Deterrent Strategy Planning for Asian Carp in the Ohio River Basin

Geographic Location: Tennessee and Cumberland rivers including Mississippi, Alabama,Tennessee, and Kentucky.

Participating Agencies: Kentucky Department of Fish and Wildlife Resources (KDFWR), Mississippi Department of Wildlife, Fisheries, and Parks (MDWFP), Alabama Department of Conservation and Natural Resources, U.S. Army Corps of Engineers (USACE), Tennessee Valley Authority (TVA), Murray State University, Tennessee Technological University (TTU), U.S. Geological Survey (USGS), U.S. Fish and Wildlife Service (USFWS).

Introduction:

Adult bigheaded carp including Silver Carp (*Hypophthalmichthys moltrix*) and Bighead Carp (*H. nobilis*) have invaded the Ohio River Basin. Silver Carp were first reported in the state of Tennessee in 1989, and Bighead Carp were reported in 1994 (Kolar et al. 2007). Despite occupancy data suggesting bigheaded carp presence in Tennessee for over three-decades, the invasion may still be in early stages as evidenced by skewed sex ratios, high growth rates, and robustness (Ridgway 2016). Bigheaded carp are highly effective planktivores that can impose considerable ecosystems alterations by altering zooplankton communities (Sass et al. 2014). Bigheaded carp have been shown to pass through locks making them capable of invading new reservoirs or continuing to immigrate into reservoirs. Therfore, dettering bigheaded carp from immigrating into vulnderable reservoirs will help to prevent and ameliorate bigheaded carp invasions. Furthermore, surveliance and detections of changes in the leading edge of invasion will inform prioritization of management actions.

Data regarding pool-to-pool movement and passage at lock and dams will inform placement of deterents that minimize trade-offs. Furthermore, baseline data will allow efficacy of deterents to be measured after implimentation. The project supports the goals of the Ohio River Basin Asian Carp Control Strategy Framework including prevention and monitoring and response. The specific strategy supported is to evaluate the use of deterrent barriers at strategic locations to limit further dispersal of Asian carp in the Ohio River Basin.

Project Objectives:

1) Characterize the need for deterrents and evaluate priority locations for deterrent placement to control movement of Asian carp in the Tennessee and Cumberland rivers.
2) Collect baseline movement information among reservoirs to inform Asian carp deterrent efficacy and lock and dam passage.

Project Highlights:

Agency: TWRA

- Bigheaded carp appear to move downstream (i.e., from Pickwick Reservoir to Kentucky Reservoir) more often than upstream (i.e., from Kentucky Reservoir to Pickwick

Reservoir) at Pickwick Dam. If emigration from Pickwick Reservoir exceeds immigration, persistance of the bigheaded carp population above Pickwick Dam must rely on undetected upstream immigration as there is no evidence of local recruitment at this time. Reservoir population net movement is important to deterrent planning and population modeling.

- Bigheaded carp have moved from within the Tennessee River to the Cumberland River and vice-versa. The dynamics of movement between the Tennessee and Cumberland rivers remain unkown; however, interconnectedness of these populations via the Barkley Canal and the Ohio River should be considered during management, mitigation, and control efforts of bigheaded carp.

Agency: KDFWR

- KDFWR continues to provide field support to the Bio-Acoustic Fish Fence research project at Barkley Lock and Dam on the Cumberland River.
- Silver carp activity peaked in the spring every year for both Kentukcy and Barkley lakes and appeared to be triggered by warmer water temperatures, falling discharge rates, and lake levels rising.
- Analyses indicate that the silver carp population in Kentucky Lake and Lake Barkley is a mixture of “homers” and “roamers”, i.e. some silver carp are predisposed to stay in one area while others are more likely to roam over large distances.
- Many of the fish made their long migrations downstream during March, April, and May which may indicate moving downstream towards the Ohio River to spawn.
- The mean burst speed of KDFWR silver carp was approximately 38.4 km/day.
- In total, 66 crossings were documented at Barkley Dam, 19 crossings at Kentucky Dam, and 21 crossings which were known to be crossings, but which dam was crossed could not be determined.
- 90% of the downstream crossings were not detected in a lock, while 100% of upstream crossings were detected inside a lock, indicating that fish were moving downstream by transversing through the Dam gates when they were open.
- Fish passage occurred primarily when water temperatures were above 16^{o}C.

Methods:

Agency: All

Objective 1

Partner agencies participated in the Strategic Decision Making workshop led by the USGS in an effort to identify priority locations for invasive carp deterrents at Lock and Dams throughout the Tennessee River. Virtual meetings were held monthly or bi-weekly, depending on schedules, to facilitate discussions regarding deterrent placements. Partner agencies provided data upon request and insights from field work to inform decision processes. The TWRA Dive Team also provided field expertise and support for this process by completing freshwater mussel investigations below TVA dams.

Objective 2

Efforts to monitor, maintain, and strengthen (i.e., increasing tag numbers, adding to receiver array, and updating receiver array) acoustic telemetry movement data for bigheaded carp were continued in 2020. Receivers were monitored throughout the year including downloading data, replacing damaged receivers, and replacing disposable components (e.g., batteries). Vemco telemetry receivers are in place at all locks and dams in the Tennessee River from Kentucky Dam to Guntersville Dam and in the Cumberland River from Barkley Dam to Old Hickory Dam to inform movement among locks and dams and across reservoirs. Receiver downloading and maintenance is a multi-state effort by KDFWR, TWRA, TTU, MDWFP, and ADCNR. An effort to increase the number of tagged bigheaded carp in Kentucky and Pickwick reservoirs occurred from 2017 – 2020, and plans to continue deploying acoustic transmitters in the Tennessee and Cumberland rivers in 2021 are underway. To maximize certainty of survival of captured fish, capture methods that minimize stress on individuals were used including very short set gill nets (e.g., 20 minutes) and electrofishing during cool water conditions (e.g., < 20 degrees C). Fish were treated for minimal handling effects including electro-anesthesia and immediate release.

Telemetry receiver stations were deployed throughout the Tennessee and Cumberland rivers (Figure 1). Detection of fish moving from pool-to-pool was indicated if an individual was detected by receivers in two different pools. Higher-resolution movement data is made possible by including multiple receivers at each dam including one above, below, and in the lock(s). However, even with an array of this structure, not all fish are detected at all receivers, which results in an inability to discern when a fish entered a lock or where it was before or after entry. Therefore, evidence of pool-to-pool movements without lock data are reported in addition to evidence of pool-to-pool movements with lock data.

Objective 2

Asian Carp Deterrent Testing at Lake Barkley Lock

KDFWR is partnering with several agencies (U. S. Fish and Wildlife Service, U. S. Geological Survey, University of Minnesota, Fish Guidance Systems, and U. S. Army Corp of Engineers) to conduct field testing of a Bio-Acoustic Fish Fence (BAFF) at the downstream approach to the Lake Barkley Lock chamber (Figure 1). A research team has been established and developed a study plan for research to be conducted to determine the efficiency of the BAFF for deterring Asian carp movement. The BAFF was commissioned on November 8th, 2019. Collection and analysis of data from HTI transmitter detections is being coordinated by the USFWS through HTI and the USGS. The research group, led by the USFWS, anticipates reporting findings on a bi-annual basis (Evaluation of a Bio-Acoustic Fish Fence (BAFF) at Barkley Lock and Dam: Study Design, USFWS). KDFWR will continue to provide support to the research team monitoring the Bio Acoustic Fish Fence throughout testing of this system, including but not limited to: collecting and tagging fish, maintenance of the telemetry receiver array, turning the BAFF on and off, continued data collection through electrofishing surveys below Barkley Dam, enforcing fishing and boating restrictions near the BAFF, and aiding other members of the research team with field work as needed. In 2020, KDFWR deployed two additional VEMCO passive receivers near Barkley Lock to enhance detections of fish that have passed through Barkley Lock and Dam. KDFWR surgically implanted silver carp (N = 150), paddlefish (N = 22), freshwater drum (N = 32), and smallmouth buffalo (N = 40) with VEMCO transmitters in the Barkley Tailwaters. All fish carrying transmitters were tagged externally with a Floy loop tag. These fish will continue to be tracked through the passive receiver array at Barkley Lock to monitor interactions with the BAFF as well as throughout the Cumberland and Tennessee Rivers.

In 2020, KDFWR assisted with additional efforts to collect silver carp in Lake Barkley, translocate them to the Barkley Tailwaters, and surgically implant with HTI transmitters. The HTI technology will allow for faster ping rates of transmitters and 3D positioning fish tagged with HTI transmitters detected within the HTI receiver array near the BAFF. Efforts to tag silver carp with HTI tags in 2020 was initially scheduled for April and November. However, due to mechanical issues with the BAFF in spring and summer of 2020 that resulted in temporary failure of some components, tagging of HTI fish was only conducted in November 2020. The USGS and USFWS assisted with tagging efforts that resulted in 254 silver carp captured in Lake Barkley and translocated to the Barkley Tailwaters where they were tagged and released. KDFWR also deployed one HR3 receiver upstream of Barkley Lock and one HR3 receiver in Kentucky Lake near the canal that adjoins it to Lake Barkley to increase detections of silver carp tagged with HTI transmitters. Data from these HR3 receivers, as well as two additional receivers deployed in Barkley Lock, are downloaded on a monthly basis by KDFWR and data transferred to the USGS for analysis.

Collect Asian carp movement information

KDFWR worked with Murray State University (MSU) to continue a study tracking silver carp movement in the Tennessee and Cumberland river systems. KDFWR assisted with tagging events and data collection through manual tracking and downloading of data from passive receivers. All data analysis for this report is provided by Dr. Tim Spier of Murray State University and encompasses fish surgically implanted with VEMCO transmitters.

In addition to the tagged fish mentioned above, the USGS Columbia Environmental Research Center tagged and released 35 silver carp in Kentucky Lake for a separate study. The tags used only have a 300-day battery life and thus are not expected to be detected often, but were included in the analysis for this report.

In November of 2020, KDFWR also collaborated with USGS Upper-Midwest Environmental Science Center to surgically implant transmitters in 100 silver carp in the tailwaters of Kentucky Dam on the Tennessee River. The majority of silver carp tagged were collected in Kentucky Lake using gill nets and translocated to the Kentucky Tailwaters for release (91 fish). The 9 remaining silver carp were collected in the Kentucky Tailwaters via electrofishing. For this effort, all surgeries were performed by USGS personnel. An ongoing study being conducted by the USGS at Lock and Dam 19 on the Mississippi River has shown that translocated silver carp have a higher frequency of upstream passage when compared to fish collected in the tailwaters. Therefore, it is expected that these silver carp translocated from Kentucky Lake will provide a higher probability of upstream passage attempts at Kentucky Lock, which will further inform deterrent strategies at that location.

Tracking Effort

Boat-mounted hydrophones were used to manually track tagged silver carp on 4 separate trips in Kentucky Lake and 2 separate trips in Lake Barkley. The average linear distance tracked during these trips was 32 km in Kentucky Lake and 18 km in Lake Barkley.

In Kentucky Lake, 32 trips were taken to download data from the VEMCO passive receivers, and 6 trips were taken to deploy new receivers. In Lake Barkley, 40 trips were taken to download the passive receivers, and 2 trips were taken to deploy new receivers. Ten new VEMCO passive receivers were deployed in 2020; eight of these were deployed in and around Kentucky Lock to improve detection probability of tagged fish crossings. The network of passive receivers in Kentucky state waters (N = 37) of the Tennessee and Cumberland rivers provides thorough coverage of both lakes and the area around Kentucky and Barkley Dams. As anticipated, the passive receiver infrastructure required some maintenance in 2020; for example, one receiver was lost, two experienced connection issues and were replaced, and several receivers needed new batteries. This routine maintenance is necessary for the network to continue to provide important information on fish movements.

The VEMCO passive receiver network stretches from the tailwaters of both lakes, through both locks, into the canal connecting the lakes, and well upstream of both dams. Coordination is also ongoing with the Tennessee Wildlife Resource Agency (TWRA), Tennessee Tech University (TTU), Mississippi Department of Wildlife, Fisheries, and Parks (MDWFP), and Alabama Department of Conservation and Natural Resources, who have deployed receivers further upstream in the Tennessee and Cumberland Rivers.

Results and Discussion:

Agency: TWRA

<u>Objective 1</u>

Upon completion of the Strategic Decision Making process, partners reached a final agreement that was drafted into a letter (Appendix A). This letter was submitted to the Tennessee Valley Authority to inform their efforts of creating an Asian Carp Mitigation Programmatic Environmental Assessment for the Tennessee River.

Nintey-two tagged bigheaded carp were detected by at least one station during 2017 – 2020. There were 2 individual bigheaded carp detected by at least one station in 2017, 44 in 2018, 60 in 2019, and 44 in 2020. Bigheaded carp were detected in the locks at Pickwick Dam 1,024 times in 2020 (Table 1); however, six individuals accounted for all detections with four bigheaded carp detected in the larger lock and two in the smaller lock (Table 2). Of bigheaded carp that were detected in the locks at Pickwick Dam in 2020, one passed through the larger lock moving downstream from Pickwick Reservoir to Kentucky Reservoir, and all others returned to the reservoir from which they had entered the lock (Table 3). Carp moving from Kentucky to Pickwick Dam were often not detected in either lock. Despite only one bigheaded carp being detected above, in, and below the locks; 18 movements from Pickwick Reservoir to Kentucky Reservoir (i.e., downstream) were detected in 2020 (Table 4). No movements from Kentucky Reservoir to Pickwick Reservoir (i.e., upstream) were detected in 2020, but two were detected in 2018 and seven in 2019 (Table 4.). From 2018–2020, seven bigheaded carp moved between Kentucky and Pickwick reservoirs at least twice, domonstrating that some individuals move back and forth between reservoirs. No bigheaded carp were detected moving from Barkley to Cheatham Reservoir or vice-versa. Additonally, no passage of bigheaded carp into Wilson, Wheeler, or Old Hickory reservoirs was detected.

Bigheaded carp movement between Kentucky and Barkley reservoirs has occurred. One Silver Carp moved from Kentucky Reservoir to Barkley Reservoir and back to Kentucky Reservoir as indicated by locations at Pickwick Reservoir during the spring of 2019 followed by locations at Cheatham Lock during the spring and fall of 2019 followed by locations at Pickwick Lock in the fall of 2019. Another Silver Carp moved from Kentucky Reservoir to Cheatham Lock at some time between May 12, 2019 and April 10, 2020. Movements between locations in the Tennessee and Cumberland rivers indicate that these populations are interconnected. Therefore, management actions should consider these rivers as potential source populations to one another until movement between populations can be quantified or the populations are isolated from one another (e.g., barriers are implemented).

Individual bigheaded carp were detected moving in and out of locks many times without making passage. In 2020, three individual bigheaded carp accounted for 59 detections of fish moving from Kentucky Reservoir into the larger lock at Pickwick Reservoir and returning to Kentucky Reservoir. This may suggest that multiple attempts are necessary for an individual fish to successfully make upstream passage through some locks.

Agency: KDFWR

Objective 1

Upon completion of the Strategic Decision Making process, partners reached a final agreement that was drafted into a letter (Appendix A). This letter was submitted to the Tennessee Valley Authority to inform their efforts of creating an Asian Carp Mitigation Programmatic Environmental Assessment for the Tennessee River.

Objective 2

Asian Carp Deterrent Testing at Lake Barkley Lock

Results from the Bio-Acoustic Fish Fence testing will be reported by the research team in a separate document at the conclusion of the study in 2024.

Collect Asian carp movement information

Fish Detections

Tracking effort now spans the entire Kentucky Lake and Lake Barkley system of the Tennessee and Cumberland rivers respectively. These efforts have confirmed that fish move throughout these river systems and beyond. Currently the live fish detection database maintained by MSU contains over 5.5 million fish locations. During 2020, 309 different silver carp were detected via active tracking and the passive receivers maintained by KDFWR and MSU in Kentucky Lake, the Lower Tennessee River, Lake Barkley, and the Lower Cumberland River (197 silver carp tagged by KDFWR and MSU; 112 silver carp tagged by other agencies: Table 5). Other species which have been detected include bighead carp, freshwater drum, grass carp, paddlefish, smallmouth buffalo, and some unidentified fish (Table 6). silver carp were located an average of 5,408 ± 729(SE) times per individual.

Swimming Speed

All fish locations were converted to the nearest river kilometer (RK) and then the mean RK and mean location time was determined for each fish on each date. Movement rates were calculated by determining the change in RK between successive locations for each fish, and then dividing this value by the number of days between successive locations (so, movement rates were recorded as km/day). Only successive locations which were within 2 days of each other were used to calculate movement rates. Mean daily movement rates were averaged monthly for each fish, and then mean daily movement was determined across all fish for each month. In this way, all fish are weighted equally, and no single fish can have a disproportionate influence on the calculations simply because that fish was detected more often. Data collected prior to 2017 was not used since the VEMCO passive receiver network was not well developed then.

Mean daily speed (movement rate regardless of direction, i.e. absolute speed in km/day) was averaged monthly and compared to mean daily surface temperature (C), mean daily discharge (cubic meters per second, m^3/s or cms), and mean lake elevation (m) which were also averaged for each month. Temperature was measured only in Kentucky Lake with the value being used for Lake Barkley as well. Discharge and elevation were measured separately at Kentucky Dam and

Barkley Dam. Monthly mean speed was calculated for 136 silver carp in Kentucky Lake and 73 silver carp in Lake Barkley. Speed was calculated an average of 4.2 ± 0.3(SE) times per month for each fish in Kentucky Lake and 4.3 ± 0.5(SE) times per month for each fish in Lake Barkley. Average number of months used for speed calculations per fish was 3.7 ± 0.4(SE) in Kentucky Lake and 3.9 ± 0.5(SE) in Lake Barkley. The monthly speed was based upon an average of 10.4 ± 0.7(SE) fish per month in Kentucky Lake and 7.0 ± 0.6(SE) fish per month in Lake Barkley. Enough fish were detected in Kentucky Lake that we could estimate speed every month from 2017 – 2020 but speed was calculated in Lake Barkley for only 40 of the 48 months during this period. The missing months in Lake Barkley mostly occurred early in the study when the passive receiver network was less developed in that lake.

The maximum monthly mean speed was 55.4 km/day (N = 20 fish) for Kentucky Lake and 35.4 km/day (N = 13 fish) for Lake Barkley, and the maximum speed recorded for an individual silver carp in Kentucky Lake was 117.1 km/day and 124.5 km/day in Lake Barkley. silver carp activity peaked in the spring every year for both lakes (**Error! Reference source not found.** and **Error! Reference source not found.**). More fish were tagged and released in Kentucky Lake early in the study, the passive receiver network was established earlier in this lake, and we had data for every month over the 4-year study; thus, we examined the relationship between silver carp movement and temperature, discharge, and elevation in more detail for Kentucky Lake.

In Kentucky Lake, monthly mean speed was not related to surface temperature ($F_{1, 45} = 0.084$, $p = 0.77$, $R^2 = -0.02$: **Error! Reference source not found.**). However, **Error! Reference source not found.** suggests that movement might have been more influenced by the change in temperature. So, mean speed was compared to the mean change in temperature for each month. Speed had a significant, positive relationship to change in temperature ($F_{1, 44} = 10.11$, $p < 0.01$, $R^2 = 0.17$: **Error! Reference source not found.**). Close observation of **Error! Reference source not found.** suggests that mean speed remained at a relatively constant, low rate when temperatures were falling no matter how much the decrease in temperature. However, the speed was more variable when temperatures were climbing. A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between temperature change and speed became different at a threshold temperature change of 0^oC ($D_{max} = 0.129$, $p < 0.01$), so separate regressions were calculated both above and below the 0^oC temperature change cutoff. A linear regression comparing speed and temperature change was not significant for temperature changes below 0^oC ($F_{1,22} = 0.068$, $p = 0.80$, $R^2 = -0.04$) and was also not significant for temperature changes above 0^oC ($F_{1, 20} = 0.11$, $p = 0.74$, $R^2 = -0.04$). Mean speed when temperatures were falling (2.1 ± 0.4(SE) km/day) was significantly less ($t_{21.6} = -3.56$, $p = 0.002$) than mean speed when temperatures were climbing (13.7 ± 3.2(SE) km/day).

A similar pattern, but in the opposite direction, was observed when comparing speed to total discharge (**Error! Reference source not found.** and **Error! Reference source not found.**). As with temperature, monthly mean speed in Kentucky Lake was not related to discharge ($F_{1, 46}$ = 3.08, p = 0.09, R^2 = 0.04), but speed appeared to be influenced by the change in discharge. Change in discharge had a negative, significant effect on mean speed ($F_{1, 46}$ = 34.69, p < 0.001, R^2 = 0.42; **Error! Reference source not found.**). A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between discharge change and speed became different at a threshold discharge change of -650 cms (D_{max} = 0.0919, p = 0.05). A linear regression comparing speed and discharge change was not significant when discharges were increasing ($F_{1,24}$ = 0.21, p = 0.65, R^2 = -0.03) but mean speed had a significant, negative relationship with discharge change when discharge was declining ($F_{1, 20}$ = 26.67, p < 0.001, R^2 = 0.55). Mean speed when discharge was decreasing (12.4 ± 3.3(SE) km/day) was significantly greater ($t_{24.1}$ = 2.65, p = 0.01) than mean speed when discharge was increasing (3.3 ± 0.9(SE) km/day).

Finally, monthly mean speed was compared to lake elevation for both lakes. A spike in activity seemed to be related to rising water levels in both lakes (**Error! Reference source not found.** and **Error! Reference source not found.**), and higher water levels seemed to be related to greater swimming speeds. Mean speed was log transformed to reduce heteroscedasticity and then compared to mean lake elevation for Kentucky Lake. Elevation had a positive, significant effect on log(speed) ($F_{1, 42}$ = 14.09, p < 0.001, R^2 = 0.23; **Error! Reference source not found.**). Change in elevation was not related to mean speed ($F_{1, 46}$ = 3.02, p = 0.09, R^2 = 0.04; **Error! Reference source not found.**). A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between elevation change and speed became different at a threshold elevation change of 0 m (D_{max} = 0.109, p = 0.009). A linear regression comparing speed and elevation change was not significant for elevation changes below 0 m ($F_{1,24}$ = 0.91, p = 0.35, R^2 = -0.004) and was also not significant for elevation changes above 0 m ($F_{1, 20}$ = 0.22, p = 0.64, R^2 = -0.04). Mean speed when elevations were falling (4.1 ± 1.5(SE) km/day) was significantly less ($t_{30.2}$ = -2.11, p = 0.04) than mean speed when elevations were rising (11.4 ± 3.1(SE) km/day).

In summary, silver carp movement was not related to mean water temperature or discharge, but mean speed was greater at higher water levels. Of more importance, though, was the effect of the change in temperature, discharge, and elevation on mean swimming speed. Interestingly, a significant threshold was found at or near a change = 0 for temperature, discharge, and elevation. This suggests that the relationship of these variables to silver carp swimming speed was different when the values were falling compared to when they were rising. For example, swimming speed was the same when temperatures were falling, no matter how much they were falling, but carp swimming speed was greater the faster the water was warming up. The relationship between discharge and mean speed was opposite to temperature; that is, swimming speeds were the same when discharges were rising, but the greater the discharge decreased the faster the fish would swim. Finally, when water levels were falling, the mean speed did not change much. No significant relationship was found between rising water levels and speed, but Figure 11 shows that as water levels rose swimming speed became more variable.

Through this analysis, the effect of temperature, discharge, and elevation on silver carp swimming speed cannot be separated because the changes in these values all occurred around the same time. In the spring, when silver carp activity spiked, the water was warming up, discharge was falling, and lake levels were rising – all simultaneously. Thus, we cannot definitively say which of temperature, discharge, or elevation was the most important influencer on fish activity. Then again, the analysis does clearly show that the changes in these values, not their absolute measurement, is important. Also of interest is that for all of these variables, their relationship with silver carp swimming speed was significantly different when these parameters were falling compared to when they were rising.

However, these patterns are different between the fish tagged by different agencies. The silver carp tagged by KDFWR were captured and released in the lower portions of the lakes and the Barkley Tailwaters; and those fish seemed to demonstrate slower monthly mean speeds with a steadier rate of movement and only moderate increases in activity in the spring (**Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**). The fish captured by MDFWP and TWRA were tagged and released outside of the study area referenced in this report in the upstream portion of Kentucky Lake near Pickwick Dam or in Pickwick Lake and then later migrated downstream through Kentucky Lake and Lake Barkley (hereafter referred to as nonresident fish). Those nonresident fish showed a clear spike in movement rate in the spring as temperatures were rising, discharges were falling, and water levels were rising. Analysis of covariance (ANCOVA) showed that the interaction between temperature change and tagging agency was significantly related to mean speed ($F_{2, 100} = 6.48$, $p = 0.002$), so separate regressions of swimming speed on temperature change were calculated for nonresident and resident fish. Temperature change had a significant, positive effect on mean speed for nonresident fish ($F_{1, 58} = 20.86$, $p < 0.001$, $R^2 = 0.25$) but had no significant relationship with mean speed for resident fish ($F_{1, 44} = 2.79$, $p = 0.10$, $R^2 = 0.04$).

Similarly, an ANCOVA showed that the interaction between change in discharge and tagging agency was significant ($F_{2, 106} = 13.04$, $p < 0.001$), so separate regressions of swimming speed on discharge change were calculated for resident and nonresident fish. Discharge change had a significant, negative effect on mean speed for nonresident fish ($F_{1, 62} = 39.97$, $p < 0.001$, $R^2 = 0.38$) but had no significant relationship with mean speed for resident fish ($F_{1, 46} = 3.75$, $p = 0.06$, $R^2 = 0.06$).

Lastly, an ANCOVA showed that the interaction between change in elevation and tagging agency was significantly related to mean speed ($F_{2, 106} = 3.22$, $p = 0.04$), so separate regressions of swimming speed on elevation change were calculated for resident and nonresident fish. Elevation change had a significant, positive effect on mean speed for nonresident fish ($F_{1, 62} = 8.32$, $p = 0.005$, $R^2 = 0.10$) but had no significant relationship with mean speed for resident fish ($F_{1, 46} = 0.0071$, $p = 0.93$, $R^2 = -0.02$).

Many of the silver carp detected on receivers used for this analysis as resident fish were captured, tagged, and released in the Barkley Tailwaters by KDFWR to study the effectiveness of the BAFF in the Barkley Lock (hereafter referred to as BAFF fish). Any of these BAFF fish which were detected in the lakes (i.e. upstream of the dams) crossed through either Kentucky or Barkley Locks voluntarily. Thus, these fish might represent a separate population whose origin is closer to our study area relative to the nonresident fish from in or near Pickwick Lake but may also be somewhat more prone to movement. No matter the time of year, the nonresident fish had greater mean monthly speeds than the resident fish (**Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.**). In fact, mean speed was significantly greater for nonresident fish compared to the resident fish ($F_{3,140} = 9.316$, $p < 0.001$; **Error! Reference source not found.**). Although the BAFF fish had a higher average speed compared to the fish tagged by KDFWR and released in Kentucky Lake, this difference was not significant. The BAFF fish mean speed was also not significantly different from the fish tagged by TWRA. Additionally, nonresident fish not only moved faster than resident fish, but also their mean range (maximum river kilometer (RK) minus the minimum RK) was significantly greater than resident fish ($F_{3,164} = 102.6$, $p < 0.001$; **Error! Reference source not found.**). The range of the BAFF fish was not significantly different from the range of the fish tagged by KDFWR in Kentucky Lake.

These analyses indicate that the silver carp population in Kentucky Lake and Lake Barkley is a mixture of “homers” and “roamers”, i.e. some silver carp are predisposed to stay in one area while others are more likely to roam over large distances. Both “homers” and “roamers” have likely been tagged in Kentucky waters, but our “roamers” have left and not returned, while the nonresident fish from near or in Pickwick Lake which move down through Kentucky Lake are more likely to roam. The BAFF fish which were detected above the dams could be considered “roamers” on a smaller scale relative to the fish that originated near Pickwick Lake, but neither their mean swimming speed nor their mean range was significantly different from the fish which were captured, tagged, and released in Kentucky Lake by KDFWR and MSU. The difference in activity between KDFWR fish and Pickwick Lake fish was not likely due to size. Mean size of KDFWR silver carp in Kentucky Lake (including the BAFF fish) was 787.7 ± 12.9(SE) mm which was not significantly different from MDWFP fish (786.9 ± 9.0(SE) mm) but fish from these groups were significantly longer than TWRA fish (584.7 ± 10.6(SE) mm, $F_{2,155} = 63.85$, $p < 0.001$). Overall, fish length was not related to movement rate ($F_{1, 122} = 0.0035$, $p = 0.95$, $R^2 = -0.008$) nor was sex ($t_{28.9} = -0.56$, $p = 0.58$). However, no information was available concerning the sex of the nonresident fish from near or in Pickwick Lake.

Close examination of the nonresident fish showed that many of these fish made their long migrations downstream during March, April, and May of 2019 and 2020. Since these fish presumably came from Pickwick Lake or its tailwaters they might have been more influenced by the discharge at Pickwick Lake Dam. The plot of monthly mean discharge from 2015 – 2020 shows that the Pickwick Lake discharge was extremely high in February of 2019 and 2020, which might have triggered those fish to move downstream (**Error! Reference source not found.**). Other researchers have shown that silver carp are triggered to move upstream by rising water levels and increases in discharge, presumably as part of spawning activities (Coulter et al. 2016), so the fact that the nonresident fish were stimulated by peaks in discharge to move downstream is interesting.

Also interesting is the overall relationship of discharge to spawning activity in Kentucky Lake. During the summer of 2015 young of year (YOY) silver carp were documented in Kentucky Lake for the first time, and have not been documented in the lakes since then. Therefore, it is likely that silver carp spawned in Kentucky Lake in 2015, so examination of the monthly mean discharge in Kentucky Lake was conducted for 2015 and compared to the monthly mean discharge for the years 2016 – 2020 when no YOY silver carp were documented. Discharge was lower during winter of 2015 relative to the other years, and a large spike in discharge was seen in July of 2015 (**Error! Reference source not found.**). Analysis of adult age classes of silver carp collected in Kentucky Lake suggested that other strong year classes were present in 2010, 2011, and 2012. These strong year classes might also be evidence of spawning in Kentucky Lake, so these were considered spawning years along with 2015 for analysis and compared to other years which were considered non-spawning years (2009, 2013, 2014, and 2016 – 2019). Monthly mean discharge from Kentucky Lake during the years when a spawn likely occurred was consistently lower than years when no spawn occurred (**Error! Reference source not found.**). A paired t-test showed that discharge was significantly lower in potential spawning years compared to non-spawning years ($t_{11} = 3.45$, $p = 0.005$).

Burst Speed

Silver carp movement can be studied at several scales; for example, the previous analysis summarized each fish's swimming rate in km/day and then summarized these values by month. Such an analysis is good for looking at overall activity levels across times, and it gives an idea of the distances that a silver carp can cover in a day. These values are based upon an "average" location and an "average" time each day, which gives an estimate of the general location of a fish each day. However, this analysis underestimates the swimming rates of fish because it is greatly influenced by the time periods when the fish is not moving much. To understand short-term swimming rates, we focused only on those times when a fish was moving from one set of passive receivers to the next nearest set of passive receivers, which we call "burst" swimming speed.

To calculate burst speed, the distance traveled (in km) when the fish was moving between different locations was divided by the time (in hours) it took to swim that distance. Only successive locations which were 24 hours apart or less were used to calculate burst speed. Also, since synchronization of the clocks on all passive receivers is not perfect, and sometimes a fish sitting between 2 receivers can be detected by both of them at the same time, all locations which were less than 1 hour apart were also excluded.

The mean burst speed of KDFWR silver carp was 1.6 ± 0.2(SE) km/hr which would translate into approximately 38.4 km/day (**Error! Reference source not found.**). silver carp which were tagged by other agencies had a higher mean burst speed as did BAFF fish (**Error! Reference source not found.**).

Location

Not only is swimming speed and activity important, but also of interest is the location of the fish within each lake over time. To determine the average location of the silver carp within our study area of Kentucky Lake over time, the average river kilometer (RK) for each fish on each day was calculated first. Next, the mean RK for each fish each month was calculated which provides the average location of each fish each month. Finally, the mean RK across all fish each month was calculated to provide a general idea of the location of the silver carp population within the lake each month. The median monthly RK in Kentucky Lake for 2017 – 2020 was 72.5 km which is near the Hancock Biological Station (HBS), so the mean location of silver carp each month was compared to this location. To understand the relative position of silver carp, we subtracted the median value of 72.5 from each month's mean RK to get an adjusted RK. The adjusted RK for a month would be negative if the average location of the fish was downstream from HBS, and positive if the average location was upstream from HBS. Using this analysis, silver carp in Kentucky Lake seemed to be located in the lower part of the lake in 2017, mostly upstream in mid-2018 to late 2019, and then in the middle to low portion of the lake in 2020 (**Error! Reference source not found.**).

In Lake Barkley, the median RK of our study area was 72.8 which is just downstream from Eddy Creek, so all monthly mean RK values were adjusted based upon their relationship to this median location. Silver carp location was mostly downstream in Lake Barkley from 2017 through mid-2019, then the fish all shifted upstream from mid-2019 through 2020 (**Error! Reference source not found.**).

The location of the silver carp population was also visualized by calculating the mean RK for each fish each season. A point location for each of these mean values was created in ArcMap, and then all points for a season were used in the Kernel Density Estimate tool to create a heat map of fish locations in each lake (**Error! Reference source not found.**). In the spring tagged silver carp in Kentucky Lake were concentrated in the middle portion of the lake, but in Lake Barkley fish were concentrated near the dam. In the summer, the fish spread out in both lakes but more so in Kentucky Lake. The fish were concentrated near the dam during fall in both lakes, while the winter pattern was similar to the spring pattern for both lakes.

The distribution of the silver carp population in each season was likely influenced by the migration of the nonresident fish from near or in Pickwick Lake down into Kentucky Lake and back upstream each year. To visualize the movement direction of the carp, the daily movement of each fish was categorized as upstream, downstream, or no movement. The percentage of each type of movement was calculated for each fish each month, and then the mean percentage of each type of movement was determined across all fish each month. Most of the time, fish did not move much in each lake, but in Kentucky Lake the fish moved downstream slightly more often in early spring and then back upstream over a longer time period later in each year (**Error! Reference source not found.**). Lake Barkley fish did not show a clear pattern in their upstream and downstream movements, and they seemed to have a higher proportion of fish that did not move. The passive receiver network is not as developed in Lake Barkley as in Kentucky Lake, so there is less ability to detect subtler movement.

Dam Passage

Determining whether a tagged fish crossed a dam is done by documenting detections of that fish on either side of the dam. However, which dam was crossed or when it was crossed cannot always be determined. Also, sometimes there are detections of a fish on either side of the dam, but the fish may not have crossed the dam. For example, often fish are detected on a receiver below the dam, in the lock, and above the dam all around the same time. This usually indicates that the fish is in or near the lock, but the signal is bouncing all the way through (perhaps when the gates are open) even though the fish has not actually crossed the dam. So, for the following analysis, only dam crossings which are unambiguous where the fish is detected far enough upstream or downstream to indicate that it definitely crossed a dam were used.

In total, 66 crossings were documented at Barkley Dam, 19 crossings at Kentucky Dam, and 21 crossings which were known to be crossings, but which dam was crossed could not be determined (**Error! Reference source not found.**). The majority of crossings detected were silver carp, which is unsurprising given that more silver carp have been tagged relative to other species (**Error! Reference source not found.**). The “unknown dam” crossings occurred when fish were not detected inside a lock, but were detected on either side of the dam. However, a long enough time had elapsed between detections (usually more than 24 hours) that the fish might have crossed either Kentucky or Barkley dam.

Many of the fish in this study were captured, tagged, and released just below the Lake Barkley Dam to study the effectiveness of the BAFF (**Error! Reference source not found.**). Percent of BAFF fish which eventually crossed a dam ranged from 2% (freshwater drum) to 13% (paddlefish; **Error! Reference source not found.**), but the percent of fish that crossed a dam was not significantly different among species ($\chi^2 = 4.40$, df = 3, p = 0.22). Most BAFF fish crossed the Lake Barkley Dam (34) but 6 of the crossings by BAFF fish were across the Kentucky Dam, and 1 crossing of a BAFF fish was for an unknown dam. For BAFF fish that eventually crossed a dam, mean days until first crossing was not significantly different among species ($F_{3,33}$ = 0.702, p = 0.56; **Error! Reference source not found.**).

Some of the silver carp which were captured, tagged, and released above Kentucky and Barkley dams also crossed the dams; the fish tagged near or in Pickwick Lake crossed more often than fish which were tagged closer to the dams (**Error! Reference source not found.**). Many of these fish, after swimming the length of Kentucky Lake, crossed one of the dams but then came back into the lakes by crossing a dam again. Fish tagged by TWRA and MDWFP had more individuals which crossed a dam multiple times compared to fish tagged by other agencies (**Error! Reference source not found.**).

Although the locks are small and any fish passing through them should be detected, we recorded 36 downstream crossings which were not detected inside one of the locks (**Error! Reference source not found.**). Possibly these fish were not detected because they can cross the dam without using the lock. For example, the fish might be going through the dam when the water levels are high enough that the gates are opened. In fact, 90% of the downstream crossings were not detected in a lock, while 100% of upstream crossings were detected inside a lock (**Error! Reference source not found.**). Clearly the fish are using different routes to cross the dams in the downstream direction compared to the upstream direction.

If the fish were crossing downstream through the dam gates during high water levels, an increase in such crossings when the dams are spilling water would be expected. Indeed, at Barkley Dam silver carp were detected going downstream on 9 separate dates (13 carp crossings total) and the dam was spilling on all but 2 of those dates (mean spill volume = 455 ± 149(SE) m^3/s, range = 0 – 1,419 m^3/s, **Error! Reference source not found.**). Interestingly, only 2 other fish were detected crossing Barkley Dam going downstream; both were paddlefish and both crossed while the dam was not spilling. Fish crossing downstream at Barkley Dam only used the lock 2 times; 1 paddlefish used the lock when the dam was not spilling, and 1 silver carp used the lock, again when the dam was not spilling. Thus, 1 paddlefish and 1 silver carp crossed the dam heading downstream when the dam was not spilling, but these fish were not detected inside the lock so we are unsure how they crossed the dam. The paddlefish was detected at Green Turtle Marina and then was detected below Barkley Dam about 2 hours later. Given the number of receivers both inside and nearby Barkley Lock, we would expect to have detected this fish if it did indeed use the lock. So, it found an alternate route for downstream crossing even though the gates were not spilling. Similarly, the silver carp which crossed downstream when the dam was not spilling was detected at Green Turtle and just above the lock, but it was not detected at all by any of the other receivers in and around the Barkley Lock. One potential explanation of this phenomenon could be that the fish are using the filling and discharge ports for the Lock as a means of traversing the dam structure.

All silver carp upstream crossings at Barkley Dam, except 1, occurred when Lake Barkley was not spilling (**Error! Reference source not found.**). Spill flow for this 1 carp crossing was 115 m^3/s. Similarly, all smallmouth buffalo which crossed Barkley Dam heading upstream crossed when the spill discharge was = 0 m^3/s. Barkley Dam was moderately spilling when upstream crossings occurred for paddlefish (mean spill volume = 87 ± 58(SE) m^3/s, range = 0 – 380 m^3/s) and freshwater drum (mean spill volume = 379 m^3/s).

At Kentucky Dam, carp again only crossed the dam heading downstream when the dam was spilling, but at a higher spill rate than the downstream crossings at Barkley Dam (4 dates, 1 silver carp on each date; mean spill volume = 5,453 ± 2,223(SE) m^3/s, range = 753 – 10,798 m^3/s; **Error! Reference source not found.**). On 2 dates silver carp crossing Kentucky Dam heading downstream were detected inside the lock, so although the lake was spilling those fish decided to use the lock instead of the gates. Interestingly, on both those dates the spill discharge was very high because the turbines were not running. Perhaps a maximum spill threshold exists beyond which the carp cannot pass through the gates, so when the turbines are off the fish cannot use the gates and instead choose to use the lock. Just like at Barkley Dam, most of the upstream crossings at Kentucky Dam occurred when the dam was not spilling, but upstream crossings sometimes did occur when the dam was spilling water at a low volume (**Error! Reference source not found.**, mean spill volume of these crossings = 345 ± 187(SE) m^3/s, range = 0 – 2,376 m^3/s). As with Barkley Dam, all upstream crossings at Kentucky Dam were detected in the lock.

On 21 occasions silver carp crossed downstream, but we were unable to determine exactly when the fish crossed, and which dam was crossed (**Error! Reference source not found.**). Since all these crossings were downstream and were not detected in any locks, these fish most likely went through the dam gates or some alternate passageway.
Spill discharge was averaged each month for Barkley Dam and then compared to the direction of silver carp dam crossings. carp crossed Barkley Dam at significantly lower spill discharges relative to months when no crossings occurred ($F_{2, 34}$ = 8.41, p = 0.001; **Error! Reference source not found.**) but mean monthly spill was not significantly different between downstream and upstream crossings. At Kentucky Dam, downstream crossings happened when spill discharge was significantly higher than upstream crossings or no crossings ($F_{2, 34}$ = 8.41, p = 0.001; **Error! Reference source not found.**). Note that spill discharge was 2-3 times as great at Kentucky Dam as at Barkley Dam; also recall that 2 of the silver carp downstream crossings at Kentucky Dam took place during such high spill discharge that the fish used the lock to go downstream instead of swimming through the gates.

Since temperature seemed to influence activity in silver carp, dam crossings were compared to temperature for both lakes (**Error! Reference source not found.** and **Error! Reference source not found.**). Mean monthly temperature was compared among months that had no crossings, downstream crossings, and upstream crossings. Mean temperature during upstream crossings of Barkley Dam was significantly higher than months when no crossing happened but was not different from mean temperature during downstream crossings ($F_{2, 33} = 14.92$, $p < 0.001$; **Error! Reference source not found.**). Similarly, fish crossed Kentucky Dam at significantly higher temperatures relative to downstream crossings and no crossings ($F_{2, 33} = 7.00$, $p = 0.003$; **Error! Reference source not found.**).

Since both spill discharge and temperature seemed to influence silver carp dam crossings, linear regression was used to investigate the influence of these parameters on the total number of fish that crossed Barkley Dam each month. The original model suggested that temperature, but not spill discharge nor the interaction of temperature and spill discharge, had a significant relationship to total number of fish crossing each month. So, the model was simplified and showed that temperature had a significant, positive effect on total number of fish crossing each month ($F_{1, 34} = 23.06$, $p < 0.001$, $R^2 = 0.39$; **Error! Reference source not found.**). A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between temperature and number of silver carp crossing became different at a threshold temperature of 16°C ($D_{max} = 0.180$, $p = 0.000$). In fact, only a single carp ever crossed the Lake Barkley Dam at a temperature below 16°C. We did not perform this analysis for crossings at Kentucky Dam because we did not observe sufficient variability in the number of fish crossing per month to make the regression viable.

Mean temperature and spill discharge when fish crossed a dam was compared among all species which crossed a dam and also between downstream and upstream crossings. For Barkley Dam, the mean temperature of fish crossings was not significantly different among species ($F_{3,47} = 1.65$, $p = 0.19$) but mean temperature for downstream crossings was significantly higher compared to upstream crossings ($F_{1,47} = 17.65$, $p < 0.001$); however, a significant interaction between species and crossing direction indicated that the mean temperature for each crossing direction was different for different species ($F_{1,47} = 24.68$, $p < 0.001$; **Error! Reference source not found.**). The mean spill discharge of fish crossings was not significantly different among species ($F_{3,51} = 1.20$, $p = 0.32$) but mean spill discharge for downstream crossings was significantly higher compared to upstream crossings ($F_{1,51} = 31.86$, $p < 0.001$); however, a significant interaction between species and crossing direction indicated that the mean spill discharge for each crossing direction was different for different species ($F_{1,51} = 10.79$, $p = 0.002$; **Error! Reference source not found.**4). Not enough different species crossed the Kentucky Dam for comparison of crossing temperature and spill discharge among different species.

Many fish have been tagged and released in the Lower Cumberland and Lower Tennessee Rivers, and several fish which were tagged above the dams have crossed out of the lakes. The receiver network in the lower Ohio River has been expanded in recent years and has detected several of these fish (**Error! Reference source not found.**)

Conclusion

Silver carp movement data will continue to be collected in Kentucky Lake and Lake Barkley while funding and staff are available. The passive receiver network in both lakes is well-developed, and no significant gaps exist. The network will require a great deal of maintenance in 2021 and into the future as receivers need to be downloaded, batteries need to be replaced, and malfunctioning receivers need to be replaced. Now that the Bio-Acoustic Fish Fence below Barkley Lock is active, measuring fish movement across the dams will continue to be very important. We have been able to draw many conclusions from the data because the receiver network is so dense, plus large numbers of fish have been tagged every year.

Recommendation:

- Continued monitoring of telemetry receivers and data analyses are required to determine what conditions encourage successful lock passage, which will allow a more comprehensive review of detterent options and prioritization.
- Interpopulation dynamics (e.g., immigration and emigration) between bigheaded carp in Barkley and Kentucky reservoirs should be described to determine the importance of isolating populations (e.g., will source-sink population dynamics occur if carp are suppressed in one reservoir and not the other or will effective population controls on one river be negated by ineffective controls on the other).
- Telemetry reciever arrays should be tested and adaptivley-managed to ensure robust ability to detect transmitters above, in, and below locks. Providing robust data regarding not only successful passage but also unsuccessful passage attempts is necessary to evaluate management needs and prioritize future detterents.

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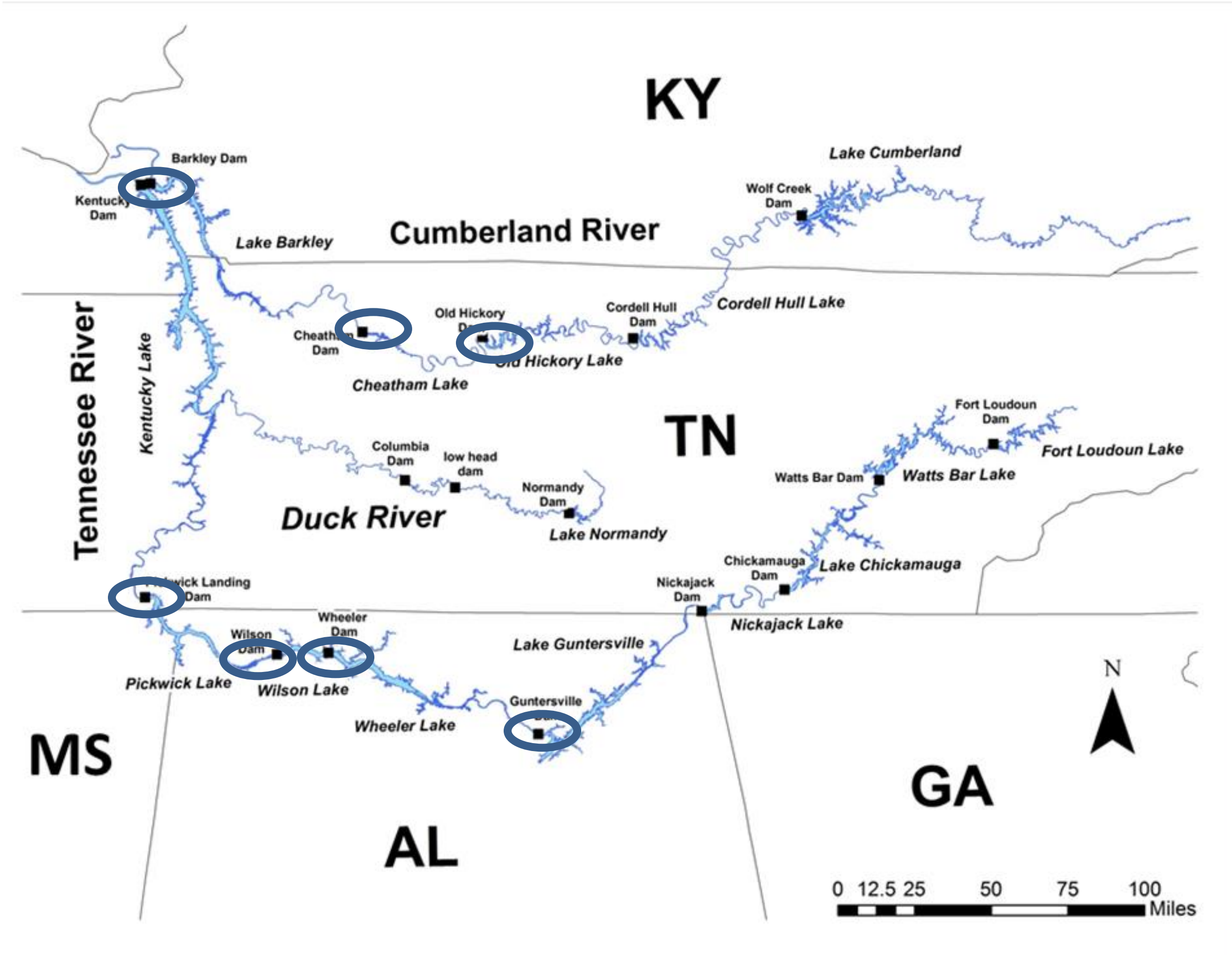


Figure 1. *The Tennessee River and Cumberland River locks and dams (circled) that are monitored using acoustic telemetry receivers to measure Asian carp upstream invasion.*

Table 1. Number of detections of tagged bigheaded carp detected by receivers in the indicated area and year.

	Year			
Area	2017	2018	2019	2020
Cheatham Lock	0	0	10	19
Pickwick Lock A	0	174	920	700
Pickwick Lock B	0	49	310	324
Pickwick Reservoir	3,412	13,260	8,798	23,286
Kentucky Reservoir	209	219,673	59,110	18,135
Total	3,621	233,156	69,148	42,464

Table 2. Number of individual bigheaded carp detected by receivers in the indicated area and year.

	Year			
Area	2017	2018	2019	2020
Cheatham Lock	0	0	1	2
Pickwick Lock A	0	2	4	4
Pickwick Lock B	0	2	6	2
Pickwick Reservoir	2	13	32	22
Kentucky Reservoir	1	40	50	38

Table 3. Number of individual bigheaded carp that were detected inside a lock at Pickwick Reservoir by travel-type, year, and lock. Travel-type includes direction of travel and weather the fish passed through the lock or returned to the pool it had entered the lock from (e.g. return downstream indicates a bigheaded carp entered the lock from Kentucky Reservoir and returned to Kentucky Reservoir).

	Lock A			Lock B		
Travel-type	2018	2019	2020	2018	2019	2020
Return Downstream	1	4	3	2	3	1
Return Upstream	0	0	0	0	3	0
Pass Downstream	0	0	1	0	0	0
Pass Upstream	2	3	0	0	1	0

Table 4. Detected movements of bigheaded carp between Kentucky and Pickwick reserovirs. Detections of movement between reservoirs occurred when an individual fish was detected on any two recievers that were in different reservoirs.

	Movement between Kentucky and Pickwick	
Year	Downstream	Upstream
2018	9	2
2019	18	7
2020	18	0

KDFWR

Table 1. Summary of silver carp surgically implanted with acoustic transmitters in the Barkley Tailwaters during 2020.

Surgery Date	# Tagged F	# Tagged M	TL (mm) Mean ± SE F	TL (mm) Mean ± SE M	W (g) Mean ± SE F	W (g) Mean ± SE M	Release Location
April 2020	31	44	653 ± 15	662 ± 11	2,743 ± 182	2,764 ± 153	Barkley Tailwaters
December 2020	39	36	644 ± 5	639 ± 7	2,303 ± 68	2,201 ± 66	Barkley Tailwaters
Total	70	80	648 ± 7	652 ± 7	2,498 ± 92	2,511 ± 94	

Table 2. Summary of freshwater drum surgically implanted with acoustic transmitters in the Barkley Tailwaters during 2020.

Surgery Date	# Tagged	TL (mm) Mean ± SE	W (g) Mean ± SE	Release Location
April 2020	12	489 ± 26	1,818 ± 383	Barkley Tailwaters
December 2020	20	437 ± 9	1,061 ± 72	Barkley Tailwaters
Total	32	457 ± 12	1,345 ± 161	

Table 3. Summary of paddlefish surgically implanted with acoustic transmitters in the Barkley Tailwaters during 2020.

Surgery Date	# Tagged	TL (mm) Mean ± SE	W (g) Mean ± SE	Release Location
April 2020	2	610 ± 35	2,380 ± 580	Barkley Tailwaters
December 2020	20	816 ± 22	7,319 ± 708	Barkley Tailwaters
Total	22	797 ± 24	6,870 ± 714	

Table 4. Summary of smallmouth buffalo surgically implanted with acoustic transmitters in the Barkley Tailwaters during 2020.

Surgery Date	# Tagged	TL (mm) Mean ± SE	W (g) Mean ± SE	Release Location
April 2020	20	484 ± 16	1,875 ± 243	Barkley Tailwaters
December 2020	20	520 ± 16	2,165 ± 220	Barkley Tailwaters
Total	40	502 ± 12	2,020 ± 163	

Table 5. Summary of live silver carp detections by tagging agency and year for study area encompassing portions of Kentucky Lake, the Lower Tennessee River, Lake Barkley, and the Lower Cumberland River combined. Table values indicate the number of unique individuals detected in each category.

	2016	2017	2018	2019	2020
KDFWR	36	38	82	174	197
MDWFP			9	24	27
TWRA			11	24	25
USFWS			1	1	
USGS					60
Total	36	38	103	223	309

Table 6. Summary of live fish detections by species, excluding silver carp, and year for study area encompassing Kentucky Lake, the Lower Tennessee River, Lake Barkley, and the Lower Cumberland River combined. Table values indicate the number of unique individuals detected in each category.

Species*	2016	2017	2018	2019	2020
Bighead carp	1	1	1		
Freshwater drum				14	33
Grass carp			1		
Paddlefish	4	5	4	20	33
Smallmouth buffalo				35	72
Unknown			4	12	25
Total	5	6	10	81	163

*Bighead carp was tagged by Southern Illinois University, Carbondale (SIUC); freshwater drum were tagged by KDFWR; grass carp was tagged by the Missouri Department of Conservation (MDC); paddlefish prior to 2019 were all tagged by MDC and paddlefish from 2019 on were a mix of fish tagged by MDC and KDFWR; smallmouth buffalo were tagged by KDFWR; and the Unknown fish have not yet been identified.

Table 7. Mean burst speed for silver carp in Kentucky Lake, 2017 – 2020. Burst speed represents the swimming speed of a fish when it is swimming from one set of passive receivers to the next nearest set of passive receivers.

Agency	Mean Swimming Speed (km/hr)	SE	N	Range (km/hr)
BAFF*	1.8	0.3	21	(0.4 – 5.6)
KDFWR	1.6	0.2	24	(0.5 – 4.7)
MDWFP	3.7	0.2	39	(1.0 – 6.9)
TWRA	2.7	0.2	34	(0.6 – 5.9)

* BAFF = Bio-Acoustic Fish Fence (fish captured, tagged, and released by KDFWR in the Lake Barkley tailwaters)

Table 8. Number and direction of fish crossing either Kentucky or Barkley dam 2018-2020. Fish crossing totals include any species tagged by any agency, including unknown species, and represent the total number of crossings, not the total number of individuals (i.e. totals include some fish which crossed more than once).

Dam Crossed	Downstream	Upstream
Barkley	15	51
Kentucky	4	15
Unknown dam	21	-
Total	40	66

Table 9. Number and direction of fish crossing either Kentucky or Barkley dam 2018-2020 by species. Fish crossings totals include any species tagged by any agency, including unknown species, and represent the total number of crossings, not the total number of individuals (i.e. totals include some fish which crossed more than once).

	Dam Crossed	Downstream	Upstream
Freshwater drum	Barkley	-	1
	Kentucky	-	-
	Unknown dam	-	-
Paddlefish	Barkley	2	7
	Kentucky	-	-
	Unknown dam	-	-
Silver carp	Barkley	13	38
	Kentucky	4	14
	Unknown dam	21	-
Smallmouth buffalo	Barkley	-	5
	Kentucky	-	-
	Unknown dam	-	-
Unknown species	Barkley	-	-
	Kentucky	-	1
	Unknown dam	-	-

Table 10. Number of fish captured, tagged, and released by KDFWR below Barkley Dam by species and year.

Date	Freshwater drum	Paddlefish	Silver carp	Smallmouth buffalo
2017	0	0	20	0
2018	0	0	41	0
2019	20	16	149	41
2020	32	22	150	40
TOTAL	52	38	360	81

Table 11. Number of fish which were captured, tagged, and released by KDFWR below Barkley Dam which eventually crossed Barkley or Kentucky dams. Crossing rate was similar among all species (χ^2 = 4.40, df = 3, p = 0.22).

	Freshwater drum	Paddlefish	Silver carp	Smallmouth buffalo
Did not cross a dam	51	33	334	76
Did cross a dam	1	5	26	5
Total Fish Tagged	52	38	360	81
Pct.	2%	13%	7%	6%

Table 12. Mean time (days) from tagging to first dam crossing by species for fish which were captured, tagged, and released below Barkley Dam. Mean days until first crossing was not significantly different among species ($F_{3,33}$ = 0.702, p = 0.56).

	Freshwater drum	Paddlefish	Silver carp	Smallmouth buffalo
Mean days until first crossing	16.0	187.4	162.5	116.0
SE	-	58.8	25.3	45.5
Range (days)	-	28 – 394	2 – 534	26 – 237

Table 13. Number of silver carp crossings for fish which were captured, tagged, and released upstream of Kentucky and Barkley dams 2017-2020. Fish crossings represent the total number of crossings, not the total number of individuals (i.e. totals include some fish which crossed more than once).

	Dam Crossed	Downstream	Upstream
KDFWR	Barkley	-	1
	Kentucky	1	2
	Unknown dam	5	-
MDWFP	Barkley	6	8
	Kentucky	2	3
	Unknown dam	10	-
TWRA	Barkley	7	9
	Kentucky	1	-
	Unknown dam	5	-

Table 14. Frequency distribution of the number of dams crossed by individual fish for each species and owner.

		# Dams Crossed			
Species	Owner	1	2	3	4
Freshwater drum	BAFF	1	-	-	-
Paddlefish	BAFF	3	1	1	-
	MDC	1	-	-	-
Silver carp	BAFF	25	1	-	-
	KDFWR	3	3	-	-
	MDFWP	7	9	-	1
	TWRA	4	9	-	-
Smallmouth buffalo	BAFF	5	-	-	-
Unknown	Unknown	1	-	-	-

Table 15. Number of detections inside a lock for fish (all species combined) which were crossing in a downstream direction compared to fish crossing in an upstream direction.

	Downstream		Upstream	
Dam Crossed	Not Detected in Lock	Detected in Lock	Not Detected in Lock	Detected in Lock
Barkley	13	2	-	51
Kentucky	2	2	-	15
Unknown dam	21	-	-	-
TOTAL	36	4	-	66
% of total	90%	10%	0%	100%

Table 16. Number of unique individuals detected at passive VEMCO receiver stations on the lower Ohio River, 2018-2020. The Tennessee River mouth is at RK 1,502 and the Cumberland River mouth is at RK 1,485**.**

Species	Owner	Brookport Bridge (RK 1,509)	Smithland Lock and Dam (RK 1,479)	J. T. Meyers Lock and Dam (RK 1,362)	Newburgh Lock and Dam (RK 1,250)
Freshwater drum	BAFF	11	-	-	-
Paddlefish	BAFF	6	8	1	1
	MDC	2	-	-	-
Silver carp	BAFF	66	25	-	-
	KDFWR	-	1	-	-
	MDWFP	10	15	4	3
	TWRA	1	8	2	-
Smallmouth buffalo	BAFF	4	2	-	-
Unknown	Unknown	4	1	-	3

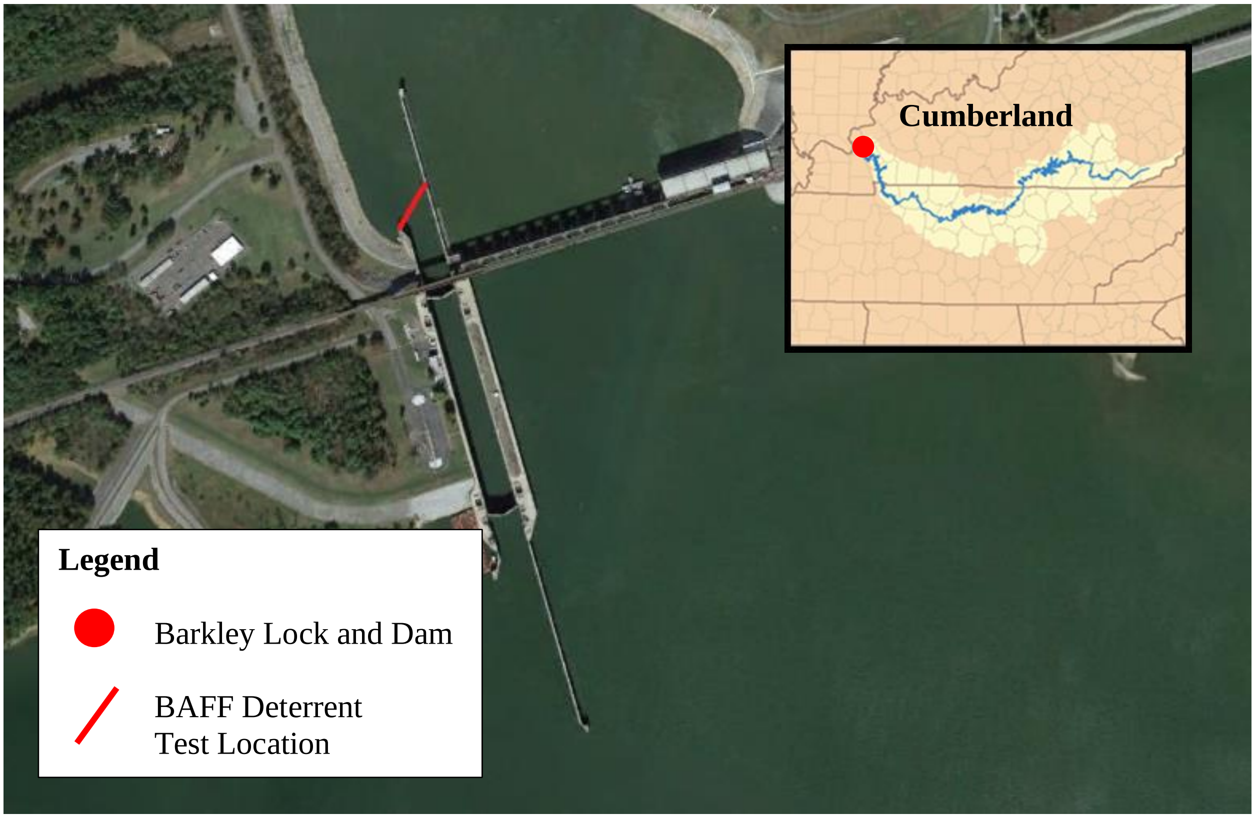


Figure 1. Location of Bio-Acoustic Fish Fence (BAFF) deterrent system being tested at Lake Barkley Lock and Dam on the Cumberland River.

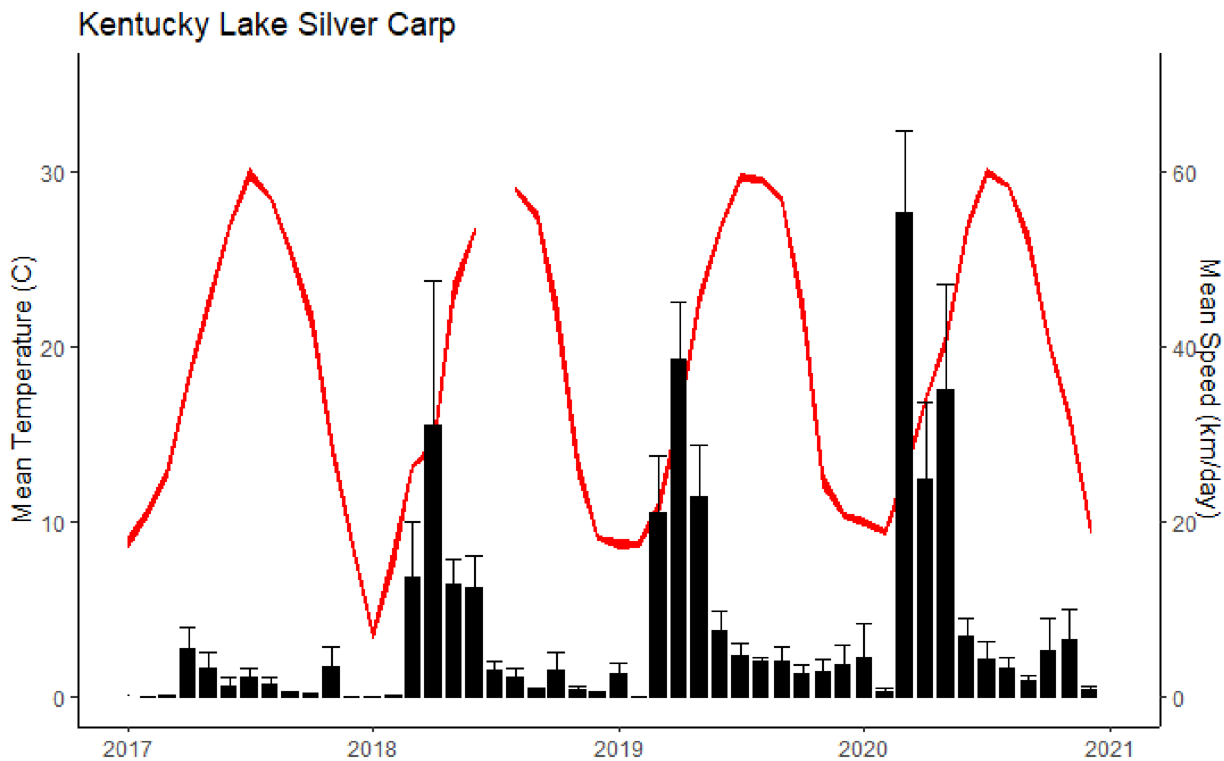


Figure 2. Monthly mean (with SE) surface temperature (ºC, red line, measured in Kentucky Lake) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp in Kentucky Lake, 2017 – 2020. Fish were detected every month, so months with mean speed = 0.0 km/day represent actual movement rates and not missing data.

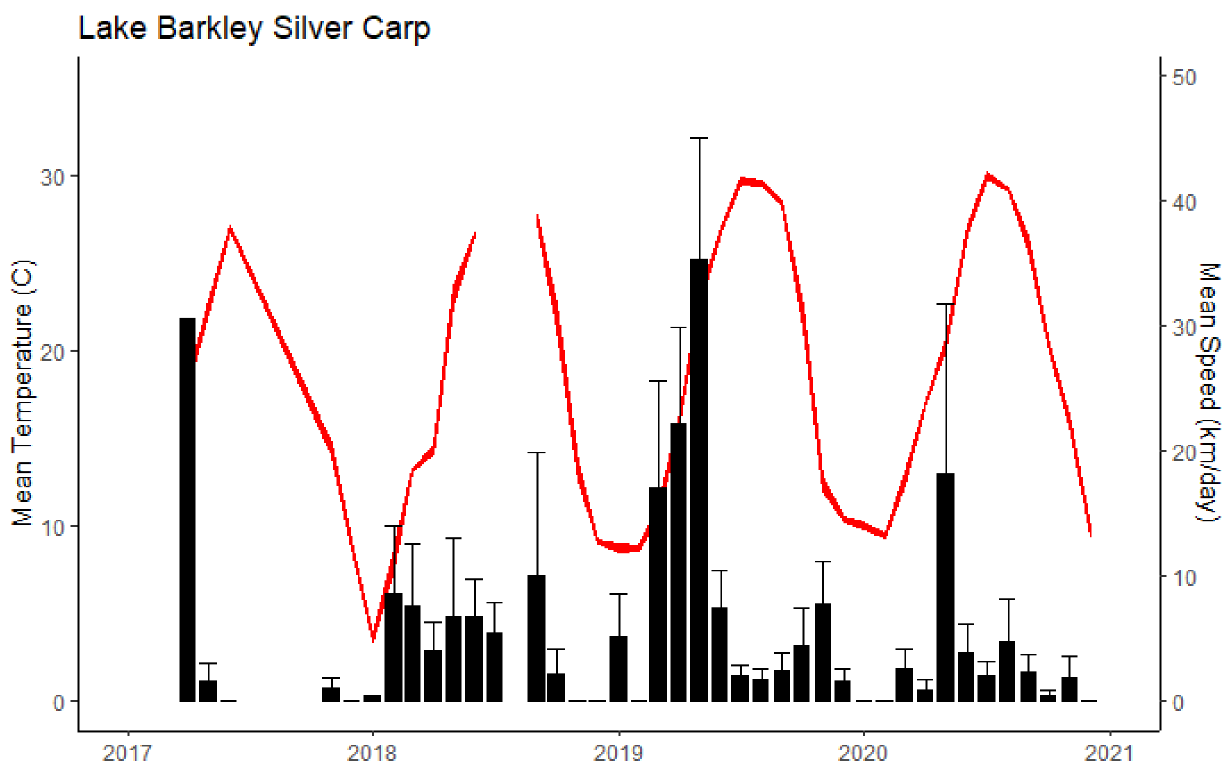


Figure 3. Monthly mean (with SE) surface temperature (ºC, red line, measured in Kentucky Lake) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp in Lake Barkley, 2017 – 2020. Fish were detected every month after 2017-11 except 2018-08, so months with mean speed = 0.0 km/day represent actual movement rates and not missing data.

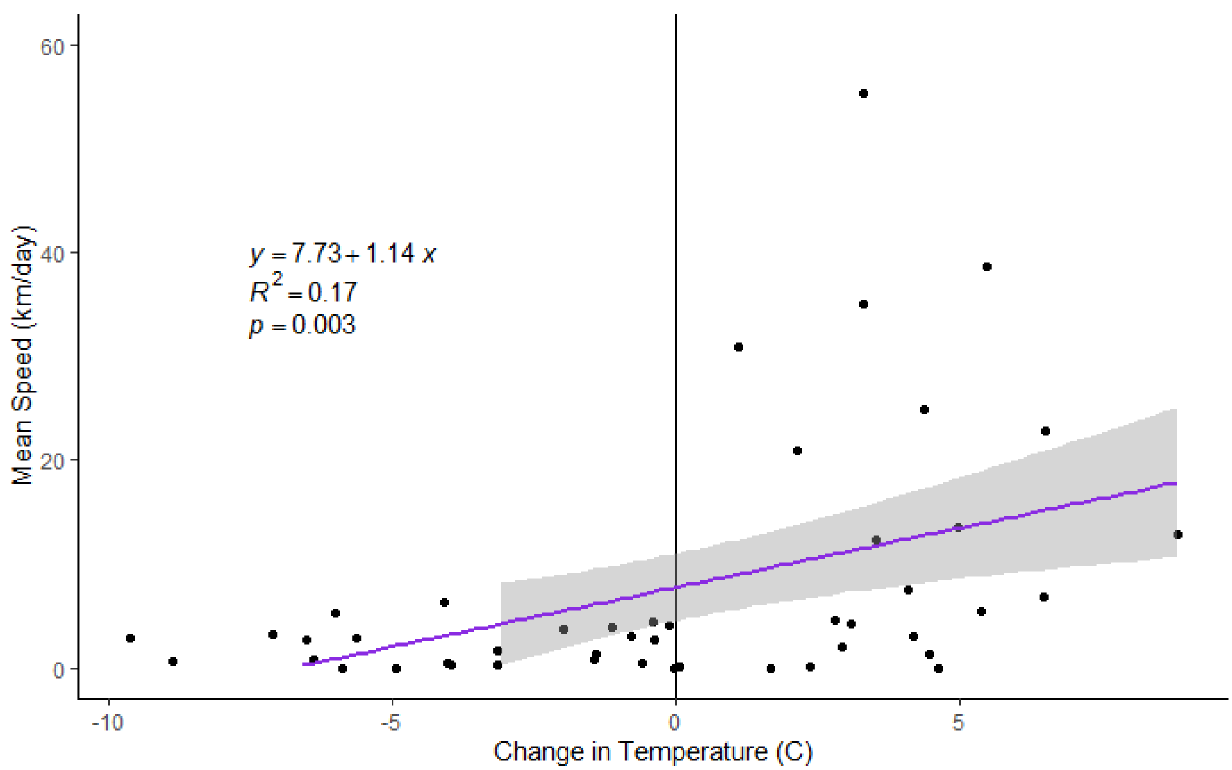


Figure 4. Change in temperature had a significant, positive relationship to silver carp swimming speed in Kentucky Lake ($F_{1, 44} = 10.11$, $p < 0.01$, $R^2 = 0.17$). A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between temperature change and speed became different at a threshold temperature change of 0ºC ($D_{max} = 0.129$, $p < 0.01$). The relationship between speed and temperature change was not significant for temperature changes below 0ºC ($F_{1,22} = 0.068$, $p = 0.80$, $R^2 = -0.04$) and was also not significant for temperature changes above 0ºC ($F_{1, 20} = 0.11$, $p = 0.74$, $R^2 = -0.04$).

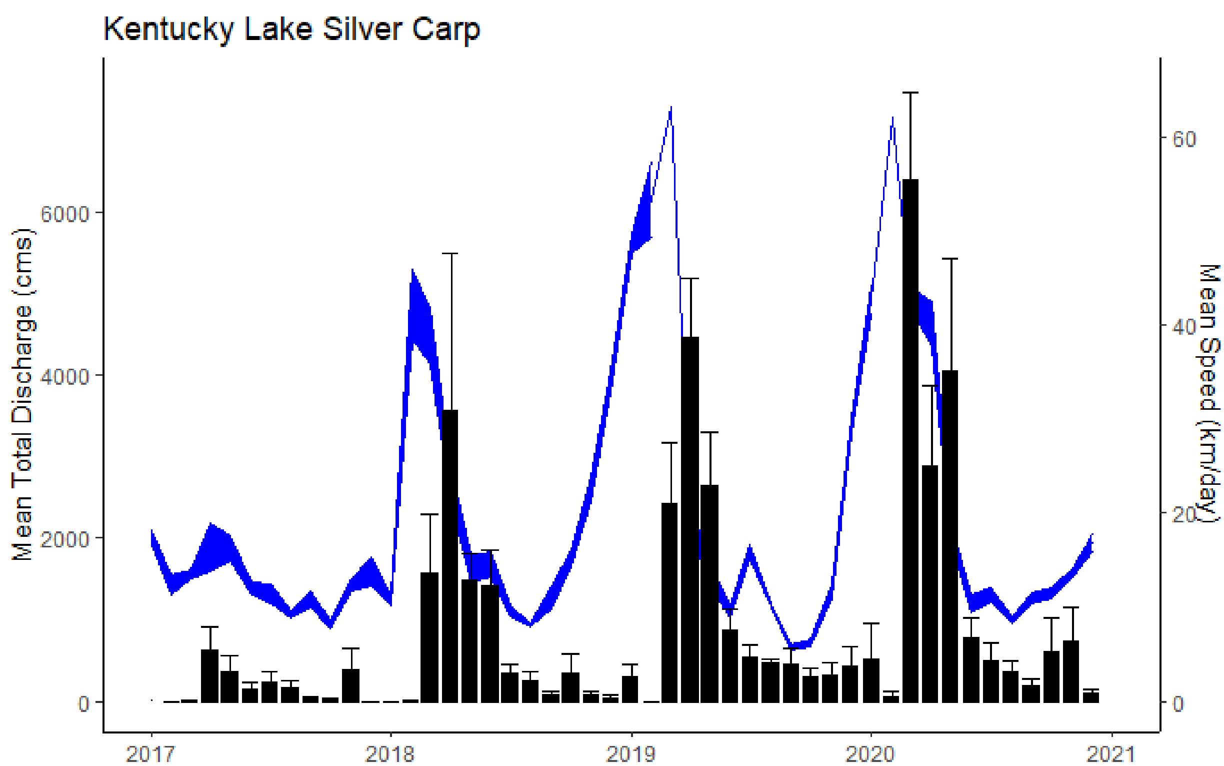


Figure 5. Monthly mean (with SE) discharge (cms, blue line, measured at the Kentucky Dam) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp in Kentucky Lake, 2017 – 2020.

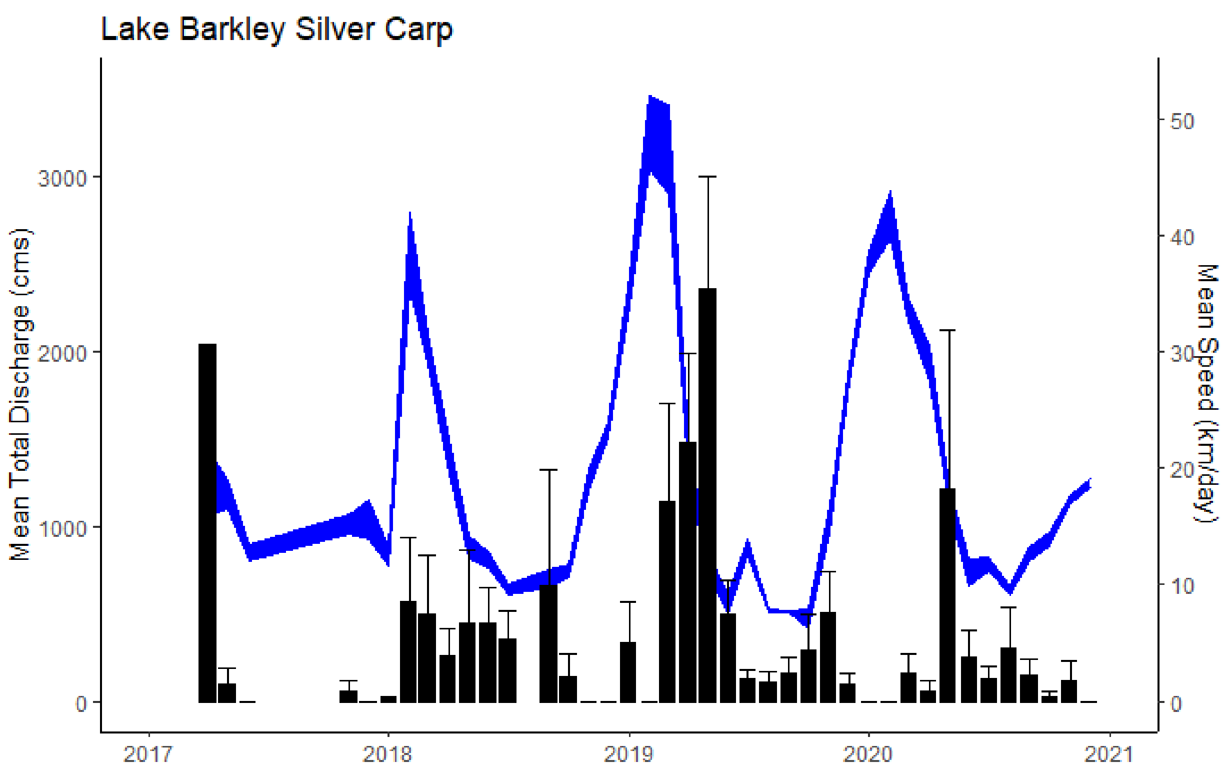


Figure 6. Monthly mean (with SE) discharge (cms, blue line, measured at the Barkley Dam) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp in Lake Barkley, 2017 – 2020.

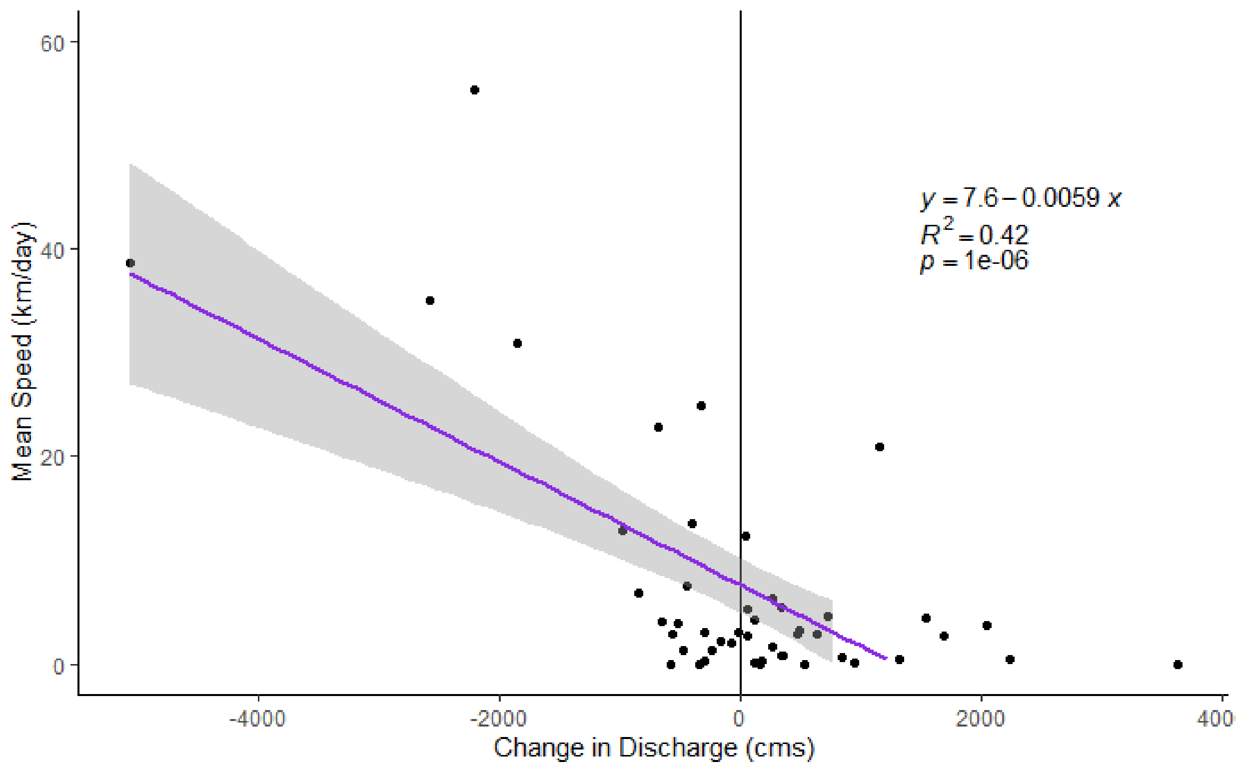


Figure 7. Change in discharge had a negative, significant effect on silver carp swimming speed in Kentucky Lake ($F_{1, 46} = 34.69$, $p < 0.001$, $R^2 = 0.42$). A 2-dimensional Kolmogorov-Smirnov test indicated that the relationship becomes different at a threshold change in discharge = -650 cms ($D_{max} = 0.0919$, $p = 0.05$). The relationship between speed and discharge change was significant for discharge changes below 0 cms ($F_{1, 20} = 26.67$, $p < 0.001$, $R^2 = 0.55$) but was not significant for discharge changes above 0 cms ($F_{1,24} = 0.21$, $p = 0.65$, $R^2 = -0.03$).

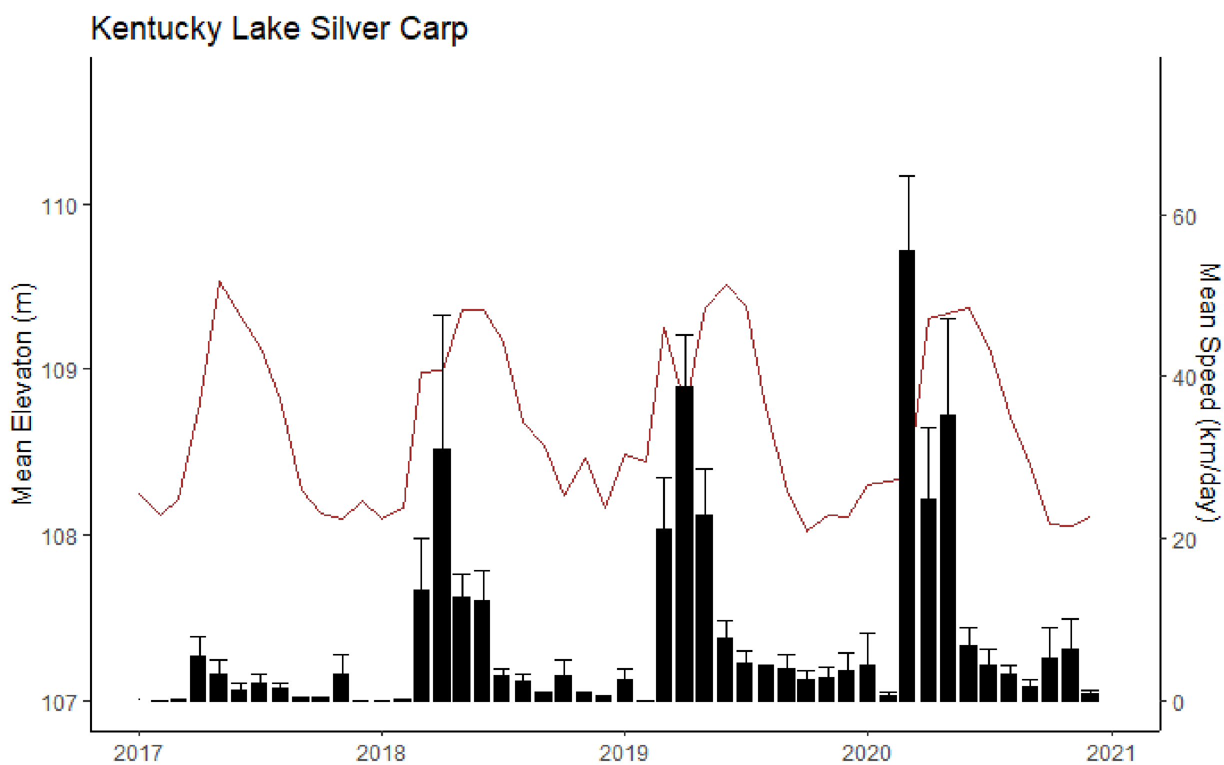


Figure 8. Monthly mean elevation (m, brown line, measured in Kentucky Lake) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp in Kentucky Lake, 2017 – 2020.

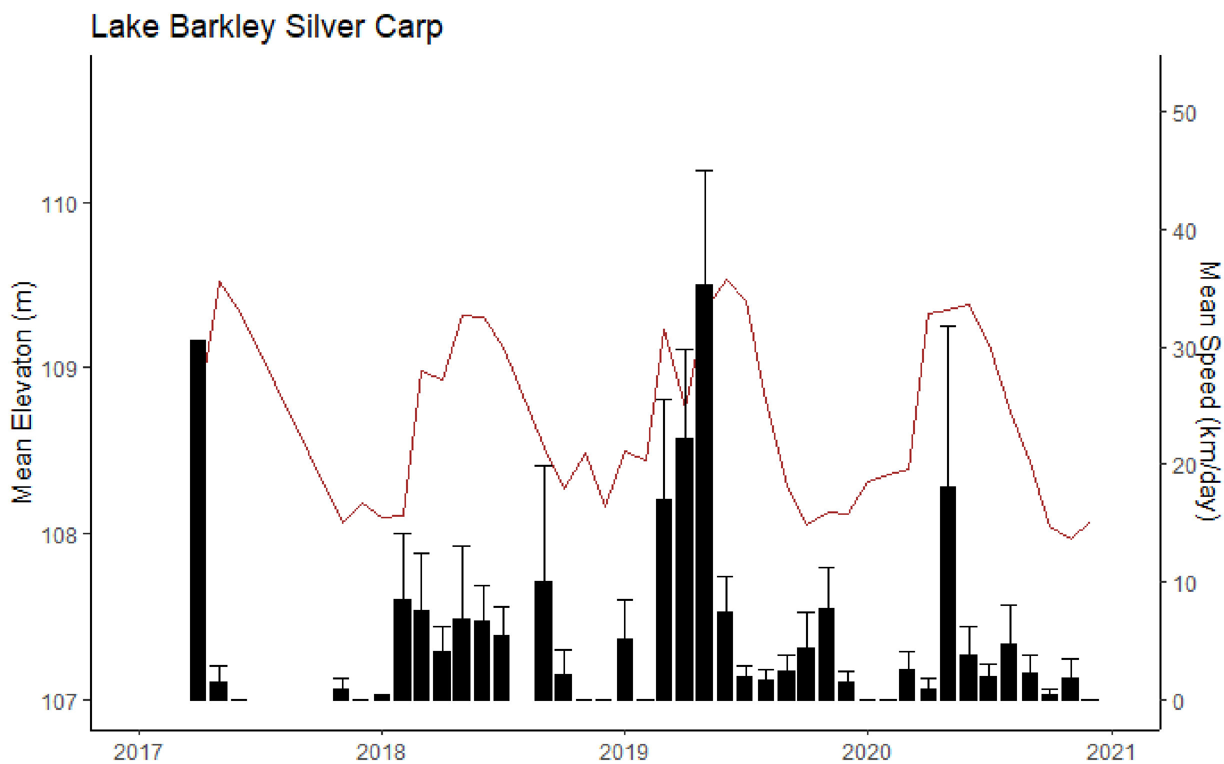


Figure 9. Monthly mean elevation (m, brown line, measured in Lake Barkley) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp in Lake Barkley, 2017 – 2020.

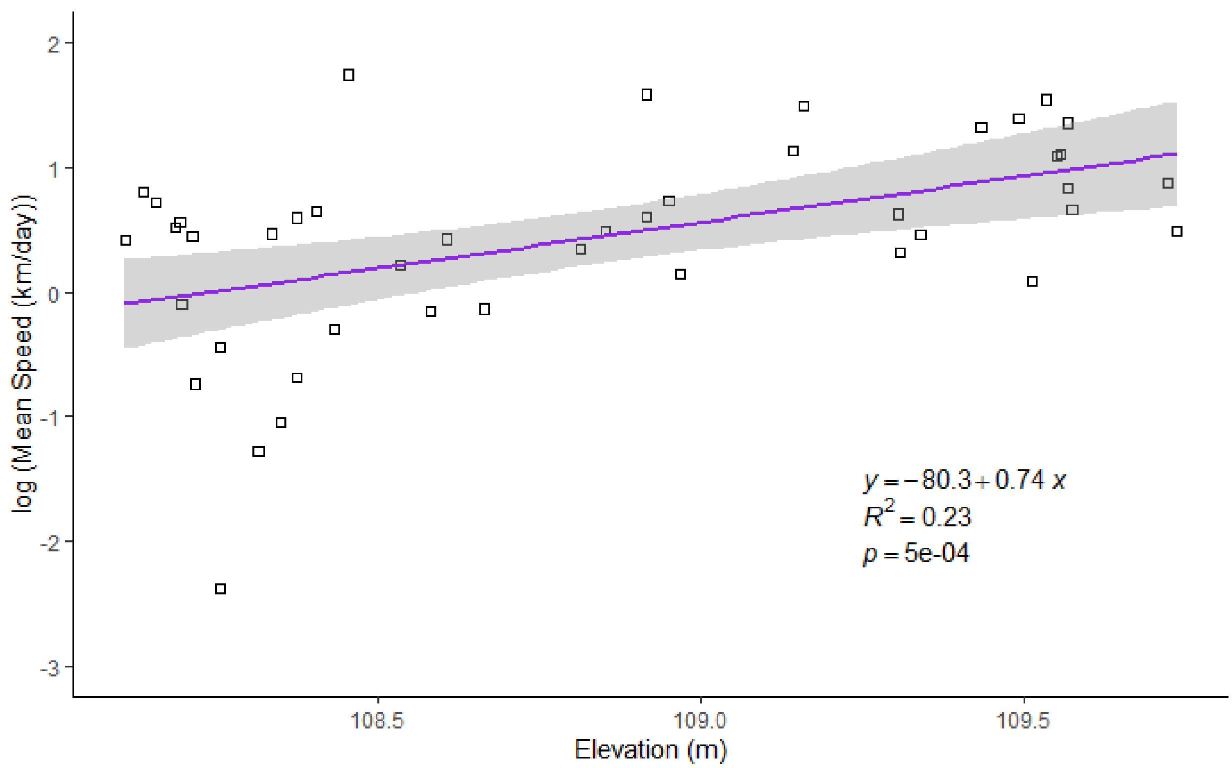


Figure 10. Lake elevation had a positive, significant effect on silver carp log(speed) ($F_{1, 42} = 14.09$, $p < 0.001$, $R^2 = 0.23$) in Kentucky Lake.

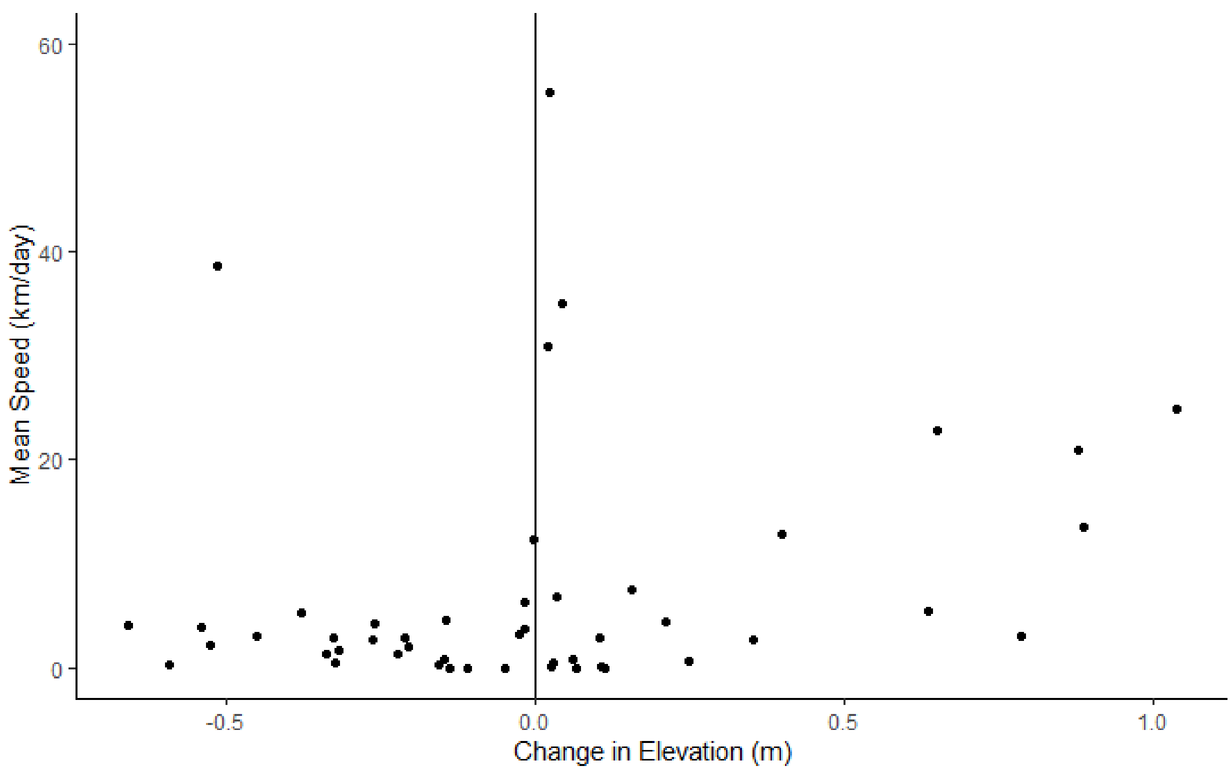


Figure 11. Change in elevation in Kentucky Lake was not related to silver carp mean speed ($F_{1, 46} = 3.02$, $p = 0.09$, $R^2 = 0.04$). A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between elevation change and speed became different at a threshold elevation change of 0 m ($D_{max} = 0.109$, $p = 0.009$). A linear regression comparing speed and elevation change was not significant for elevation changes below 0 m ($F_{1,24} = 0.91$, $p = 0.35$, $R^2 = -0.004$) and was also not significant for elevation changes above 0 m ($F_{1, 20} = 0.22$, $p = 0.64$, $R^2 = -0.04$).

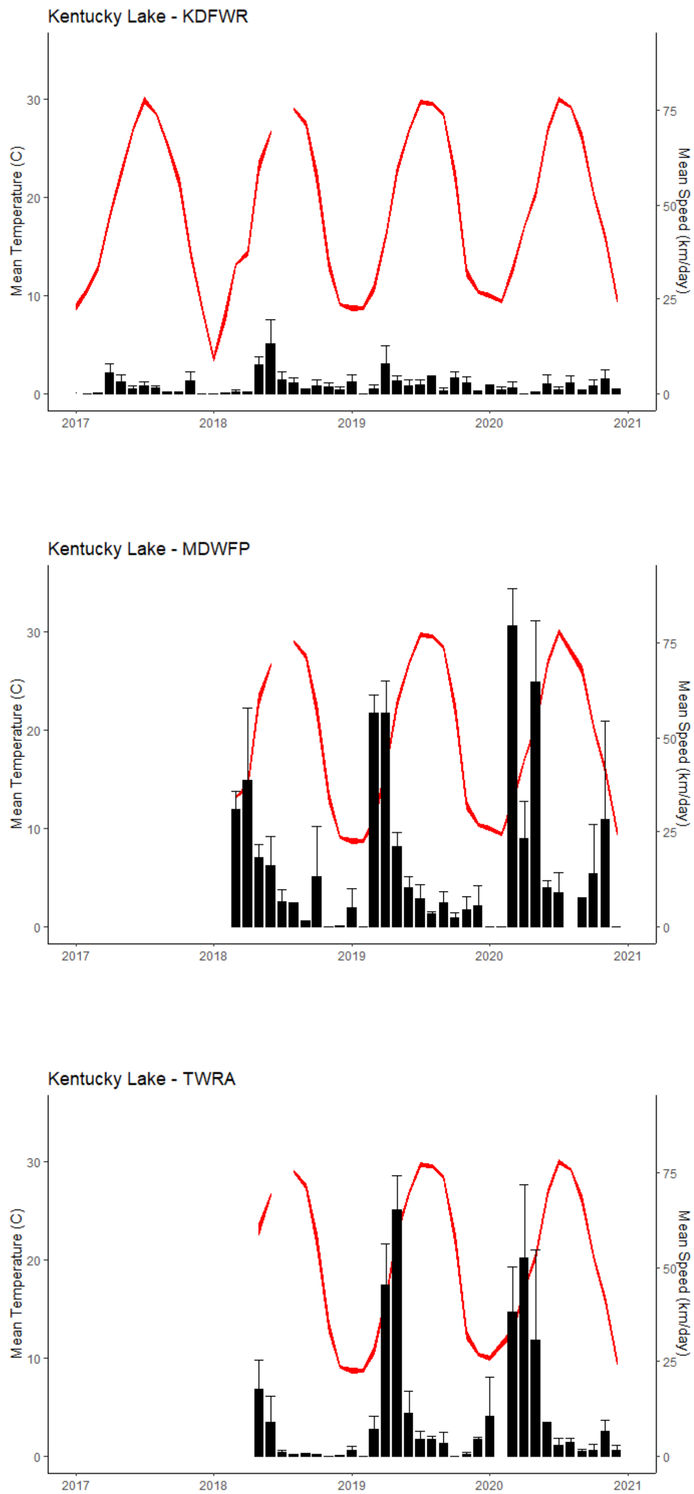


Figure 12. Monthly mean (with SE) surface temperature (C, red line, measured in Kentucky Lake) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp detected in Kentucky Lake tagged by different agencies, 2017 – 2020.

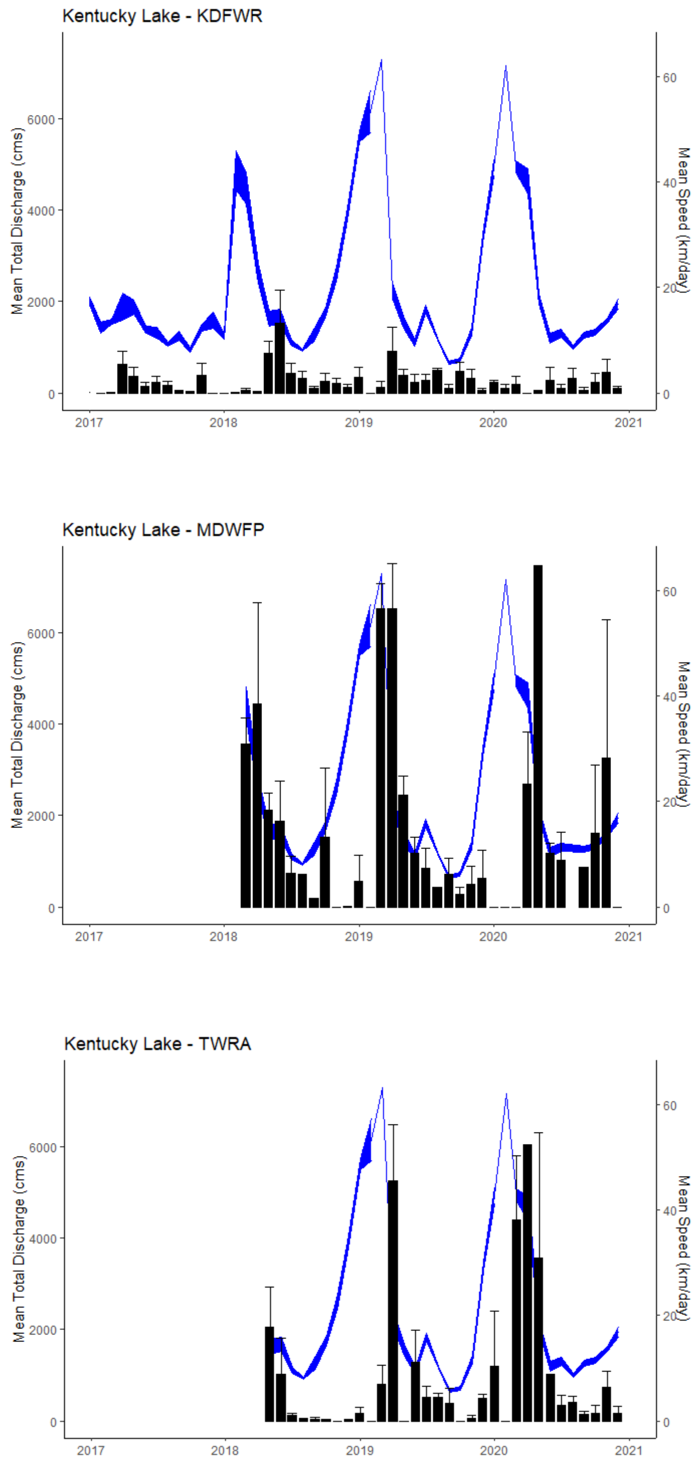


Figure 13. Monthly mean (with SE) total discharge (cms, blue line, measured in Kentucky Lake) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp detected in Kentucky Lake tagged by different agencies, 2017 – 2020.

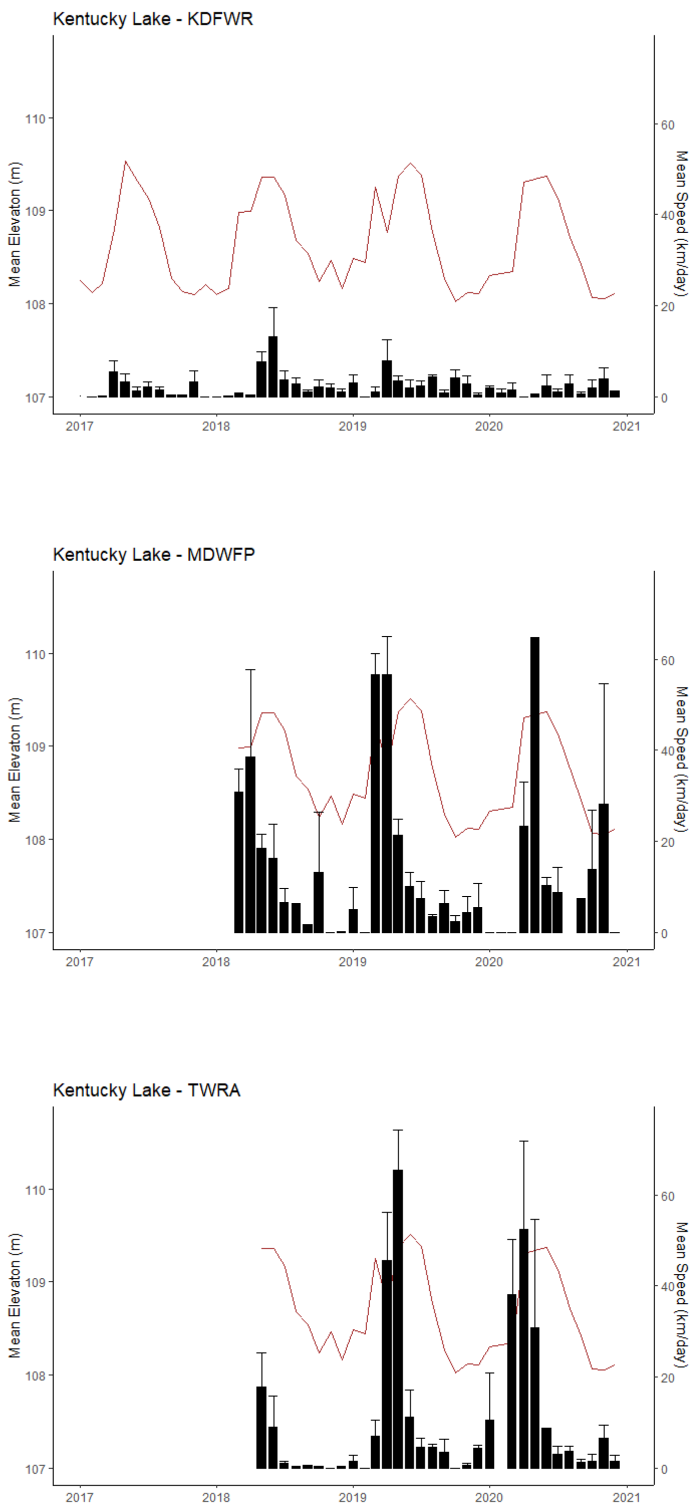


Figure 14. Monthly mean elevation (m, brown line, measured in Kentucky Lake) and monthly mean (with SE) swimming speed (km/day, black bars) for silver carp detected in Kentucky Lake tagged by different agencies, 2017 – 2020.

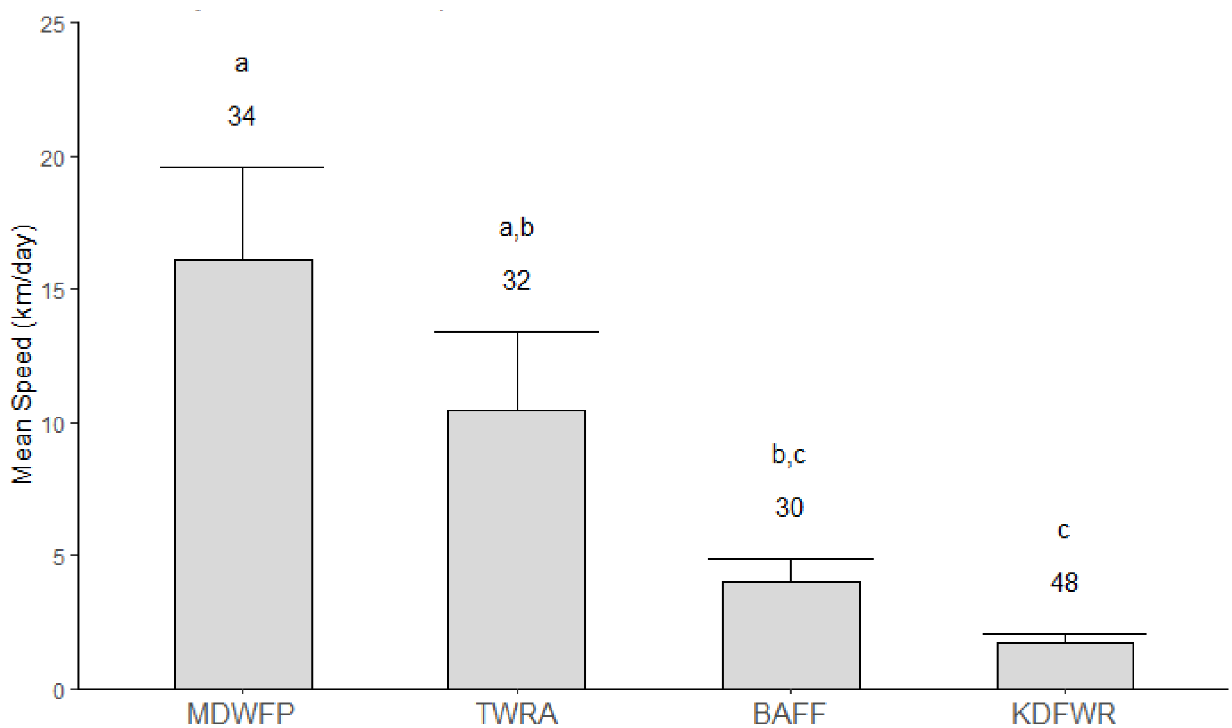


Figure 15. Mean (with SE) speed for silver carp detected in Kentucky Lake tagged by different agencies, 2017 – 2020. Number above each bar indicates number of months, and bars with different letters are significantly different (Tukey HSD test following ANOVA ($F_{3,140} = 9.316$, $p < 0.001$)).

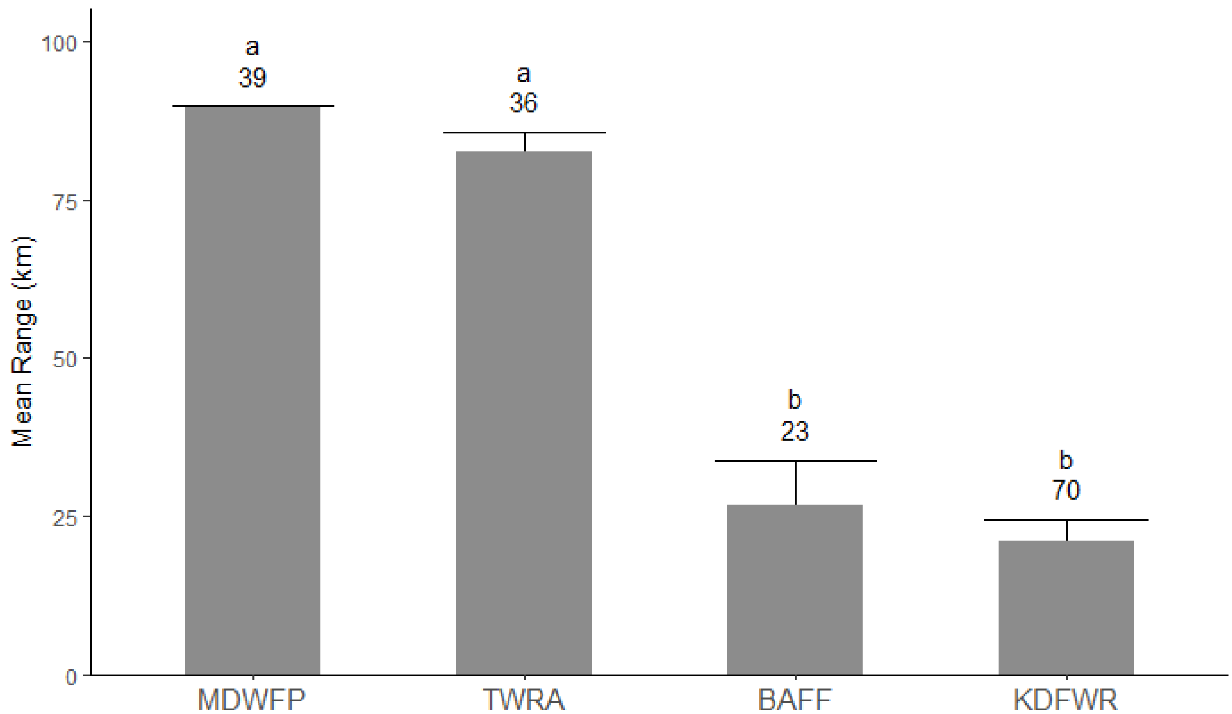


Figure 16. Mean (with SE) range size (maximum river kilometer – minimum river kilometer) for silver carp detected in Kentucky Lake tagged by different agencies, 2017 – 2020. Number above each bar indicates number of fish, and bars with different letters are significantly different (Tukey HSD test following ANOVA ($F_{3,164} = 102.6$, $p < 0.001$)).

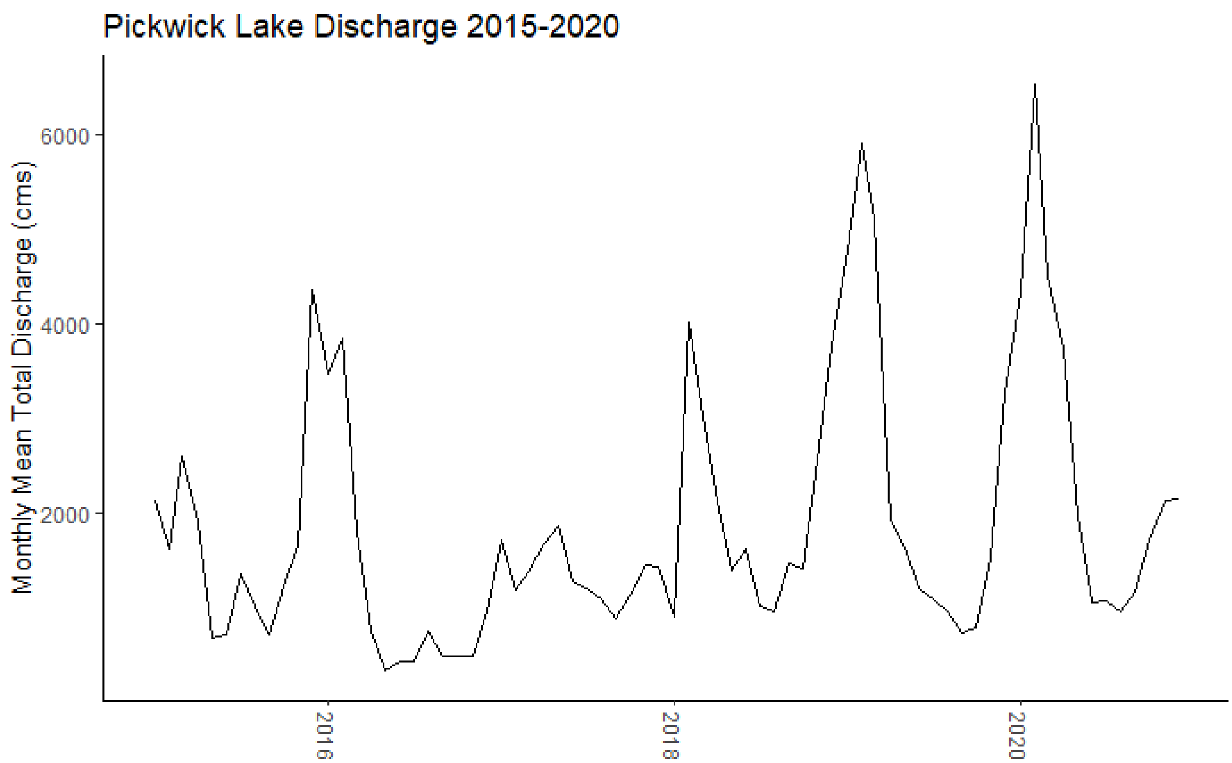


Figure 17. Monthly mean discharge for Pickwick Lake 2015 – 2020.

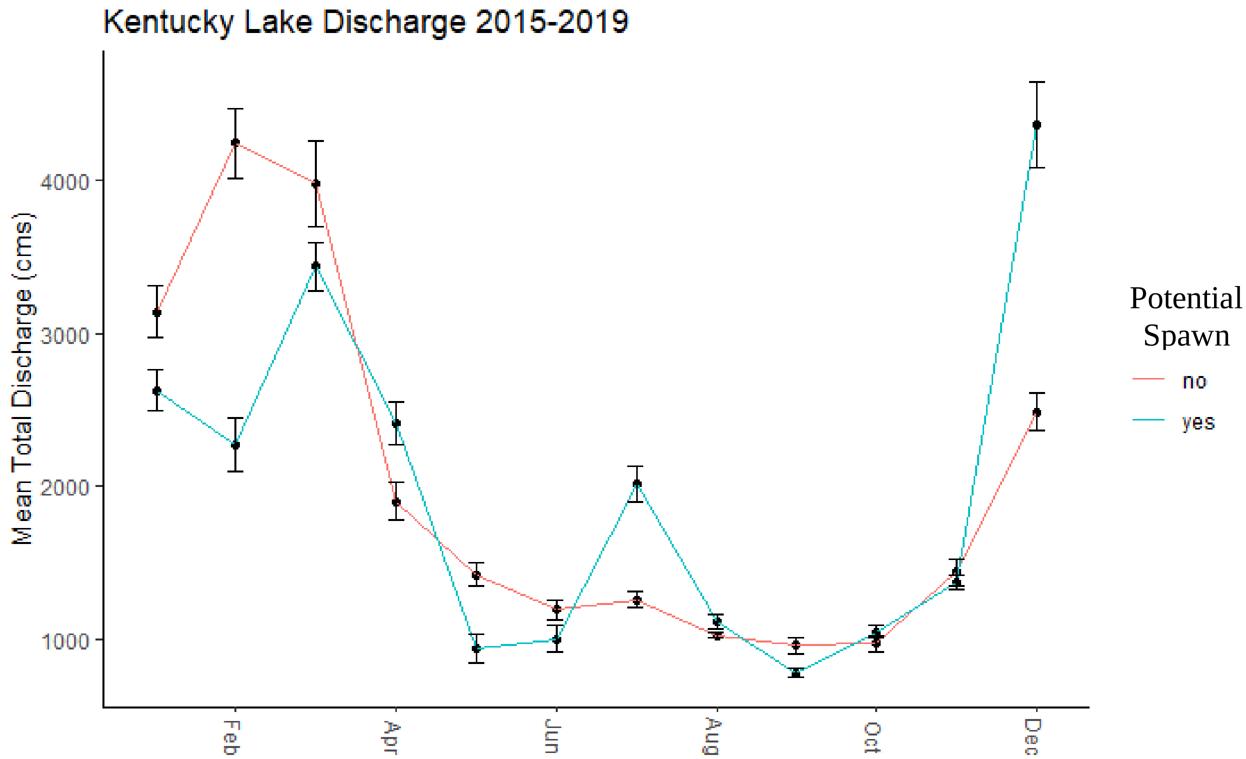


Figure 18. Monthly mean ± SE discharge for Kentucky Lake during non-spawning years (2016 – 2019) and potential spawning years (2015).

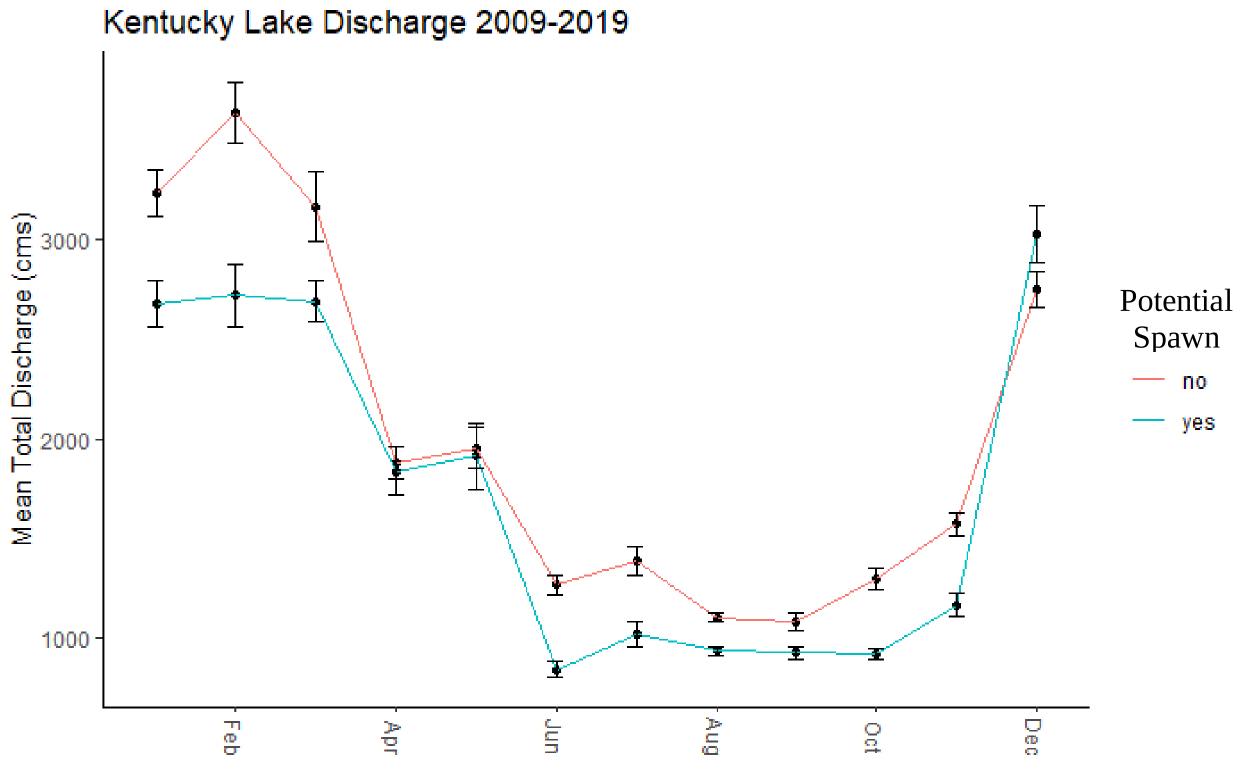


Figure 19. Monthly mean ± SE discharge for Kentucky Lake during non-spawning years (2009, 2013, 2014, and 2016 – 2019) and potential spawning years (2010 – 2012, 2015).

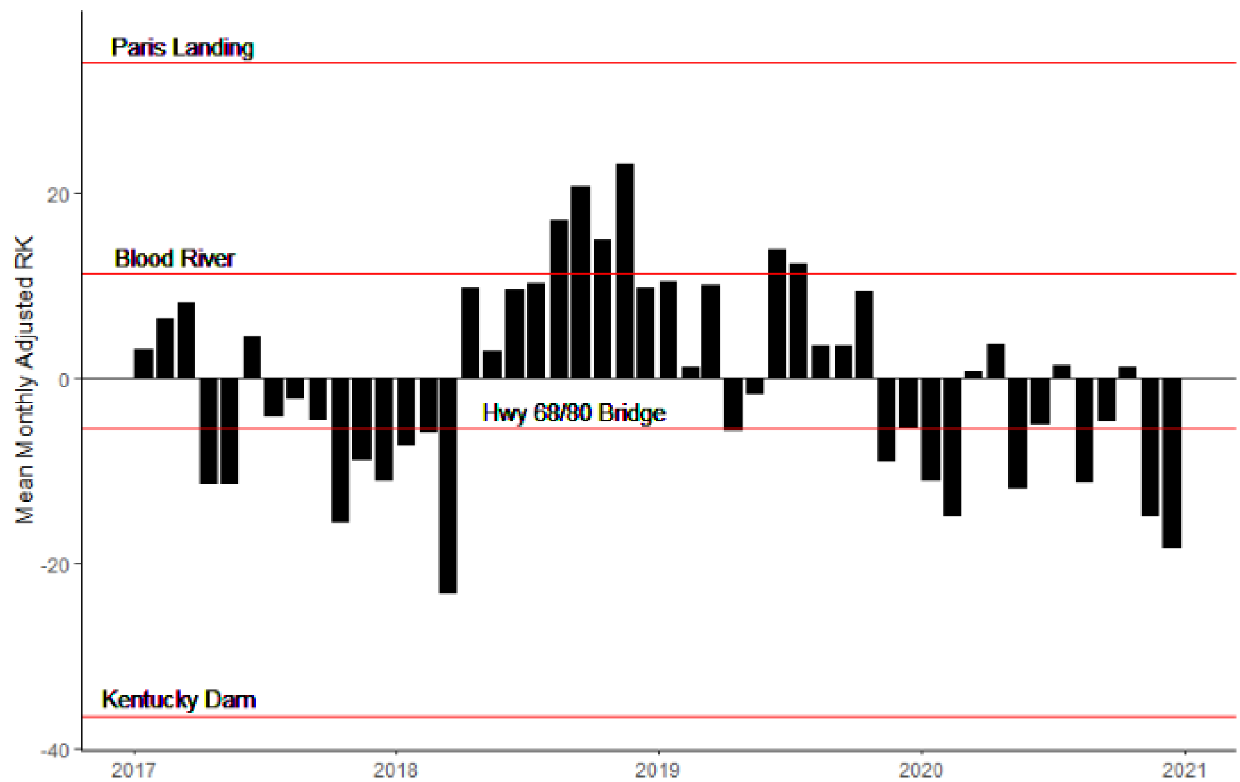


Figure 20. Mean monthly adjusted river kilometer (RK) for silver carp detected within our study area of Kentucky Lake. The RK is adjusted relative to RK 72.5 which is the median monthly RK over 2017 – 2020 and near the Hancock Biological Station. Negative values represent locations downstream from Hancock while positive values indicate locations upstream from Hancock. The adjusted RK for several landmarks on Kentucky Lake are marked with red lines.

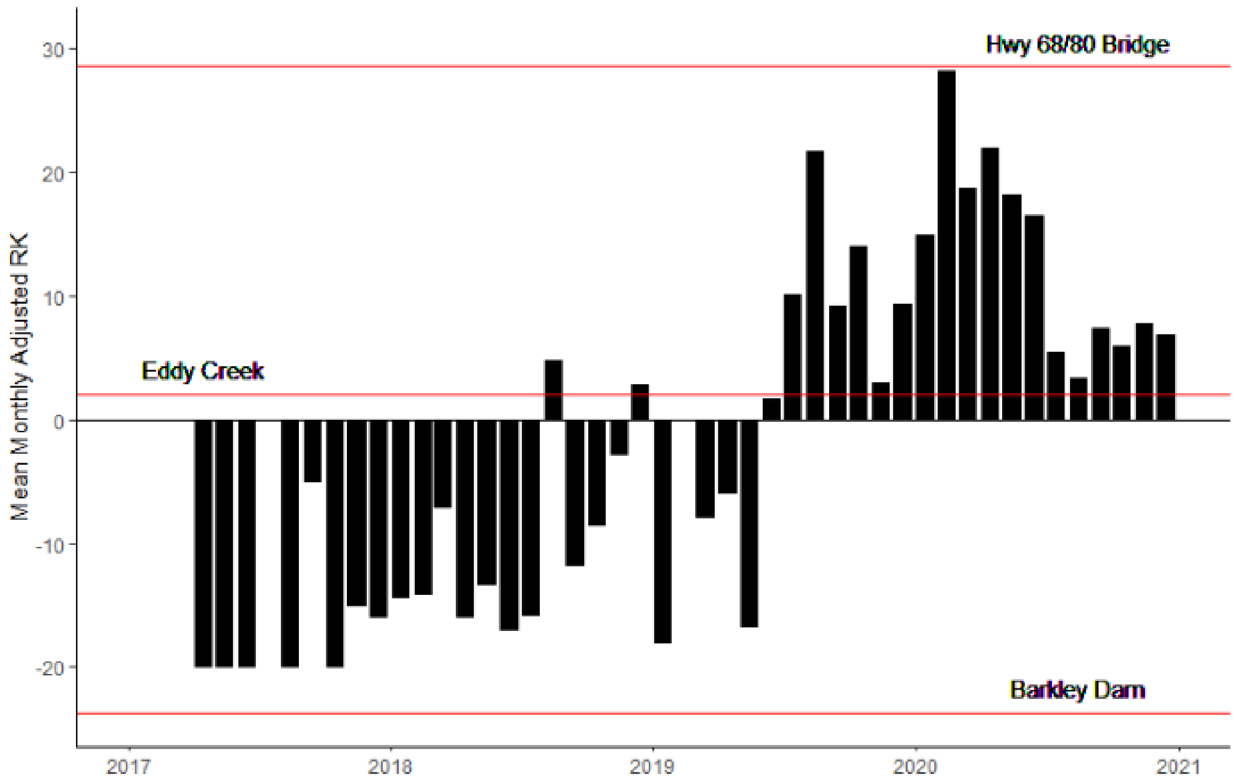


Figure 21. Mean monthly adjusted river kilometer (RK) for silver carp detected within our study area of Lake Barkley. The RK is adjusted relative to RK 72.8 which is the median monthly RK over 2017 – 2020 and near Eddy Creek. Negative values represent locations downstream from Eddy Creek while positive values indicate locations upstream from Eddy Creek. The adjusted RK for several landmarks on Lake Barkley are marked with red lines.

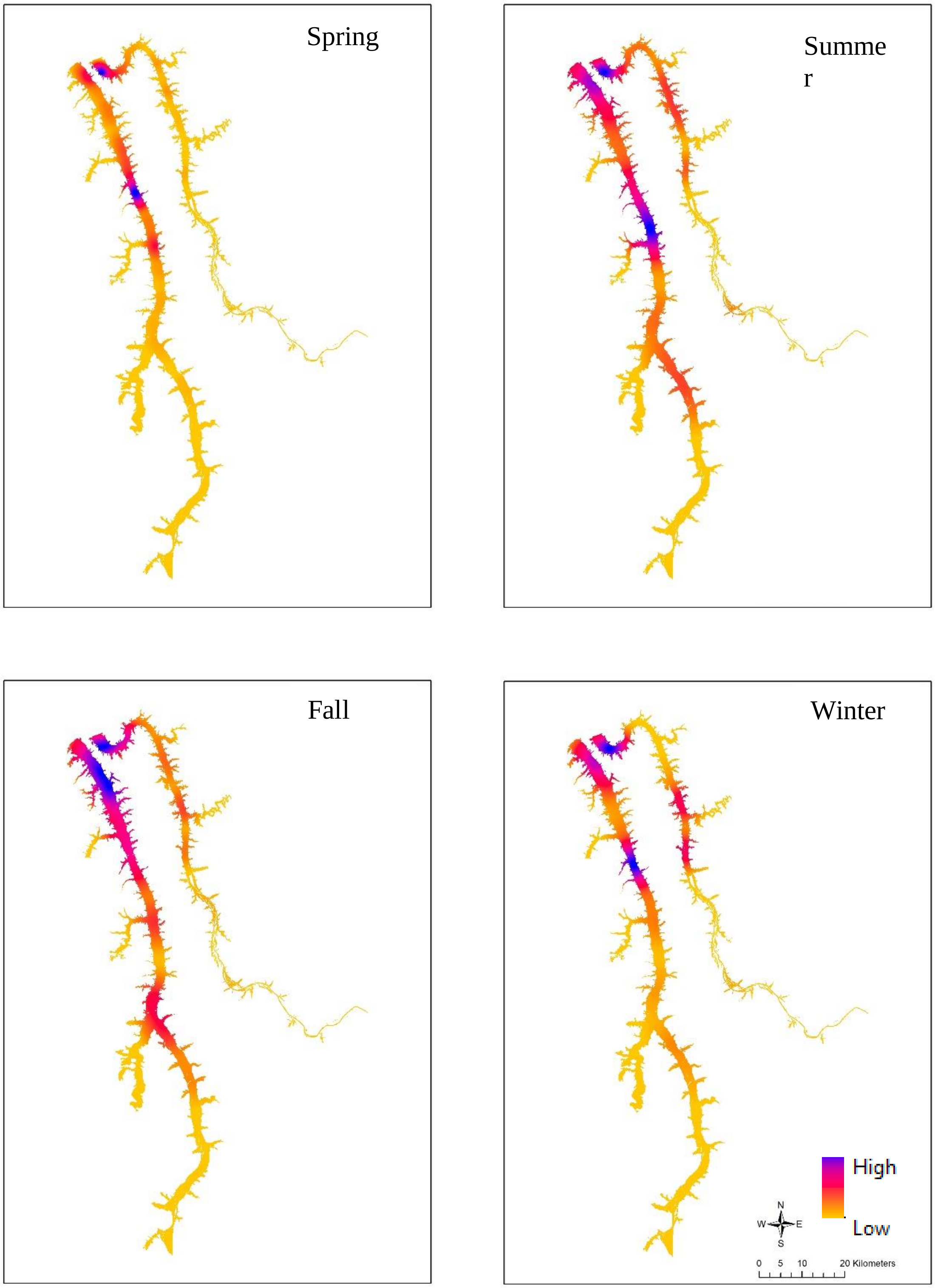
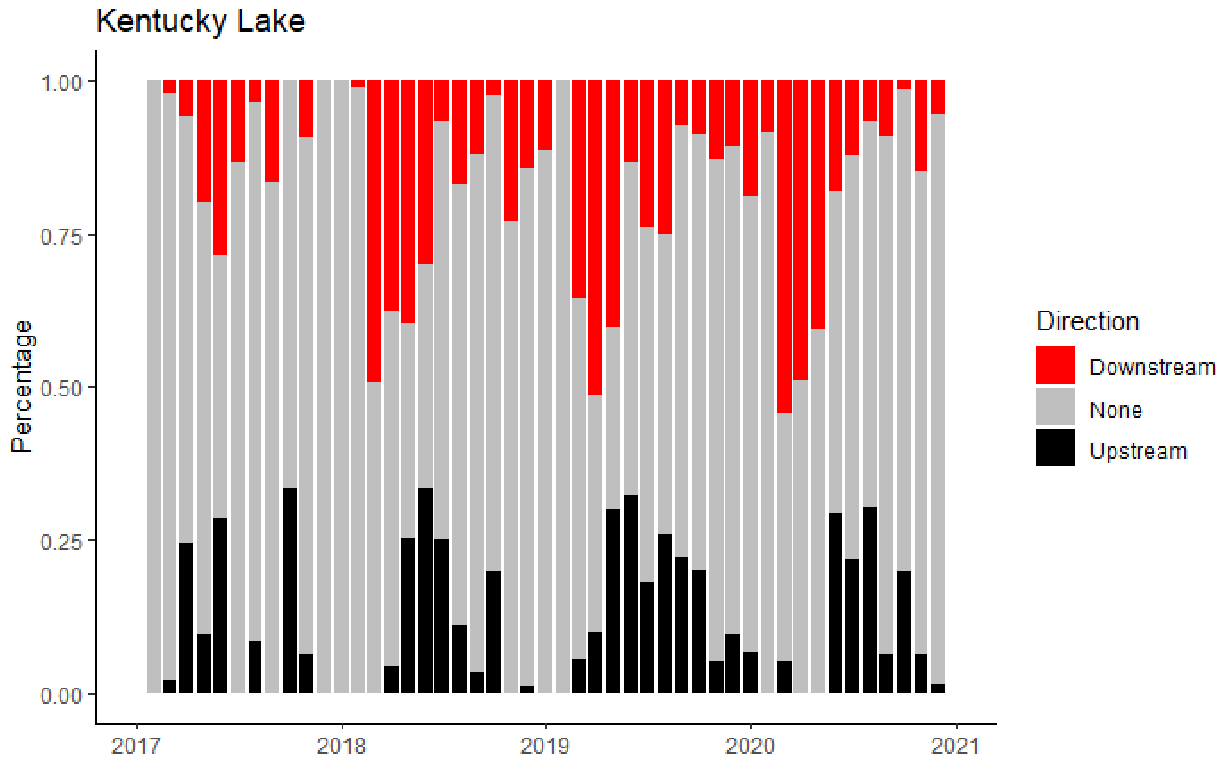


Figure 22. Heatmaps of locations for tagged silver carp in each season for both Kentucky Lake and Lake Barkley.



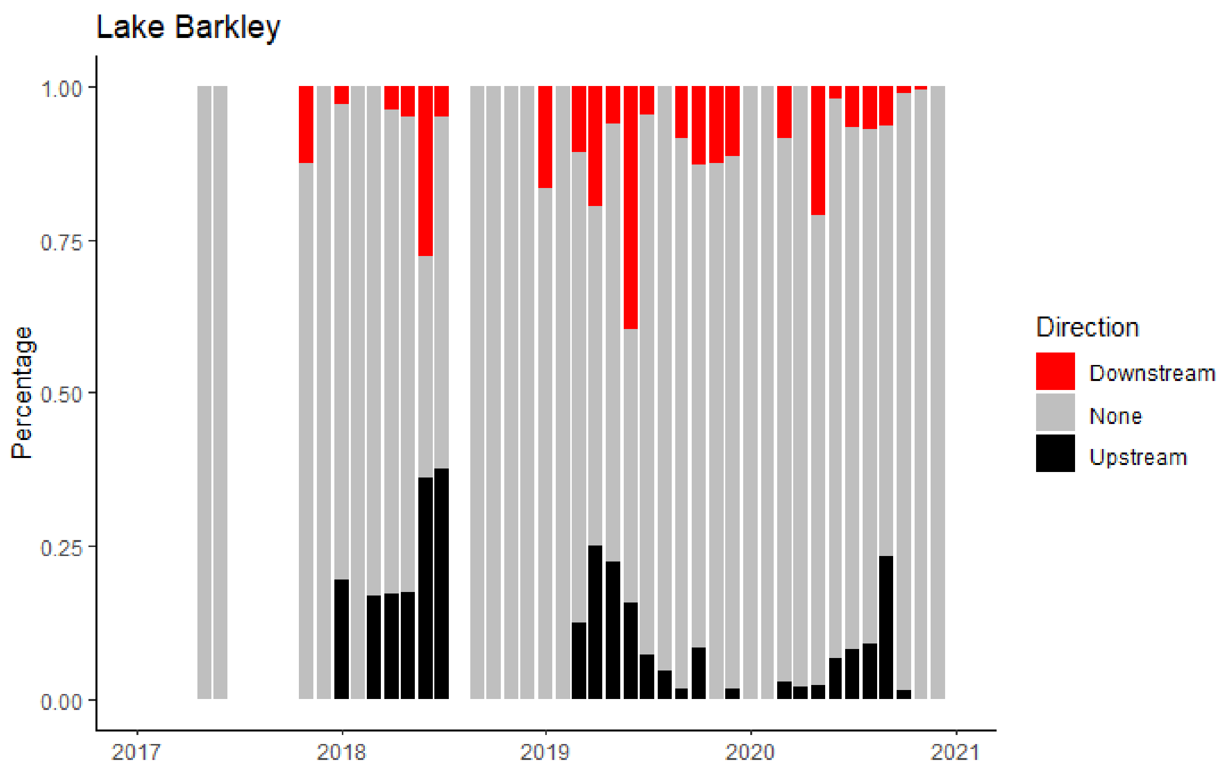


Figure 33. Percentage of movement direction by month for silver carp in both Kentucky Lake and Lake Barkley.

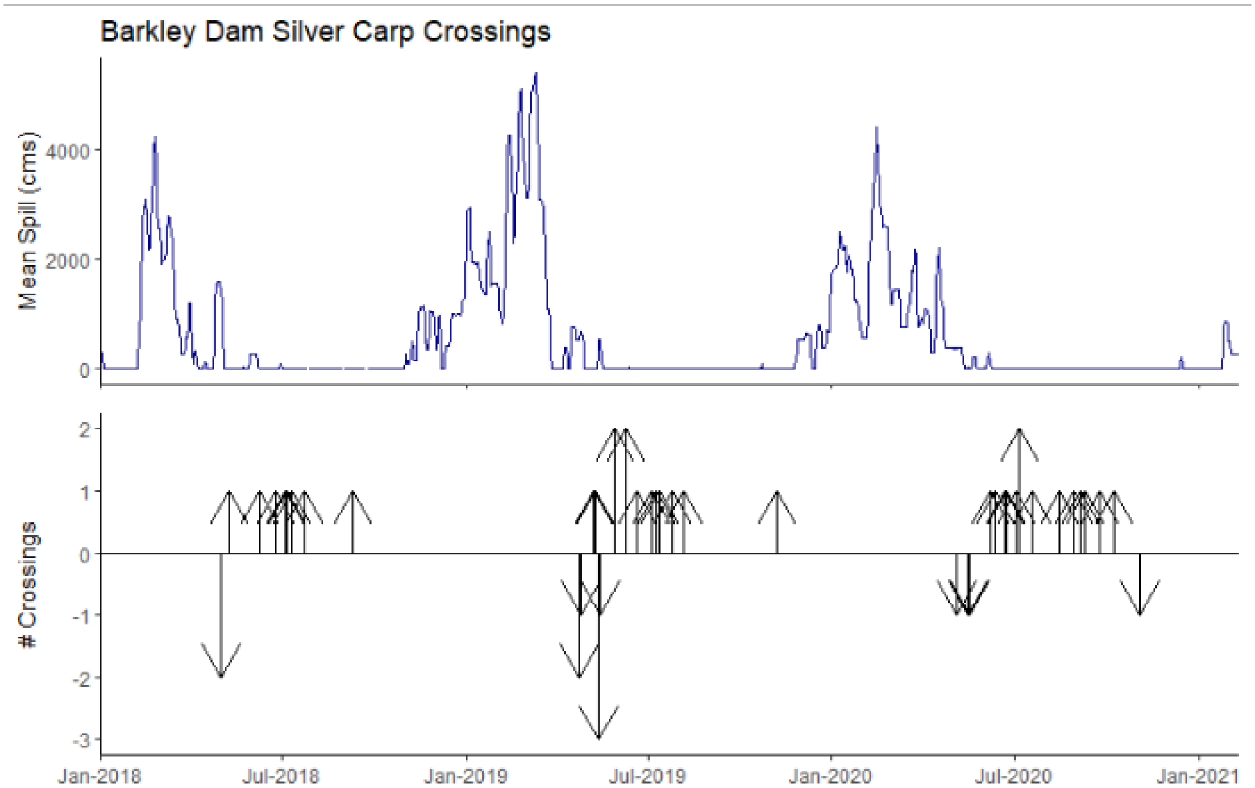


Figure 24. Rate of spilling (m^3/s) at Barkley Dam (blue line, top graph) compared to the number and direction of silver carp crossings (black arrows, bottom graph). Fish crossings are positive if the fish crossed upstream, and negative if the fish crossed downstream.

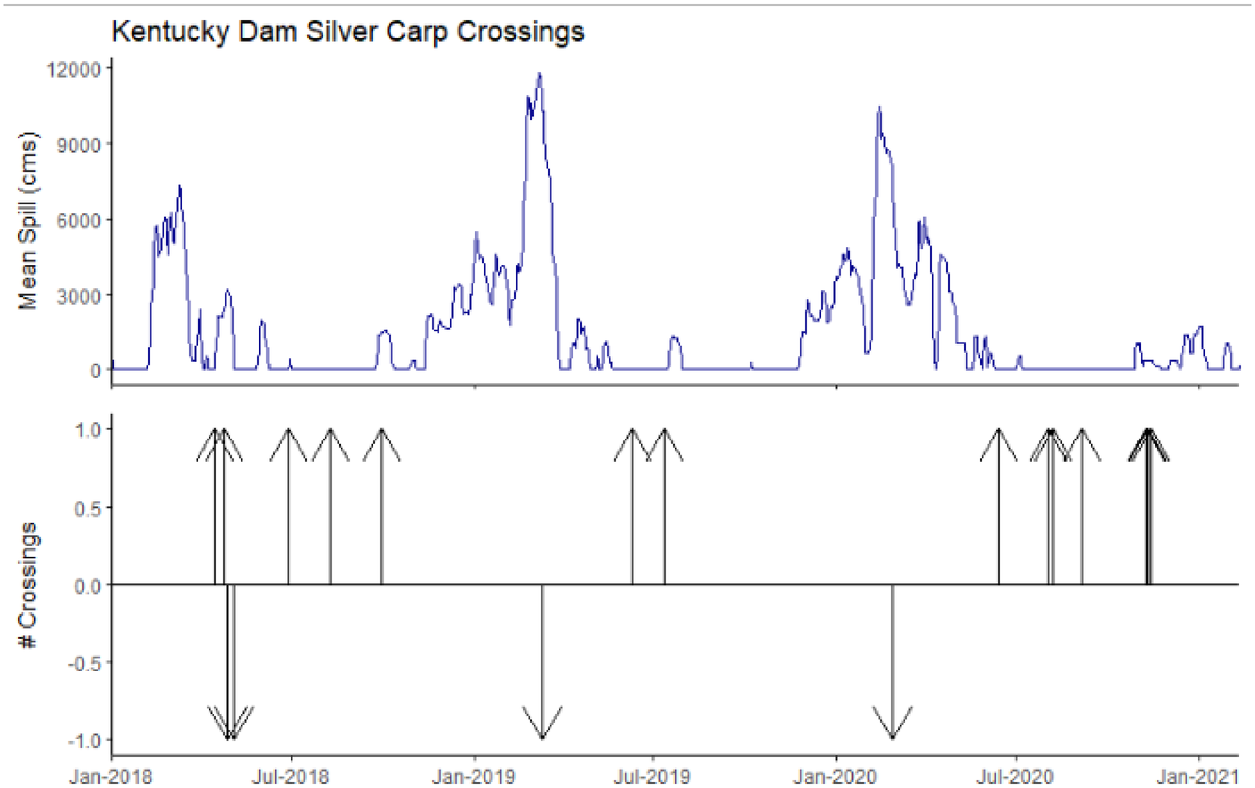


Figure 25. Rate of spilling (m^3/s) at Kentucky Dam (blue line, top graph) compared to the number and direction of silver carp crossings (black arrows, bottom graph). Fish crossings are positive if the fish crossed upstream, and negative if the fish crossed downstream.

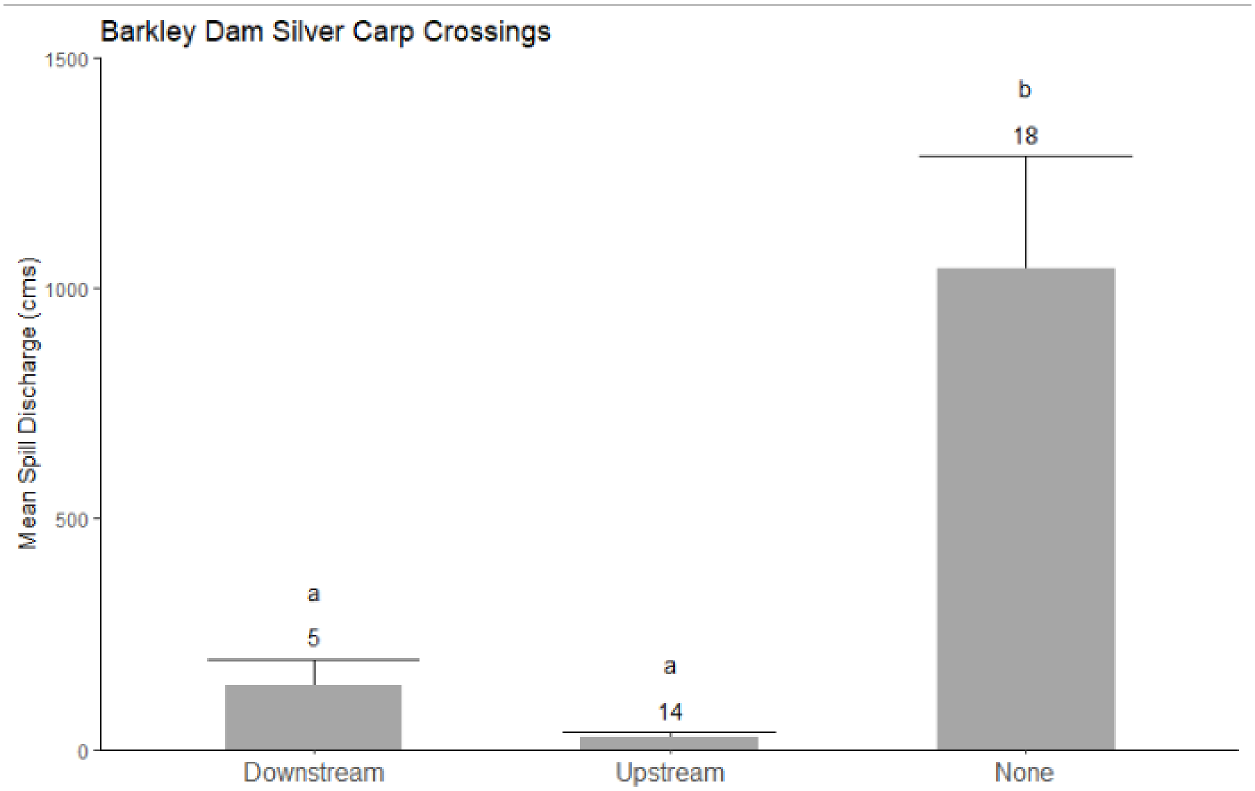


Figure 26. Mean (with SE) spill discharge (m^3/s) at Barkley Dam for months in which silver carp crossed downstream, upstream, or not at all. Number above each bar indicates number of months, and bars with different letters are significantly different (Tukey HSD test following ANOVA ($F_{2, 34} = 8.41$, $p = 0.001$)).

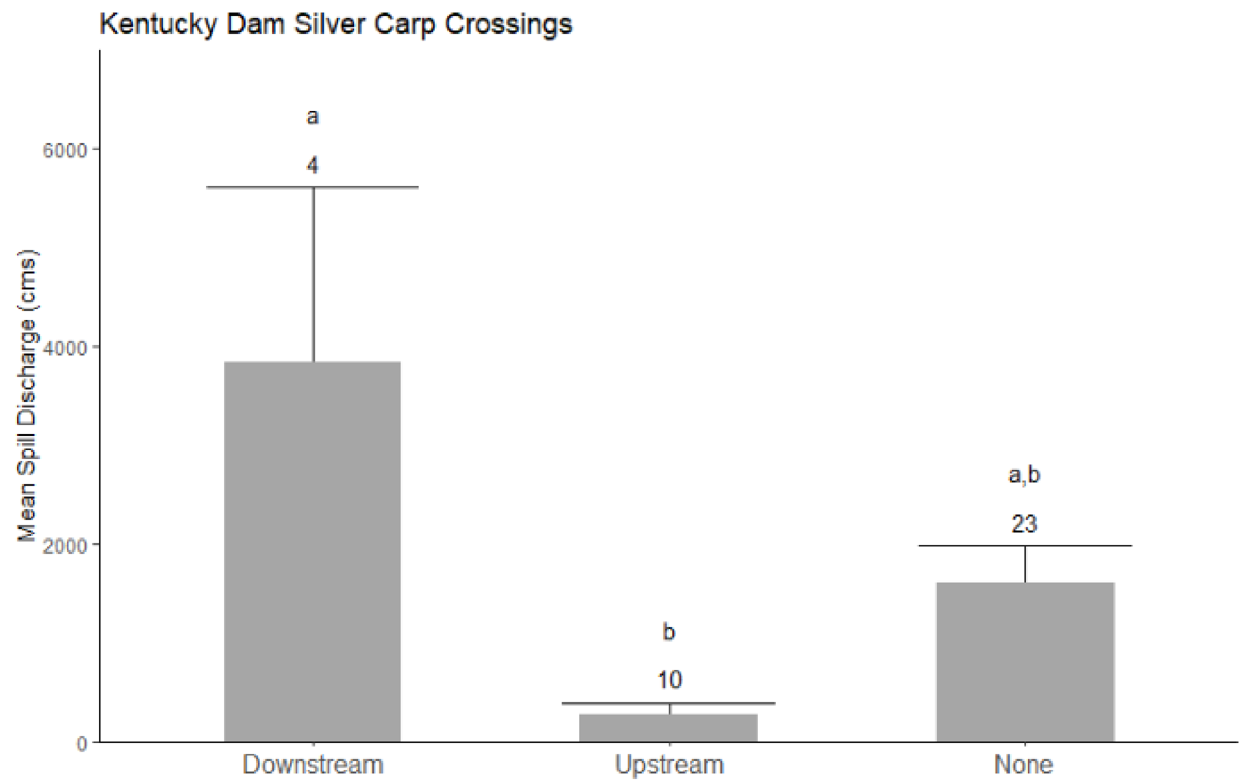


Figure 27. Mean (with SE) spill discharge (m^3/s) at Kentucky Dam for months in which silver carp crossed downstream, upstream, or not at all. Number above each bar indicates number of months, and bars with different letters are significantly different (Tukey HSD test following ANOVA ($F_{2, 34} = 5.97$, $p = 0.006$)).

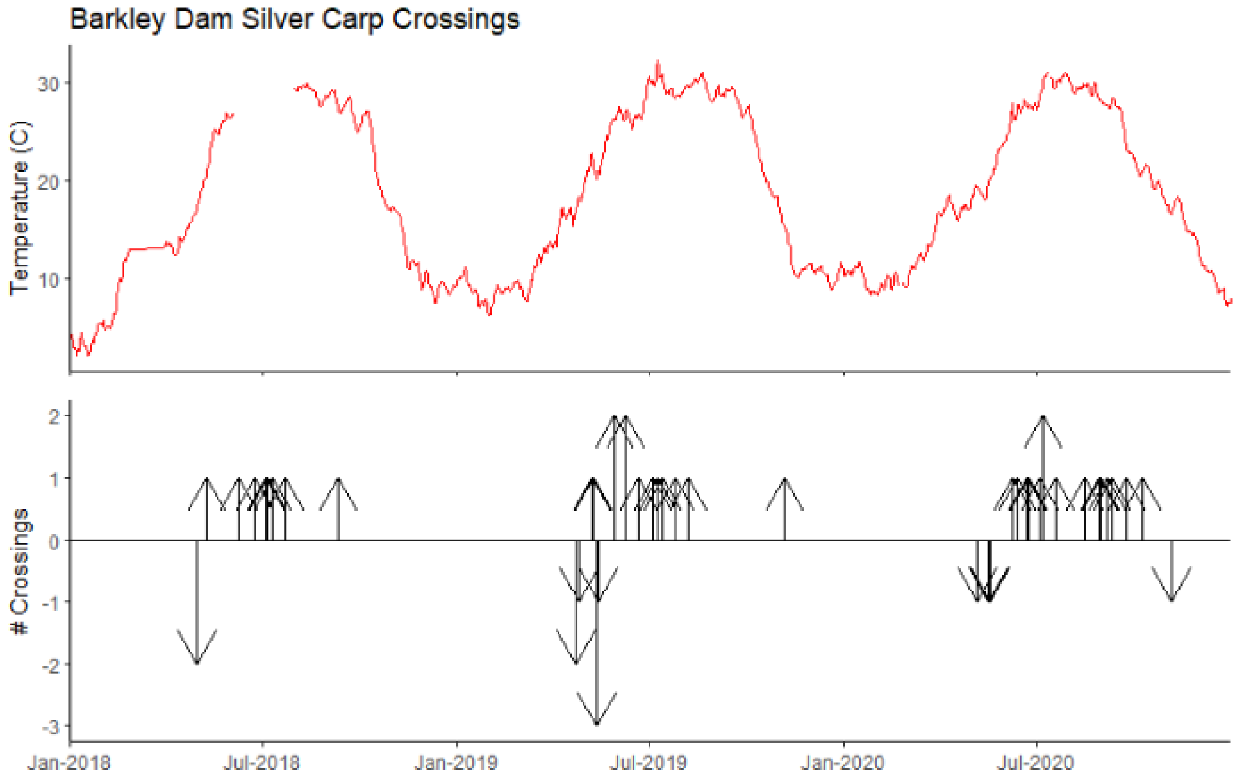


Figure 28. Surface temperature (ºC) (red line, top graph) compared to the number and direction of silver carp crossings (black arrows, bottom graph). Fish crossings are positive if the fish crossed upstream, and negative if the fish crossed downstream. Surface temperature data was taken from Kentucky Lake.

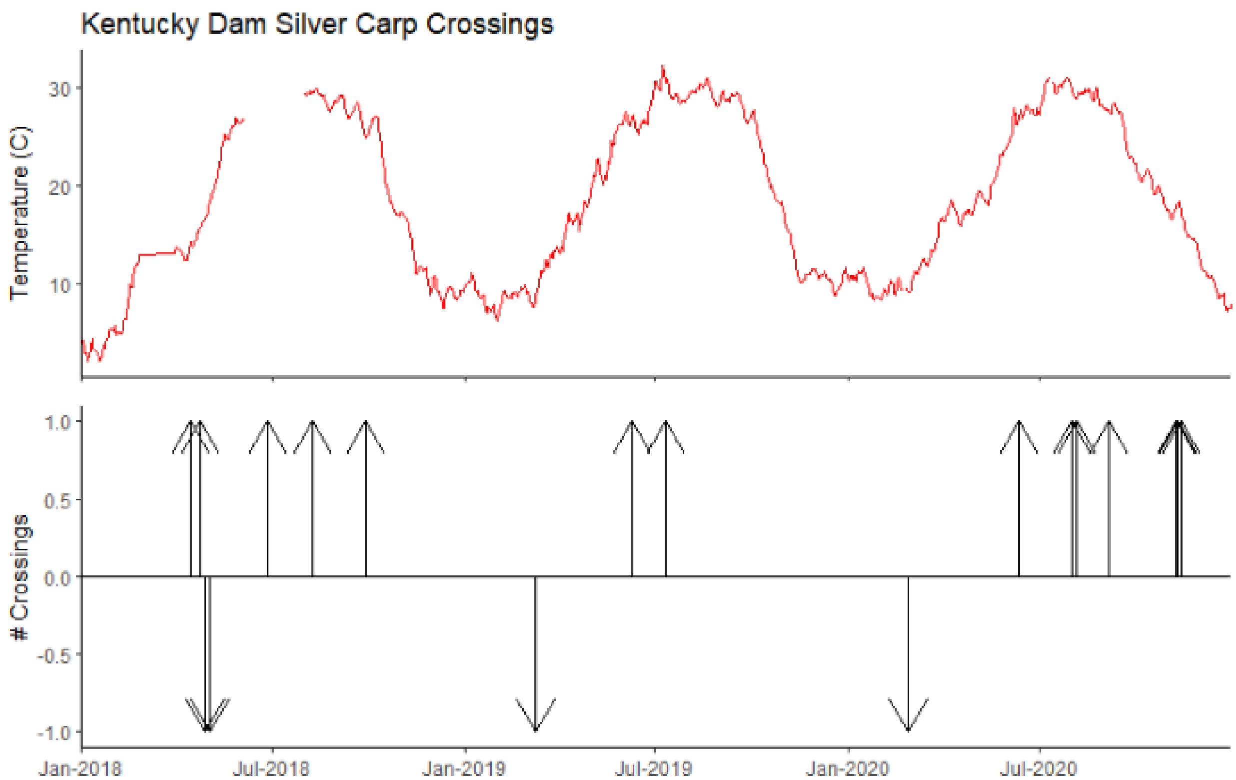


Figure 29. Surface temperature (ºC) (red line, top graph) compared to the number and direction of silver carp crossings (black arrows, bottom graph) at the Kentucky Dam. Fish crossings are positive if the fish crossed upstream, and negative if the fish crossed downstream.

Barkley Dam Silver Carp

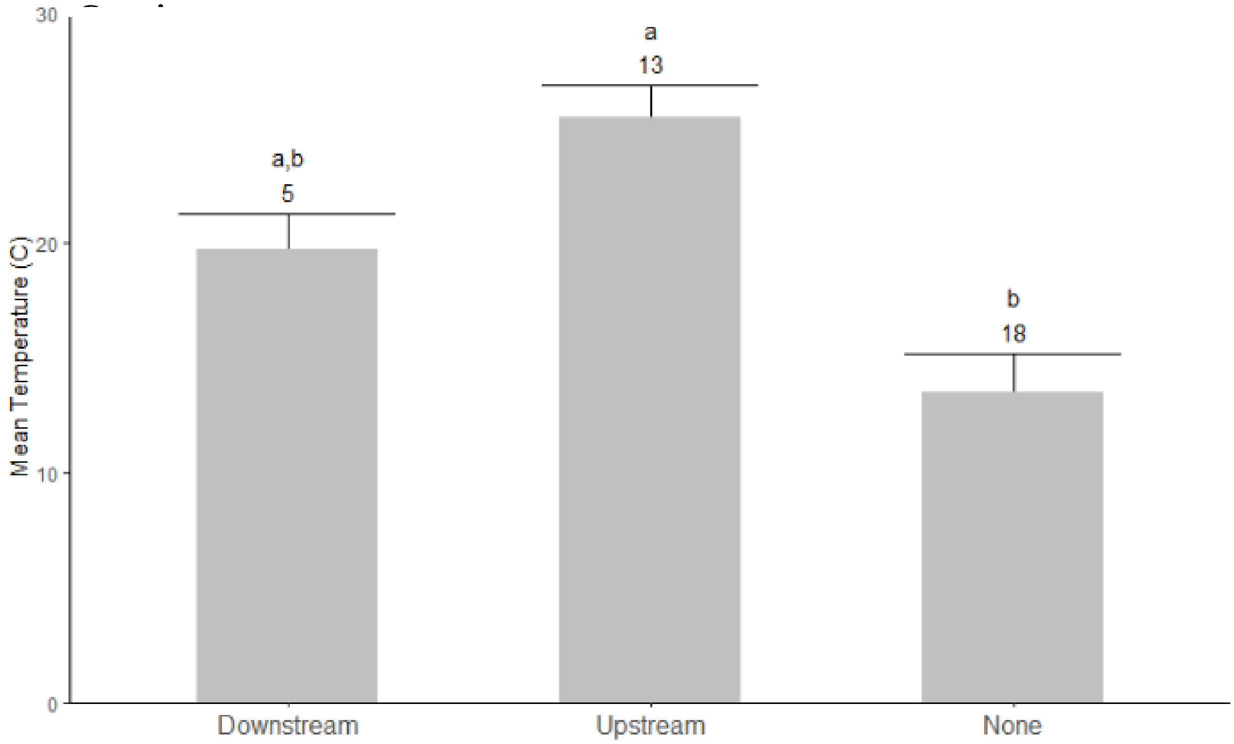


Figure 30. Mean (with SE) temperature (ºC) for months in which silver carp crossed downstream, upstream, or not at all at Barkley Dam. Number above each bar indicates number of months, and bars with different letters are significantly different (Tukey HSD test following ANOVA ($F_{2, 33} = 14.92$, $p < 0.001$)). Surface temperature data was taken from Kentucky Lake.

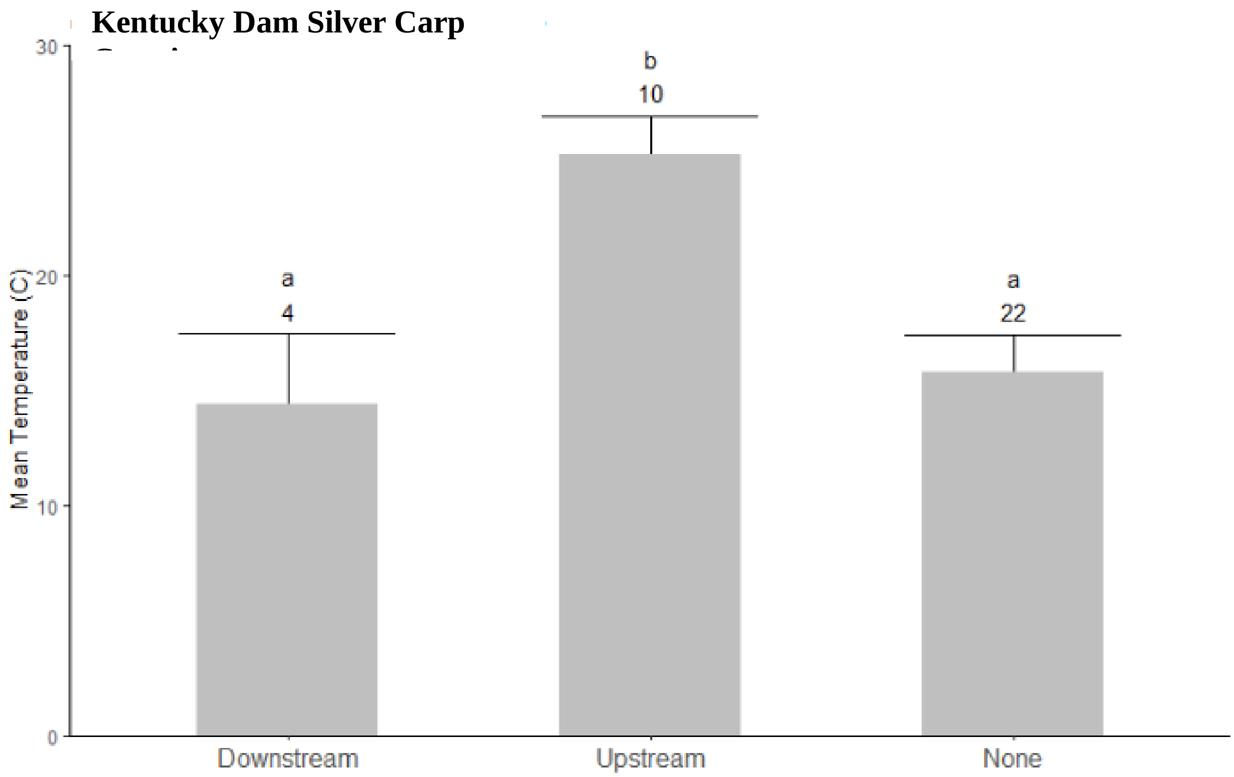


Figure 31. Mean (with SE) temperature (ºC) for months in which silver carp crossed downstream, upstream, or not at all at Kentucky Dam. Number above each bar indicates number of months, and bars with different letters are significantly different (Tukey HSD test following ANOVA ($F_{2, 33}$ = 7.00, p = 0.003)).

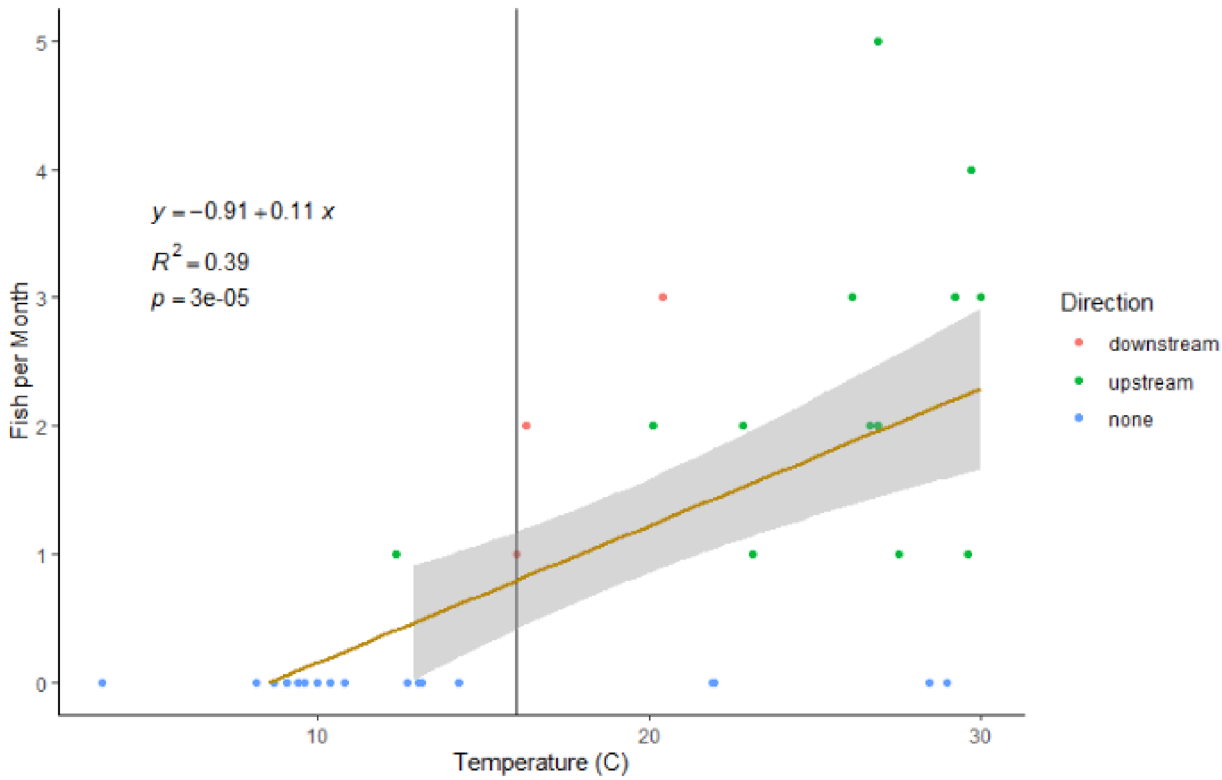


Figure 42. Regression of total number of silver carp crossings per month at Barkley Dam on mean monthly temperature. Temperature had a significant, positive effect on number of fish crossings each month ($F_{1, 34} = 23.06$, $p < 0.001$, $R^2 = 0.39$). A 2-dimensional Kolmogorov-Smirnov test showed that the relationship between temperature and number of silver carp crossings became different at a threshold temperature of 16ºC ($D_{max} = 0.180$, $p = 0.000$).

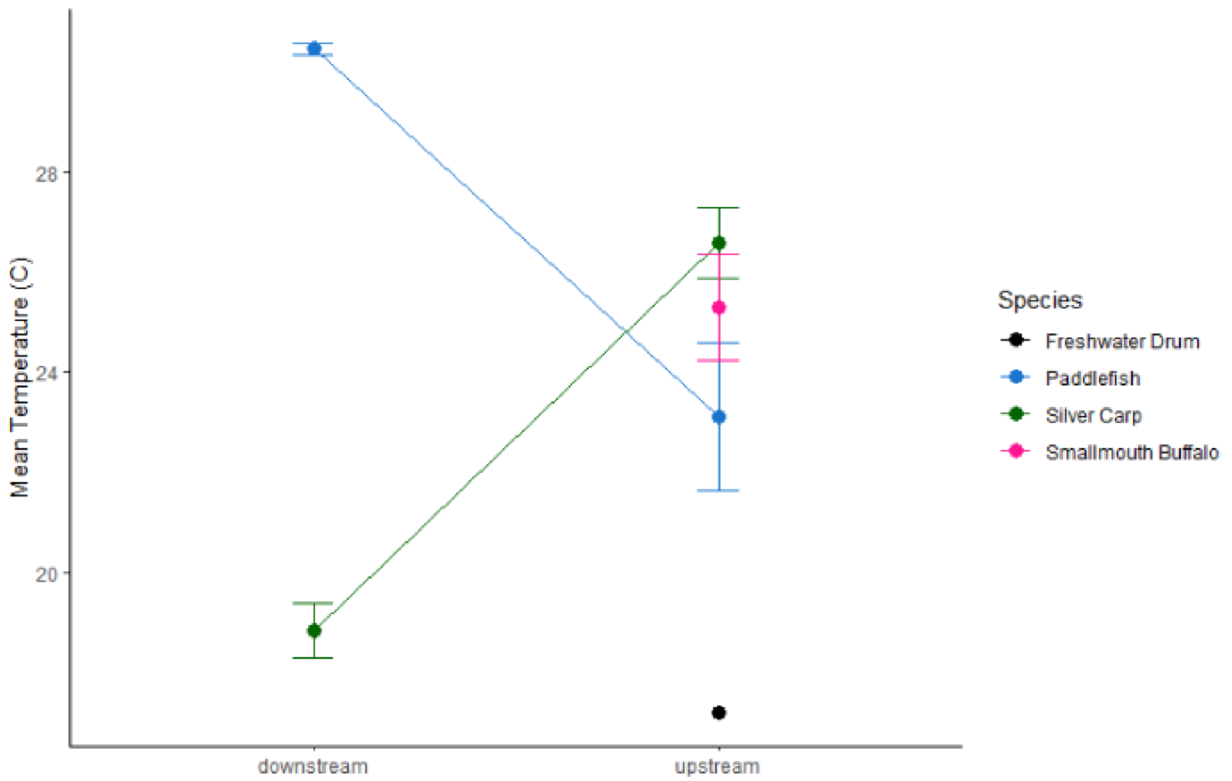


Figure 33. Mean temperature (with SE) in ºC for fish crossings at Barkley Dam by direction and species. The mean water temperature during fish crossings was not significantly different among species ($F_{3,47}$ = 1.65, p = 0.19) but mean temperature for downstream crossings was significantly higher compared to upstream crossings ($F_{1,47}$ = 17.65, $p < 0.001$); however, a significant interaction between species and crossing direction indicated that the mean temperature for each crossing direction was different for different species ($F_{1,47}$ = 24.68, $p < 0.001$).

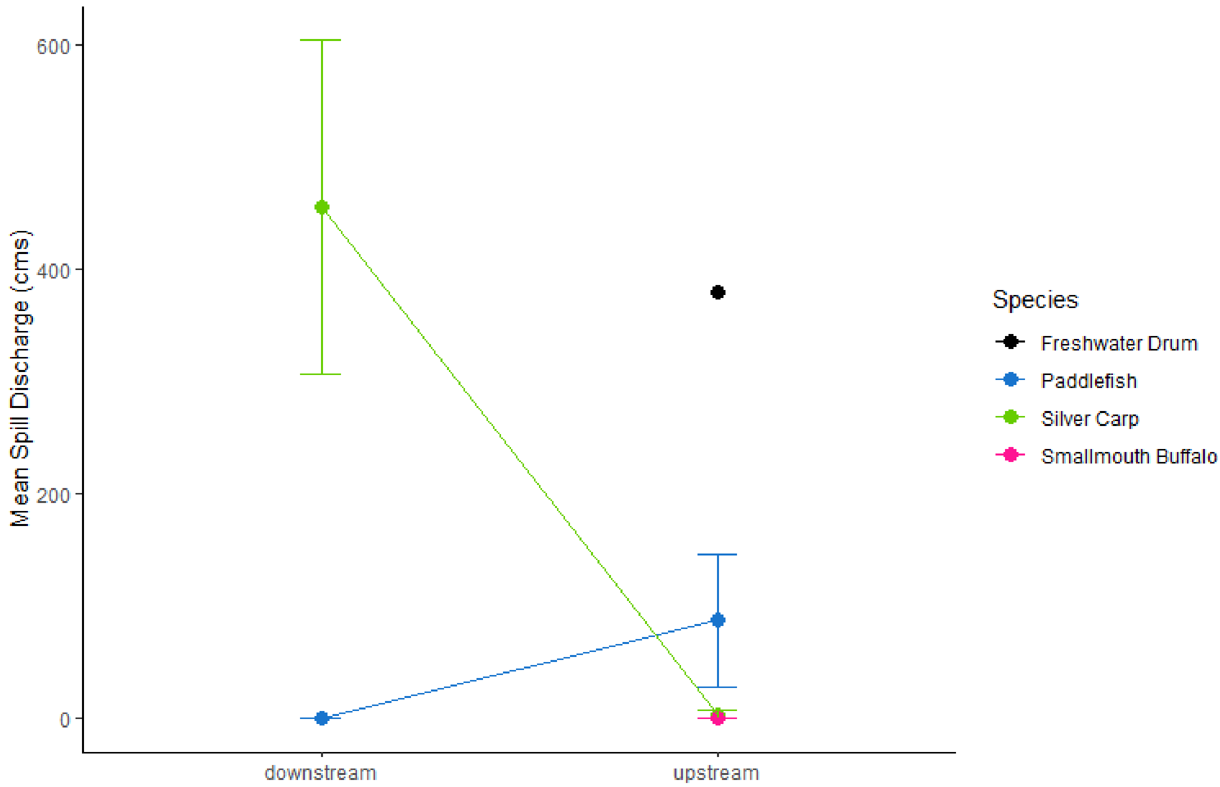


Figure 34. Mean spill discharge (with SE) in m^3/s for fish crossings at Barkley Dam by direction and species. The mean spill discharge of fish crossings was not significantly different among species ($F_{3,51}$ = 1.20, p = 0.32) but mean spill discharge for downstream crossings was significantly higher compared to upstream crossings ($F_{1,51}$ = 31.86, p < 0.001); however, a significant interaction between species and crossing direction indicated that the mean spill discharge for each crossing direction was different for different species ($F_{1,51}$ = 10.79, p = 0.002).

Appendix A.

Tennessee River Asian Carp Deterrent Workshop 2020

December 17, 2020

Dennis Baxter
Tennessee Valley Authority
dsbaxter@tva.gov

Mr. Baxter,

On behalf of participants of the Tennessee River Asian Carp Deterrent Workshop I am sharing the results of our structured decision process. Workshop participants were fisheries resource managers from the states of Kentucky, Tennessee, Mississippi, and Alabama; and federal staff from the US Geological Survey (USGS), and US Fish and Wildlife Service. This team included some of the leading experts on Asian carp in North America. Workshops were facilitated by USGS decision analysts over the course of three months.

The purpose of the workshops was to identify the most strategic locations for installation of Asian carp deterrents within the Tennessee River. Our primary objective was to minimize the number of carp in all reservoirs upstream of Wilson Dam as predicted by our models over the next twenty years. Decisions were based on our current understanding of carp abundance and population dynamics. Facilitators developed and guided participants through multiple populations models each allowing variation in deterrent efficiencies, carp movement rates, carp recruitment rates, and fishing mortality.

The cost of deterrent types varies greatly, and this did influence individual's decisions throughout the process. It did not affect the selection of locations, but cost did limit our expectations in that we only recommended four locations, as it would be challenging to fund more than four projects initially.

We considered the need for all deterrent types at all locks on the Tennessee River. The following deterrent types were considered in our analysis: lock closure, acoustic, BioAcoustic Fish Fence (BAFF), infused carbon dioxide, electricity, and combinations of these deterrents at one site. Lock closure was removed from the list of options because that action would obstruct a congressionally authorize use of the lock. We understood that we should not expect any of the deterrents to be 100% effective, and that none of deterrent types in question have been tested on Asian carp in working locks designed like those found at TVA dams.

The group agreed by consensus that unless the projects can be installed simultaneously, we recommend the following order of installation. This order recognizes a need to stop the leading edge from moving upstream, and a need to reduce immigration from the Ohio River.

Deterrent priority, location, and type(s):

1) Wilson Lock - BAFF
2) Kentucky Lock - BAFF (and Carbon Dioxide??)
3) Pickwick Lock - BAFF
4) Guntersville Lock - BAFF and Carbon Dioxide

These recommendations are based on our current understanding of carp populations and would need to be adjusted if carp populations successfully spawn in new locations, or suddenly make a major migration upstream. Such a migration is not anticipated as they have had opportunity to do so for two decades. We understand that are already a few carp upstream of the Guntersville Lock, and there are likely to be more there due to immigration by the time a deterrent is functional at Guntersville Lock. The group agrees that presence of a low-density population of carp above a dam is not a reason to forgo protection of that reservoir. We have not observed any reproductive success from these low abundance populations, therefore we feel it is not too late to protect these waters with downstream barriers. Should carp demonstrate reproductive success at a new location in the Tennessee system, deterrent locations and types would need to be reevaluated.

Thank you for the opportunity to share these recommendations.

Sincerely,

Frank Fiss, TWRA