalweg	12.3%	10.27%	8.33%	12.38%	0%	0%
N Size		59	19	48	13	1
		Chi Square: 223.9 df: 268 Pvalue: 0.9	Chi Square: 43.8 df: 76 Pvalue: 0.9	Chi Square: 158.3 df: 192 Pvalue: 0.9	Chi Square: 29.1 df: 52 Pvalue: 0.9	

Table 2-3. Summary of Silver Carp use compared to available macrohabitat in Barkley Reservoir.

Lake Barkley						
	% Available	% Used All Seasons	% Used Spring	% Used Summer	% Used Fall	% Used Winter
Canal	0.20%	.10%	5.55%	0%	0%	0%
Cove	10.10%	6.92%	11.11%	6.06%	14.29%	0%
Major Cove	28%	7.69%	5.55%	7.07%	28.57%	0%
Side Channel	55.20%	77.69%	72.22%	79.79%	57.14%	83.33%
Thalweg	6.5%	6.92%	5.55%	6.06%	0%	16.67%
N Size		67	16	55	7	5
		Chi Square: 190 df: 268 Pvalue: 0.9	Chi Square: 42.2 df: 64 Pvalue: 0.9	Chi Square: 149.1 df: 220 P value: 0.9	Chi Square: 14.4 df: 28 Pvalue: 0.9	Chi Square: 11.4 df: 20 Pvalue: 0.9

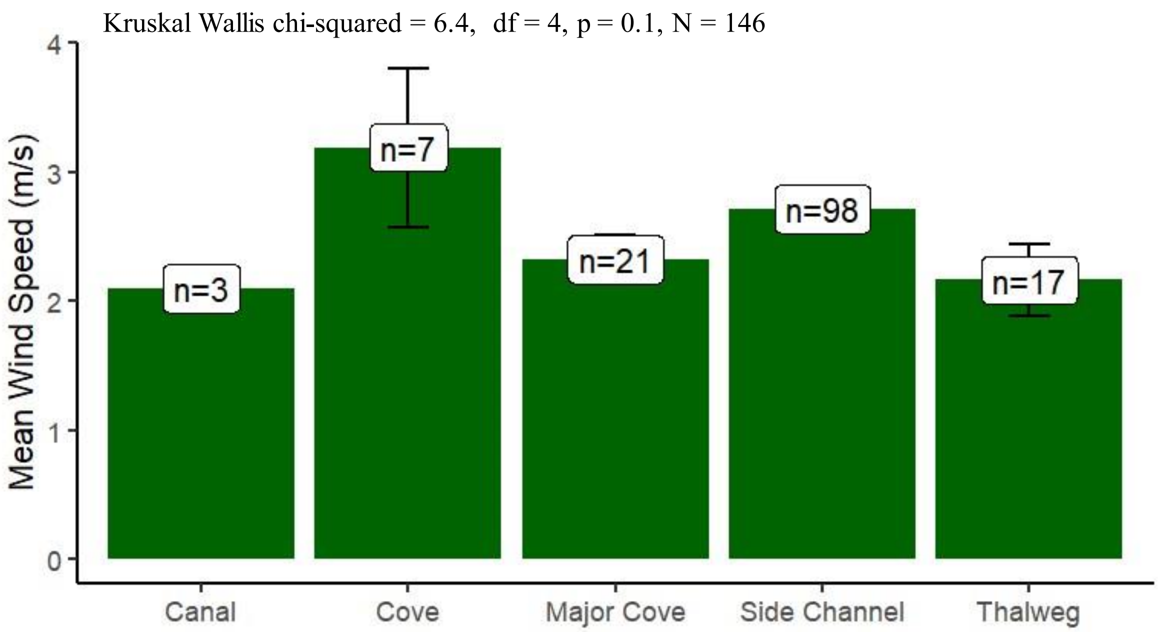

Figure 2-3. Mean wind speed (with SE) of Silver Carp locations within each macrohabitat type. A Kruskal Wallis test suggested median wind speed of locations used by Silver Carp was not significantly different among macrohabitats.

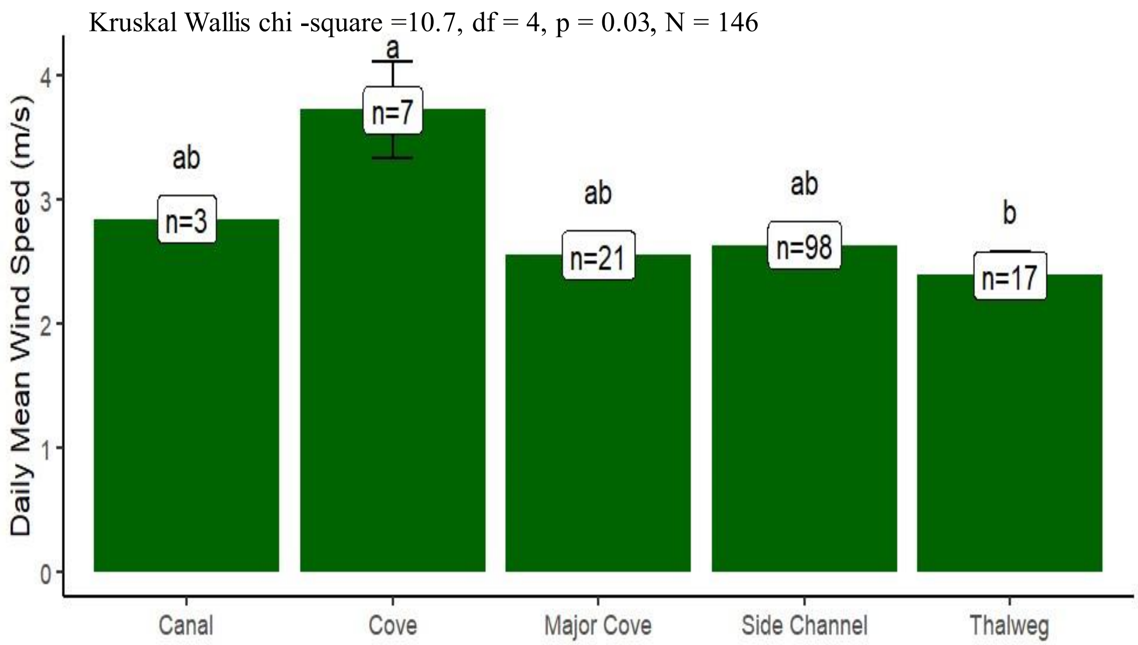

Figure 2-4. Mean daily wind speed (with SE) of Silver Carp locations within each macrohabitat type. A Kruskal Wallis test suggested the daily mean wind speed of locations used by Silver Carp was significantly different among macrohabitats.

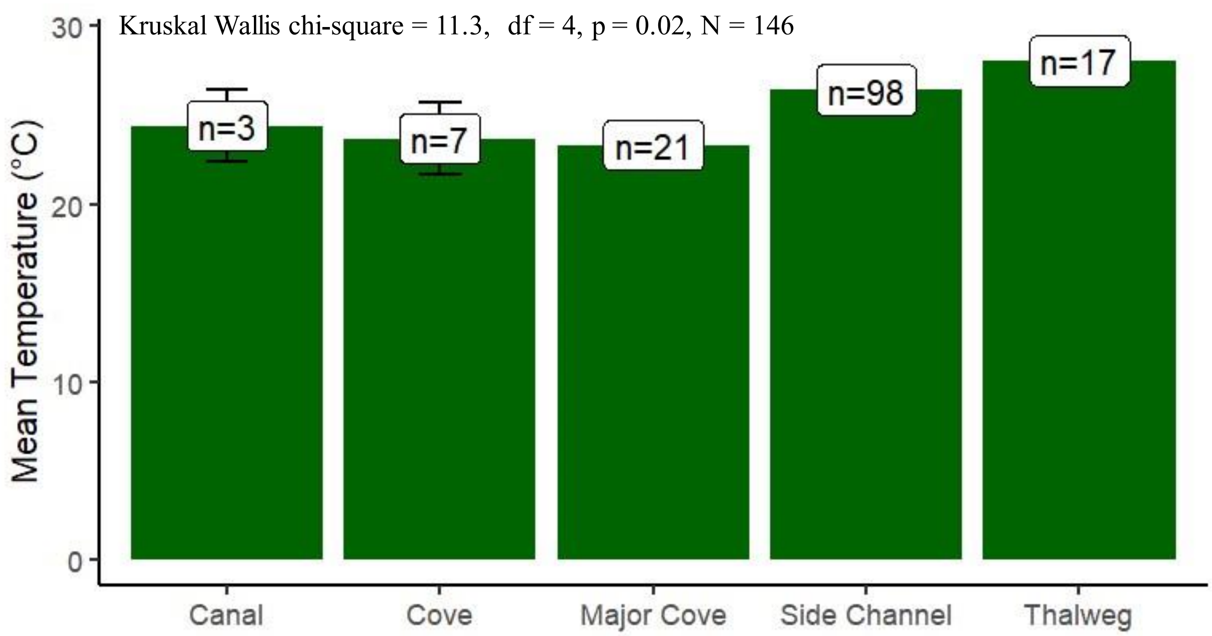

Figure 2-5. Mean daily temperature (with SE) of Silver Carp locations within each macrohabitat type. A Kruskal-Wallis test suggested median temperature of locations used by Silver Carp was significantly different among macrohabitats, but post-hoc tests were not able to pinpoint.