Title: 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. Bigheaded carp were first reported in the Tennessee River in 1995 and in the Cumberalnd River in 2002 (Kolar et al. 2007). Despite occupancy data suggesting bigheaded carp presence in the Tennessee and Cumberland rivers 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:

- KDFWR continues to provide field support to the Bio-Acoustic Fish Fence research project at Barkley Lock and Dam on the Cumberland River.

- Bigheaded carp made passages at Kentucky, Barkley, Pickwick and Cheatham dams in 2021. No passages of bigheaded carp were detected at Wilson, Wheeler, or Old Hickory dams in 2021.
- Bigheaded carp have moved from within the Tennessee River to the Cumberland River and vice-versa. Interconnectedness of these populations via the Barkley Canal and the Ohio River should be considered during management, mitigation, and control efforts of bigheaded carp.

Methods:

Partner: TWRA

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 2021. Receivers were monitored throughout the year, which included downloading data, replacing damaged receivers, and replacing disposable components (e.g., batteries). To inform pool-to-pool movement, VEMCO telemetry receivers are in place at all locks and dams from Kentucky Dam to Guntersville Dam in the Tennessee River and from Barkley Dam to Old Hickory Dam in the Cumberland River. 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 – 2021 and plans to continue deploying acoustic transmitters in the Tennessee and Cumberland rivers in 2022 are underway. Minimal-stress capture methods were used to maximize survival of captured fish, including short gillnet sets (e.g., 20 minutes) and electrofishing. Likewise, all sampling and tagging events occurred during cool water conditions, and bigheaded carp were immediately released after recovery. Telemetry receiver stations deployed throughout the Tennessee and Cumberland rivers were used to detect when a fish moved from one pool to another (Figure 1). These pool-to-pool movements were documented when an individual was reliably detected by receivers in two different pools.

All bigheaded carp tagged in the Tennessee or Cumberland rivers were included in analysis. Therefore, carp tagged by various agencies and for concurrent studies exist in the analysis. In 2021, during a concurrent study, bigheaded carp were captured upstream of select dams, tagged, and released downstream of those respective dams (referred to as translocated fish). When considering dam passage events, these fish are considered separately, as they may express behavioral changes associated with the translocation event.

Tag drags refer to an event where a distinct acoustic test tag is used to determine if receivers were efficiently detecting tagged fish below, within, and above the locks. Tag drags are occasionally performed to evaluate the telemetry receiver array. During a tag drag, the test tag is dragged roughly 1 meter below the boat to simulate a telemetry-tagged bigheaded carp. The path of the tag-drag passes downstream, inter-lock, and upstream receivers, and the unique test tag number is later used to certify that each receiver is accurately detecting tagged fish that pass by within range. The path of the tag-drag is recorded as a track layer on a GPS unit. Then, the detections by receiver are matched to the location of the test tag based on time stamps. Thus, location of the tag during detection is known and receivers can be evaluated (e.g., the range of detection can be determined). Tag-drags are important for ensuring that detection data is accurately reported.

Receiver data is filtered to remove possible false detections. Detections are considered reliable when a fish is detected at least twice by receivers in a pool or lock. The minimum two detections can both be on one receiver or can be on different receivers in the same pool. Single detections are considered false detections and removed from ananlyses. Additionaly, receivers that are determined to be unreliable by tag drags are excluded from analyses. For example, a receiver that frequently detects a test tag both in an upstream pool and in a lock would be excluded from analyses to remove the possibility of concluding that a fish made upstream or downstream passage when it never actually left the lock.

Partner: KDFWR

Objective 1

KDFWR continued to participate in meetings and discussions with partners and other interested parties regarding the implementation of invasive carp deterrents at priority locations throughout the TNCR Basin. KDFWR provided feedback on the TVA Asian Carp Mitigation Programmatic Environmental Assessment. which was finalized and published in December 2021 (https://www.tva.com/environment/environmental-stewardship/environmental-reviews/nepa-detail/asian-carp-mitigation). Additionally, KDFWR met virtually with staff of the USFWS and USACE to begin discussions to determine the disposition of the Bio-Acoustic Fish Fence currently installed at Barkley Lock. This structure was installed on a temporary basis for testing and evaluation. The evaluation period will be end in 2023 and decisions must be made regarding its future status.

Objective 2

Asian Carp Deterrent Testing at Lake Barkley Lock

KDFWR continues to partner 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). The research team, led by the USFWS, continues to oversee the efforts being conducted to determine the efficiency of the BAFF for deterring Asian carp movement, and reports findings on a bi-annual basis (Evaluation of a Bio-Acoustic Fish Fence (BAFF) at Barkley Lock and Dam: Study Design, USFWS). The BAFF was commissioned on November 8th, 2019. KDFWR continues 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 2021, KDFWR surgically implanted silver carp (N = 150), paddlefish (N = 23), freshwater drum (N = 41), 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. KDFWR offloaded data from VEMCO receivers monthly and uploaded files to a shared folder for partners to access for analysis.

In 2021, 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 2D positioning of fish detected within the HTI receiver array near the BAFF. Efforts to tag silver carp with HTI tags in 2021 were conducted in April and November. The USGS, USFWS, and TWRA assisted with tagging efforts that resulted in 800 silver carp and 46 grass carp captured in Lake Barkley and translocated to the Barkley Tailwaters where they were tagged and released. KDFWR also deployed one HR3 receiver downstream of Barkley Lock and one HR3 receiver downstream of Kentucky Lock to increase detections of silver carp tagged with HTI transmitters. Data from these HR3 receivers, as well as the others deployed around Barkley Lock, are downloaded monthly by KDFWR and data transferred to the USGS for analysis.

Collect Asian carp movement information

KDFWR worked with Murray State University (MSU) tracking silver carp movement in the Tennessee and Cumberland River systems with VEMCO technology. 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 fish tagging effort mentioned above for the BAFF, KDFWR collaborated with USGS Upper-Midwest Environmental Science Center to surgically implant transmitters in 158 silver carp in the tailwaters of Kentucky Dam on the Tennessee River. Most silver carp tagged were collected in Kentucky Lake using gill nets and translocated to the Kentucky Tailwaters for release (121 fish). The 37 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 5 separate trips in Kentucky Lake in 2021. Most of the effort for this project in 2021 was expended to service the passive receivers. The passive receivers were checked on 29 different dates in Lake Barkley (25 receivers), 35 different dates in Kentucky Lake (31 different receivers), and 6 different dates on the Ohio River (19 receivers).

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.

Partner: Murray State University:

Harvest Below Kentucky Dam as Deterrent
No effort has yet been conducted to use harvest to harass the Silver Carp below Kentucky Lake Dam. We are currently analyzing the data to collect baseline data on typical movement patterns in the Lower Tennessee River and Lower Cumberland River. We have plans to conduct manual tracking of fish in these areas to supplement the passive receiver data.

Results and Discussion:
Partner: TWRA
TTU and TWRA continued efforts to tag fish throughout 2021. Twenty-seven fish were tagged at Beech River, sixteen fish were tagged at the Duck River, and sixteen fish were tagged in the Big Sandy area of Kentucky Lake. Additionaly, collaborative tagging events with the Upper Midwest Environmental Sciences Center released 393 fish in the Tennessee and Cumberland rivers in 2021 and KDFWR transmittered 75 bigheaded carp below Barkley Dam on the Cumberland River. The number of raw detections of tagged individuals increased from 2020 in every pool and lock (Table 1). Likewise, more unique individuals were detected in pools and locks than in 2020 (Table 2). The increased detection rates can likely be attributed to interagency cooperation that has led to an increased quantity of tagged fish (Table 3) and an increased quantity of active receivers in the Tennessee and Cumberland rivers. Wilson, Wheeler, Guntersville, and Old Hickory reservoirs and locks have continued to yield zero detections of tagged bigheaded carp (Tables 1,2).

The majority of pool-to-pool movements in 2021 were made by translocated fish that made upstream movements from Barkley Lake to Cheathm Lake through the Cheatham Lock and from Kentucky Lake to Pickwick Lake through the Pickwick Lock (Table 4). Translocated fish made more upstream pool-to-pool movements in every instance throughout 2021 than fish that were not translocated. Motivation to return to capture location likely played a role in the passage of these fish. Therefore, it may be beneficial to consider what factors might motivate upstream passage of fish that are not translocated (e.g., would fish be more likely to make upstream passage if competition increased at downstream locations?).

While there were no downstream pool-to-pool movements through the Cumberland River dams in 2021, four inidividuals did move downstream in the Tenneessee River from Pickwick Lake to Kentucky Lake. However, these individuals were not detected in a lock during downstream migration. It is most likely that downstream movements without detections in locks were made by going through spill gates, which were open during the afformentioned passage events. Although, it is not possible to definitively rule out the possibility of fish passing through a lock without being detected. Pool-to-pool movements by individuals from Barkley Lake to Kentucky Lake (and vice versa) have been detected (Table 4). These movements between the Cumberland River and the Tennessee River can occur via Barkley Canal or via the Ohio River (with multiple dam passages) and highlight the need for an understanding of interpopulation dynamics. No passages were detected at upstream dams (Wilson, Wheeler, Old Hickory, or Guntersville dams).

Three receivers were added at the confluence of the Beech River and Tennessee River, and lost receivers were replaced below and above Cheatham Dam. An additional receiver was added both above and below Cheatham Dam. Receivers were maintained by TTU personnel as follows: 1) Pickwick Dam, Cheatham Dam, and Old Hickory Dam three times throughout the year; 2) Wilson Dam and Wheeler Dam twice during the year; 3) Receivers not associated with dams three times throughout the year. Additional offloads and maintenance was conducted by partners at UMESC.

Plans for 2022 include continuing to tag more bigheaded carp for further passage evaluations and understanding. Likewise, additional tag drags through the lock systems will allow for greater understanding of receiver detections and help ensure reliable detections. Analyses of data are ongoing. Future efforts will characterize environmental conditions during passage events (e.g., flow), and temporal trends of passage events (e.g., diel or annual patterns) will be evaluated. Continued telemetry efforts will allow for a better understanding of the capabilities of bigheaded carp to continue moving upstream in the Tennessee and Cumberland rivers and the conditions that may facilitate those movements.

Partner: KDFWR

Objective 1

KDFWR expressed to partners that the preferred disposition of the Bio-Acousitic Fish Fence is to keep it in place at Barkley Lock to deter invasive carp movment upstream at that location. However, KDFWR does not have the capacity to incur the cost of purchasing the unit or maintaninace of the system and is looking to federal partners for assistance. The TVA Asian Carp Mitigation Programmatic Environmental Assessment was finalized and published in

December 2021 (https://www.tva.com/environment/environmental-stewardship/environmental-reviews/nepa-detail/asian-carp-mitigation).

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. However, the USFWS has published semi annual project updates which are available on the Invasivecarp.us website (Appendix A).

Tagged Fish Detections

Since 2016, KDFWR has tagged 647 Silver Carp and 276 native fish (Table 2). Ninety-two percent of the Freshwater Drum, 97% of the Paddlefish, 81% of the Silver Carp, and 98% percent of the Smallmouth Buffalo have been detected alive somewhere since their release; most of these detections occurred on the network of passive receivers (Figure 1). However, these numbers might be inflated by the high density of passive receivers near the release point below Lake Barkley dam. After removing all detections near the Lake Barkley dam, we detected 73% of the tagged Freshwater Drum, 77% of the tagged Paddlefish, 56% of the tagged Silver Carp, and 84% of the tagged Smallmouth Buffalo. Overall, if we include the fish we tagged plus those fish tagged by other agencies, and if we include all passive receivers, we have had live detections on 2 Alligator Gar, 1 Bighead Carp, 68 Freshwater Drum, 56 Paddlefish, 813 Silver Carp, 102 Smallmouth Buffalo, and 57 unknown fish.

Directed Movments of Silver Carp

Previous research has shown that Silver Carp in Kentucky Lake make rapid, large-scale downstream migrations in the spring (April – May) when temperatures are rising and discharges are falling. This pattern is mostly driven by “nonresident-far” fish which are fish that were captured, tagged, and released well upstream on the Tennessee River (in Pickwick Lake or just below its dam). Many of the fish which make this downstream migration in the spring cross Kentucky or Barkley dam and head into the Ohio River. Thus, these fish seem to be purposely moving downstream in the spring, and we were curious about their behavior once they made it to the Ohio. Similarly, we wished to study any fish which seemed to be moving from the Ohio to the lakes with purpose.

To study these fish, we focused on all species which had crossed a dam since 2016. Once a fish was determined to have crossed a dam, we studied all locations which occurred during a short time period before the crossing and after the crossing. From these data we extracted only those fish which were detected both in the lakes and the Ohio River within a 14-day window. In this way, we observed fish which seemed to be making purposeful, directed movements from the lakes to the Ohio River or from the Ohio River to the lakes.

Within this subset of fish, we wished to determine the swimming speed during the time period when the fish was making these purposeful movements. For a fish crossing in the downstream direction (i.e. towards the Ohio River), we determined the farthest upstream point in the TNCR through our subset of locations, and we determined the latest time it was at that upstream location. Then, we determined the farthest “downstream” location in our subset (which would be in the Ohio River), and we recorded the earliest time the fish was at that far downstream location. These values were reversed for a fish crossing the dams in an upstream direction (away from the Ohio River).

Thus, within the subset of fish locations associated with a dam crossing, we were able to look at the maximum distance the fish traveled during this window of purposeful movement. Additionally, we were able to determine the amount of time it took the fish to swim this maximum distance, so we could calculate the swimming rate in km/day. Note that we were not always able to tell which dam the fish crossed, and we were not always able to tell the exact date when they crossed the dam, but our analysis is still valid because we are studying the entire time period around a dam crossing and thus the specific date of crossing is not important. However, since we could not always determine which dam was crossed, we assumed all fish entered the Ohio River at the midpoint between the mouths of the Tennessee and Cumberland Rivers (Ohio River Kilometer 1492).

As previously observed, Silver Carp tend to cross the dams in a downstream direction in the springtime when the gates are spilling and the fish can swim under (Barkley Dam) or over (Kentucky Dam) the gates, but upstream crossings occur later in the year (Figure 2). Most (36 out of 39 or 92.3%) of the downstream crossings which were headed to the Ohio River were made by “nonresident-far” fish, while only 3 of these 39 downstream crossings were by “resident” Silver Carp (i.e. fish which were captured, tagged, and released in Kentucky Lake, Table 3). Only 7 Silver Carp in this data set crossed upstream from the Ohio into the lakes (6 “nonresident-far” fish (85.7%)) and 1 “nonresident-near” fish (i.e. a fish captured, tagged, and released in the Lake Barkley tailwaters). Swimming speeds during these crossings ranged from 7.9 – 84.4 km/day; mean swimming speed (± SE) of downstream-crossing fish was 28.4 ± 3.3 km/day and was significantly greater than mean swimming speed for upstream-crossing fish (17.4 ± 2.1 km/day, $t36.1 = 2.80$, $p = 0.01$). Note that many more Silver Carp crossed the dams during the study period, but in this analysis we are only looking at those Silver Carp which moved between the lakes and the Ohio River in a relatively short period of time.

Not only did the downstream-crossing Silver Carp move rapidly during the spring, but also they tended to move upstream once they reached the Ohio River. Of the 39 downstream-crossing Silver Carp, 35 of them headed upstream in the Ohio (89.7%, Table 3). The 35 fish which headed upstream were mostly “nonresident-far” fish (32 or 91.4%). Interestingly, all the native fish which moved in a downstream direction when crossing the dams (i.e. from the lakes to the

Ohio) continued to head downstream when they reached the Ohio (1 Freshwater Drum, 1 Paddlefish, and 1 Smallmouth Buffalo). These results might be explained by the fact that the Smithland receivers are only about 8 km upstream from the mouth of the rivers, while the Brookport receivers are about 22 km downstream; thus, the fish might seem to be turning upstream just because the upstream receiver is closer. However, recall that we are only looking at a narrow window of time for these fish, and if they were detected upstream they must have moved that direction soon after crossing the dam. Also, if the fish were turning at random when they hit the Ohio River, then we would expect many more detections at the Brookport receivers. So, we feel that the data indicate that Silver Carp are purposely heading upstream in the Ohio after a long migration downstream from the lakes. KDFWR plans to deploy more receivers in the lower Tennessee and Cumberland rivers near their confluence with the Ohio River in an effort better understand fish movements between these systems, and MSU will be performing active boat tracking in this area as well.

Natvie Fish Movement

The number of tagged native fish is becoming large enough that we can start to analyze the movement patterns of some of these fish. We have been tracking some Paddlefish tagged by the Missouri Department of Conservation (MDC) over the entire duration of the study in both lakes (since 2015). These fish have been supplemented by other Paddlefish which we have recently tagged and released below Lake Barkley Dam. No Paddlefish have been captured, tagged, and released upstream of the dams, so all Paddlefish in these results have moved upstream across a dam.

We have been tracking 18 Paddlefish in Lake Barkley (16 tagged by KDFWR and 2 tagged by MDC) and 15 Paddlefish in Kentucky Lake (10 KDFWR fish and 5 MDC fish). Although we have tracked more fish in Lake Barkley, we have limited movement data on those Paddlefish due to the sparse network of receivers in that lake. In Kentucky Lake, Paddlefish mean swimming speed (± SE) was 6.3 ± 0.6 km/day (minimum = 0.0 km/day, maximum = 18.1 km/day). Although Paddlefish activity seemed to peak slightly in the spring, we could find no relationship between mean swimming speed and temperature (Figure 3) or discharge (Figure 4). Paddlefish did not seem to have any seasonal direction to their movement (Figure 5).

Dam Passage at Kentucky and Barkley Locks

Tagged Silver Carp crossed upstream into the lakes more often than they left the lakes heading downstream (Table 4), but this is not surprising given the large number of fish tagged and released just below the dams. However, the “nonresident-far” fish also crossed upstream into the lakes in large numbers even though these fish were captured, tagged, and released far upstream of the dams. The number of total crossings for the “nonresident-far” fish was much higher than for any other group, and the number of their upstream crossings was nearly equal to the number of their downstream crossings for both dams. Of the native species, Paddlefish were most likely to cross a dam (Table 5). Very few "resident" Silver Carp, "nonresident-near" Silver Carp, and native species crossed a dam more than once, but many of the "nonresident-far" fish had multiple crossings (Table 6 and Table 7). Clearly the "nonresident-far" fish are more likely to leave the lakes, but they are also quite likely to return to the lakes after leaving. All fish are unable to cross upstream without using the lock, and most fish do not use the lock when crossing downstream (Table 8). The status of the Bio-Acoustic Fish Fence (BAFF) (On vs. Off) was not included as a variable in these analyses, as that is being investigated by the USFWS led research group.

Timing of dam crossing by Silver Carp showed a clear temporal pattern. Silver Carp nearly always crossed the Lake Barkley Dam downstream in springtime when it was spilling, but not at peak spill discharge (Figure 6) and when temperatures were low but rising (Figure 7). Upstream crossings were mostly later in the year (summer through fall) when spill discharge was low and temperatures were high. These patterns generally agree with the downstream migrations we see in the spring and the upstream movement later in the year – most of which is driven by the "nonresident-far" fish. Mean spill discharge (± SE) when Silver Carp crossed the Lake Barkley Dam going downstream was 707.3 ± 135.2 cms which was significantly higher than mean spill discharge when they crossed heading upstream (72.4 ± 27.1 cms, $t_{29.2} = 4.6$, $p < 0.01$). Mean water temperature (± SE) when Silver Carp crossed downstream was 17.8 ± 0.5 C which was significantly lower than mean water temperature when these fish crossed heading upstream (26.6 ± 0.6 C, $t_{68.0} = -11.3$, $p < 0.01$). Similar patterns were seen when Silver Carp crossed the Kentucky Lake Dam.

Native fish mostly crossed the Lake Barkley Dam when it was spilling (Table 9). However, Smallmouth Buffalo only crossed this dam when it was not spilling at all. Paddlefish left the lakes when the water was very warm but chose cooler temperatures to cross upstream into the lakes (Table 10). Due to the operation of the BAFF, the timing of upstream crossings of native species such as Paddlefish compared to the upstream crossings of the Silver Carp is particularly interesting. Generally, the Paddlefish crossed the Lake Barkley Dam in an upstream direction earlier in the year when Silver Carp were mostly crossing in a downstream direction (Figure 8). Upstream crossings of Silver Carp tended to occur when spill discharge was low and water temperatures were high. Mean spill discharge was not significantly different when the Silver Carp were crossing upstream (72.4 ± 27.1 cms) than when the Paddlefish were crossing upstream (213.4 ± 84.6 cms, $t_{21.8} = 1.6$, $p = 0.13$) but mean temperature was significantly higher when the Silver Carp crossed upstream (26.6 ± 0.6 C) compared to when the Paddlefish crossed upstream (19.2 ± 1.2 C, $t_{26.1} = -5.6$, $p < 0.01$). Upstream crossing temperatures overlap slightly between the Silver Carp and the Paddlefish (Figure 9), but if the BAFF was ON when temperatures were greater than 22.5 C it may discourage many Silver Carp from entering the lakes while minimizing the effect on Paddlefish.

Recommendations:

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.

Tagging efforts should be continued to increase the quantity of bigheaded carp with active transmitters. Furthermore, tagging efforst should be spatialy stratified to ensure representation of bigheaded carp from various locations throughout the basin.

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 bigheaded 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 receiver 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 deterrents.

The receiver network continues to produce useful data, and as more native fish migrate into the lakes we will be able to collect better data on the movement patterns of these species. With the large number of tagged fish being released in the tailwaters, future analysis will focus on movement patterns through the dams and interactions with the Ohio River.

Continued coordination with other subbasins conducting telemetry work. Many fish tagged in the TNCR have been detected outside of the basin, and as far away as the Mississippi River near St. Louis. The availability to record these largescale movements is acheivable through extensive coordination with many user groups of VEMCO telemetry equipment and may aid in answering questions about population connectivity, and how that changes as deterrents are implemented throughout the range of invasive carp.

References:

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Appendix A. TWRA Figures and Tables:

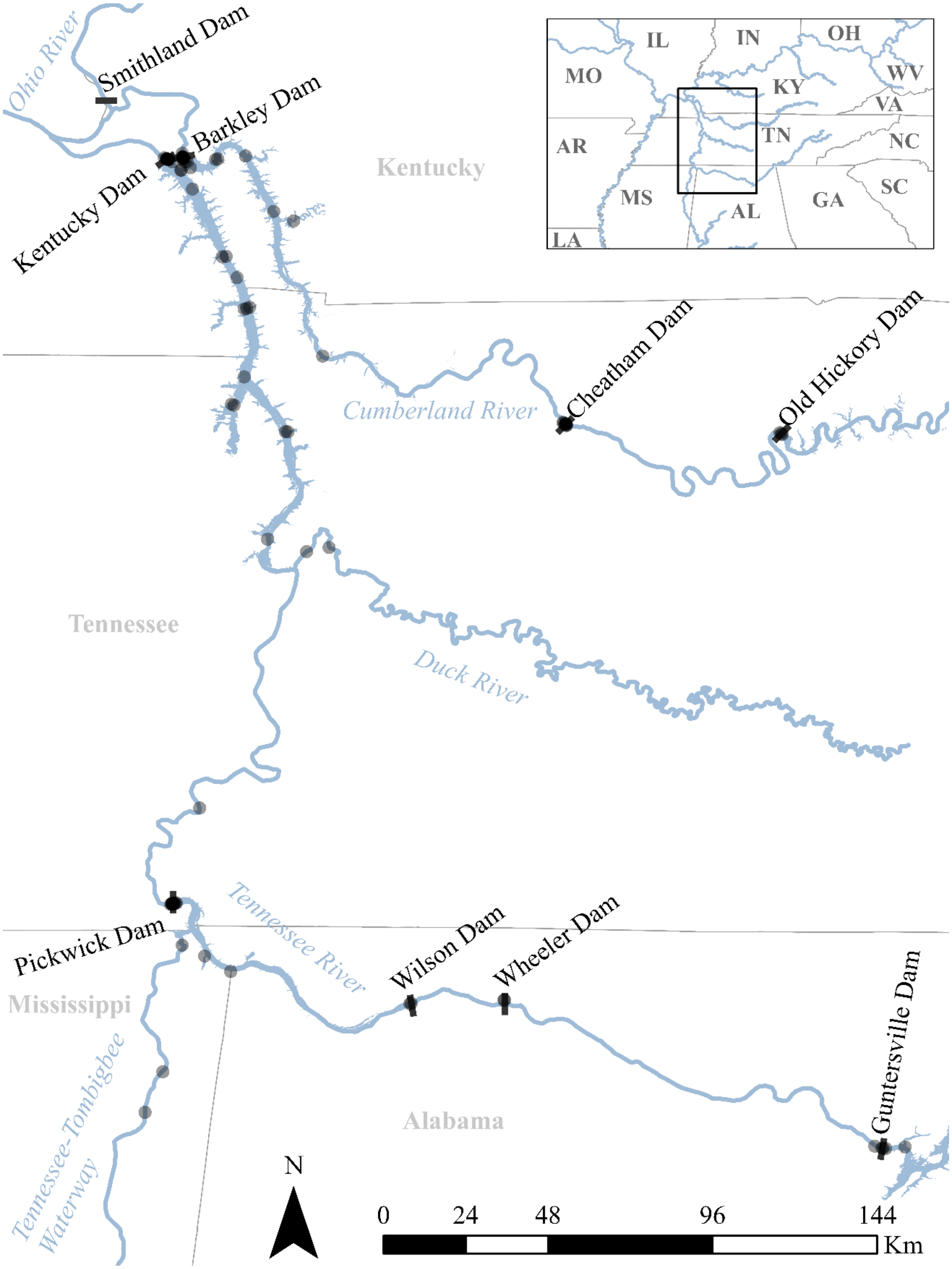


Figure 1. The Tennessee River and Cumberland River lock and dam receivers (translucent grey circles) that are monitored to evaluate pool to pool movements of Asian carp and monitor the upstream invasion of Asian carp.

Table 1. Total number of raw detetctions of tagged bigheaded carp per pool or lock by year. Location and year combinations where data are not available are marked by NA.

	Year				
Pool	2017	2018	2019	2020	2021
Below Barkley Dam					1,355,536
Barkley Lake	6,868	58,672	276,893	275,308	1,002,854
Barkley Lock					73,572
Cheatham Lake	NA	NA	0	0	25,235
Cheatham Lock	NA	NA	49	76	15,935
Old Hickory Lake	NA	NA	0	0	0
Old Hickory Lock	NA	NA	0	0	0
Below Kentucky Dam					1,092,840
Kentucky Lake	303,511	1,269,570	527,943	707,660	1,339,242
Kentucky Lock					60,542
Pickwick Aux Lock	0	245	1,240	721	27,431
Pickwick Lake	109,773	96,938	64,573	17,379	35,998
Pickwick Lock	0	200	2,574	1,821	24,146
Wilson Lake	0	0	0	0	0
Wheeler Lake	0	0	0	0	0
Wheeler Auxiliary Lock	0	0	0	0	0
Guntersville Lake	NA	NA	NA	0	0

Table 2. Total number of individual bigheaded carp detected per pool or lock by year.

	Year				
Pool	2017	2018	2019	2020	2021
Below Barkley Dam					550
Barkley Lake	7	27	48	62	139
Barkley Lock					298
Cheatham Lake	NA	NA	0	0	18
Cheatham Lock	NA	NA	1	2	53
Old Hickory Lake	NA	NA	0	0	0
Old Hickory Lock	NA	NA	0	0	0
Below Kentucky Dam					207
Kentucky Lake	15	67	81	66	183
Kentucky Lock					187
Pickwick Aux Lock	0	2	6	3	63
Pickwick Lake	7	29	32	16	33
Pickwick Lock	0	2	4	6	73
Wilson Lake	0	0	0	0	0
Wheeler Lake	0	0	0	0	0
Wheeler Auxiliary Lock	0	0	0	0	0
Guntersville Lake	NA	NA	NA	0	0

Table 3. Number and release location of transmittered bigheaded carp by year and translocation status in the Tennessee and Cumberland rivers. Translocated fish were captured upstream of the respective dam and moved to the downstream side of the dam prior to release. Cumulative transpired (i.e., out of battery) transmitters represents the number of transmitters that are expected to have become inactive. Corrected cumulative transmitters represents the estimated count of bigghеaded carp released in the Tennessee or Cumberland rivers that currently have active transmitters. Note, counts are end of year estimates (i.e., based on December 31 of each year), and true count varies throughout the year as transmitters are added or become inactive.

	Year and Translocation Status							
Pool	2016	2017	2018	2019	2020	2020 Translocated	2021	2021 Translocated
Kentucky Reservoir	69	91	24	16	NA	NA	76	63
Lower Cumberland River	NA	20	41	150	150	NA	150	NA
Pickwick Reservoir	NA	10	30	5	NA	NA	NA	NA
Lower Tennessee River	NA	NA	NA	NA	9	91	37	121
Barkley Reservoir	NA	NA	NA	NA	NA	NA	NA	80
Yearly Total	69	121	95	171	159	91	263	264
Cumulative Transmitters	69	190	285	456	615	706	969	1233
Cumulative Transpired Transmitters	0	0	0	24	118	118	389	389
Corrected Cummulative Transmitters	69	190	285	432	497	588	580	844

Table 4. Number of pool-to-pool movements (starting location, ending location, and lock traveled) by tagged bigheaded carp by year; “none” indicates no detections in locks between pools. Passage combinations that have not been detected at least once are not included. The column titled “2021 Translocated” refer to fish that had been manually moved from upstream of to downstream of a dam prior to making the detected passage event in 2021.

			Year					
From	To	Lock Used	2017	2018	2019	2020	2021	2021 Translocated
Barkley Lake	Cheatham Lake	Cheatham Lock	NA	NA	0	0	0	18
Barkley Lake	Kentucky Lake	NA	0	21	35	22	26	43
Kentucky Lake	Barkley Lake	NA	1	25	48	26	39	46
Kentucky Lake	Pickwick Lake	None	0	0	3	0	0	0
Kentucky Lake	Pickwick Lake	Pickwick Aux Lock	0	0	1	1	1	3
Kentucky Lake	Pickwick Lake	Pickwick Lock	0	2	3	2	5	21
Pickwick Lake	Kentucky Lake	None	0	11	18	16	4	0
Pickwick Lake	Kentucky Lake	Pickwick Aux Lock	0	0	1	0	0	0

Appendix B. KDFWR Figures and Tables:

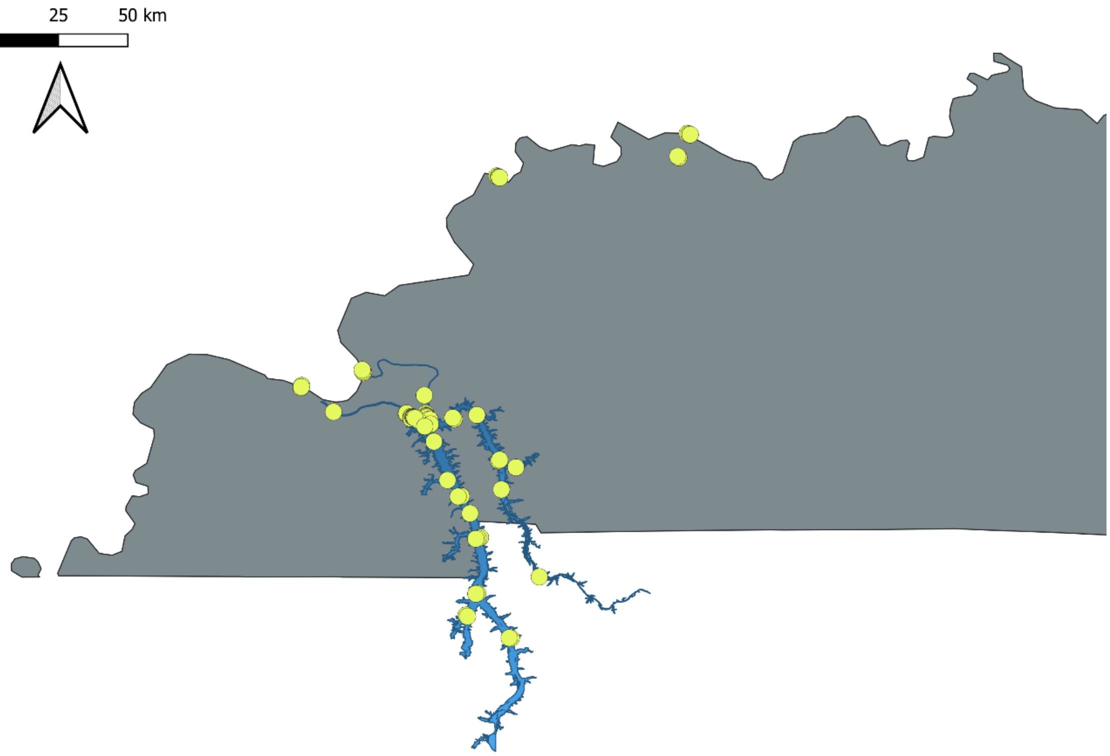


Figure 1. Location of VR2 passive receivers (yellow dots) in Lake Barkley, Kentucky Lake, the Green River, and the Ohio River.

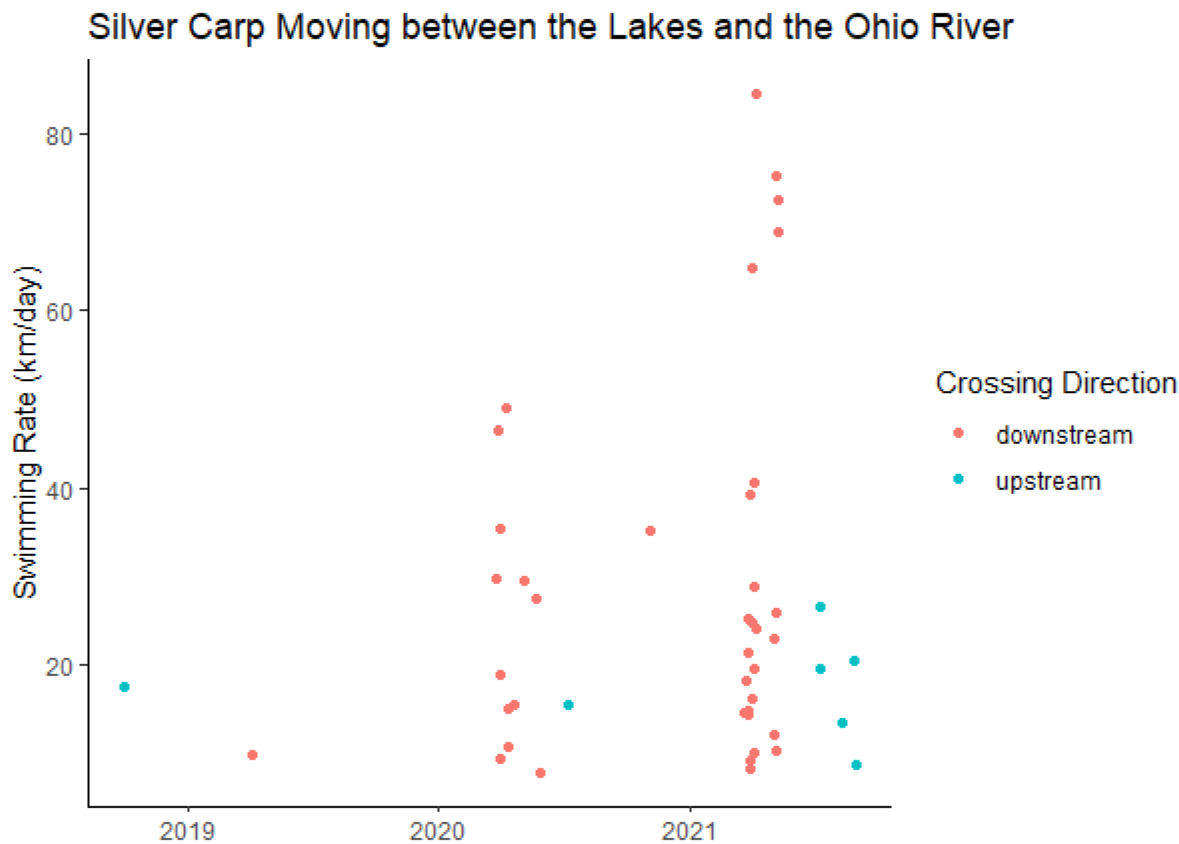


Figure 2. Swimming speed (km/day) of Silver Carp near the date they crossed one of the dams while moving between the lakes and the Ohio River.

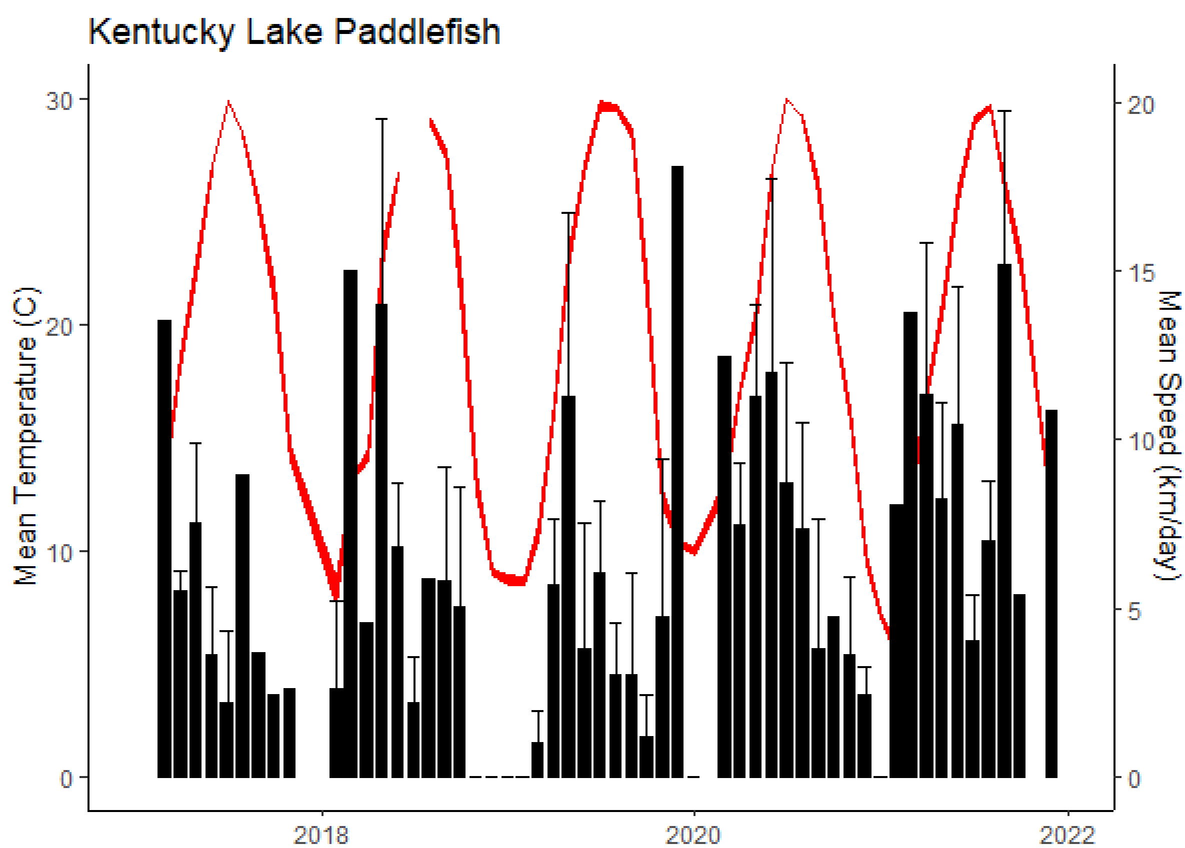


Figure 3. Monthly mean (with SE) surface temperature (oC, red line) and monthly mean (with SE) swimming speed (km/day, black bars) for Paddlefish in Kentucky Lake, 2017 – 2021.

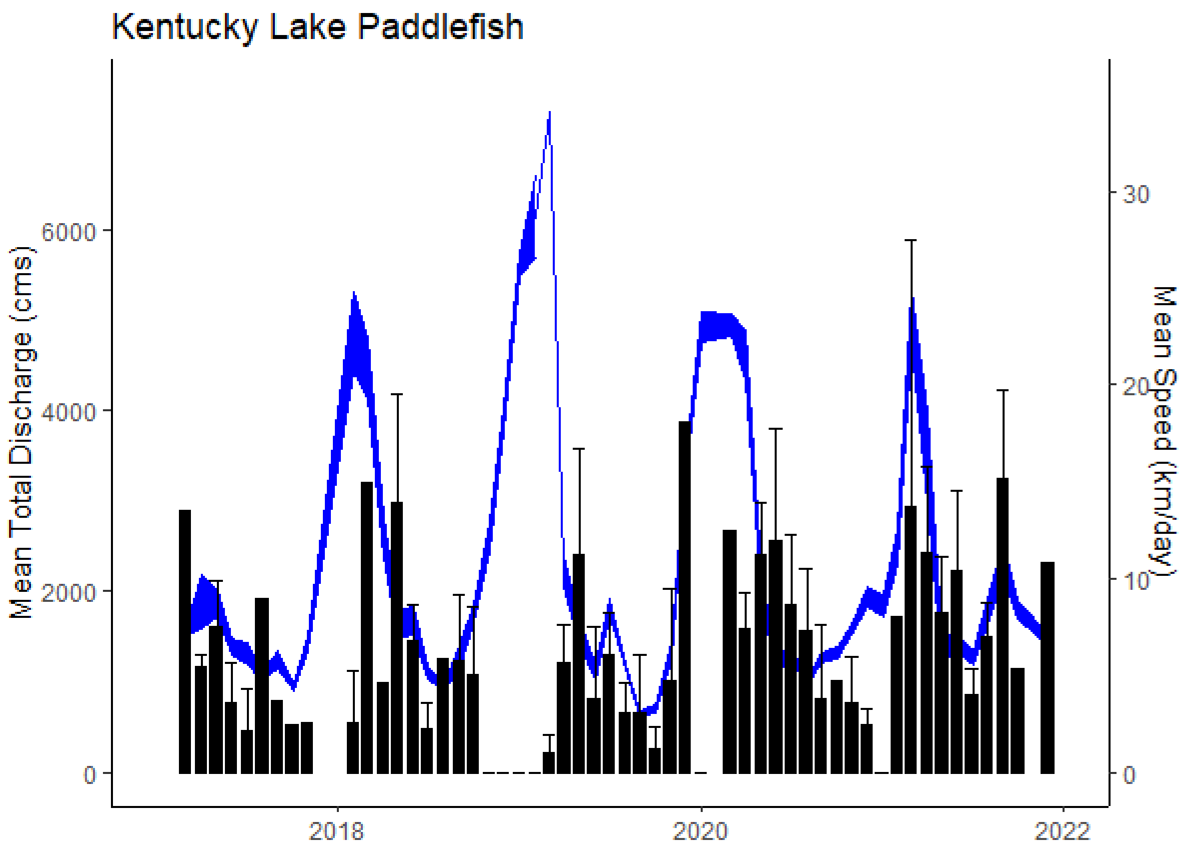


Figure 4. Monthly mean (with SE) discharge (cms, blue line, measured at the Kentucky Dam) and monthly mean (with SE) swimming speed (km/day, black bars) for Paddlefish in Kentucky Lake, 2017 – 2021.

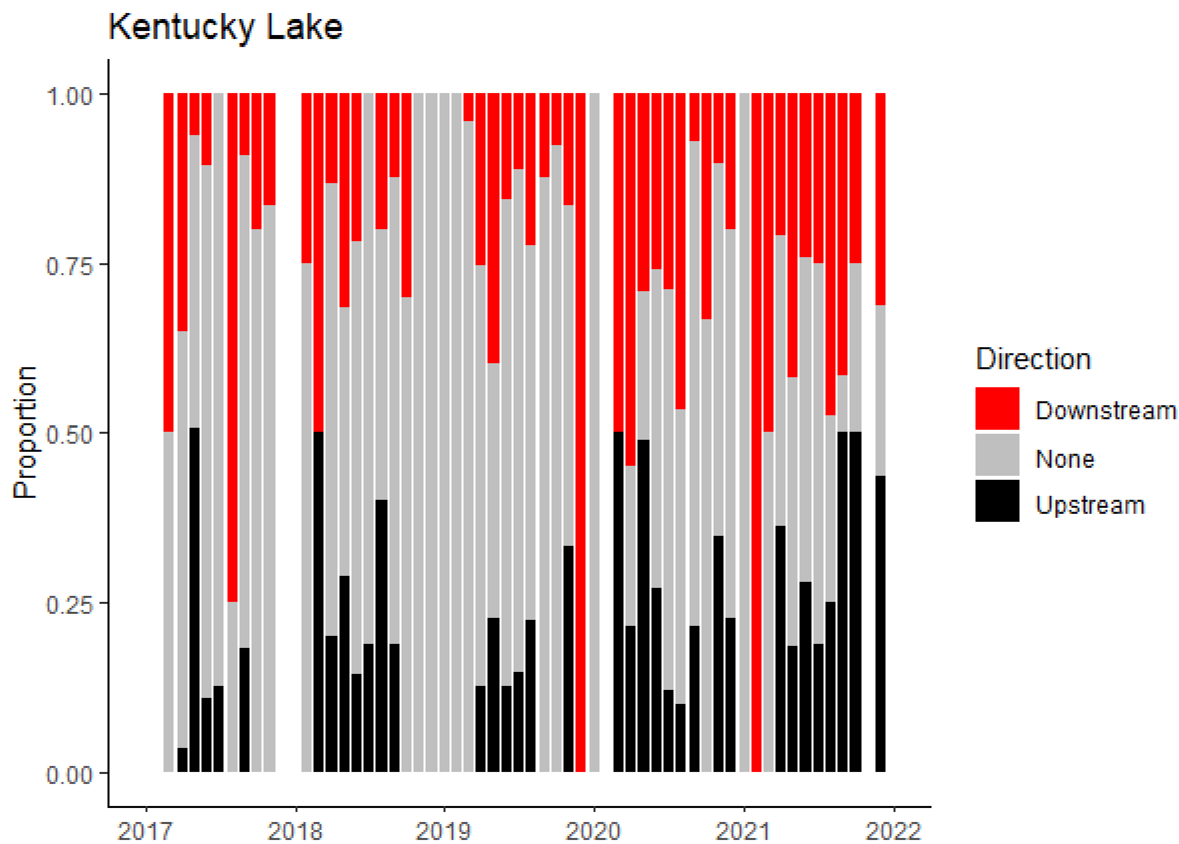


Figure 5. Percentage of movement direction by month for Paddlefish in Kentucky Lake.

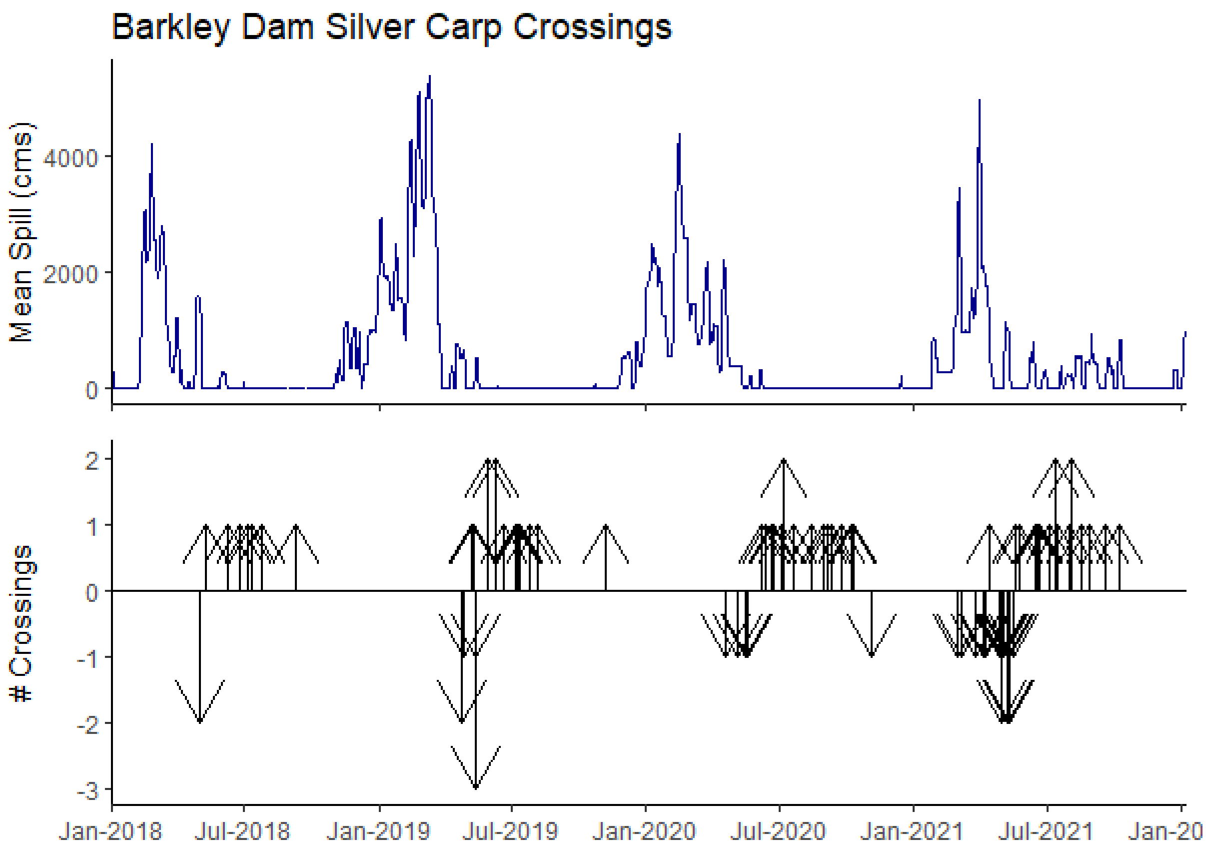


Figure 6. Silver Carp crossing Lake Barkley Dam compared to spill discharge (cms).

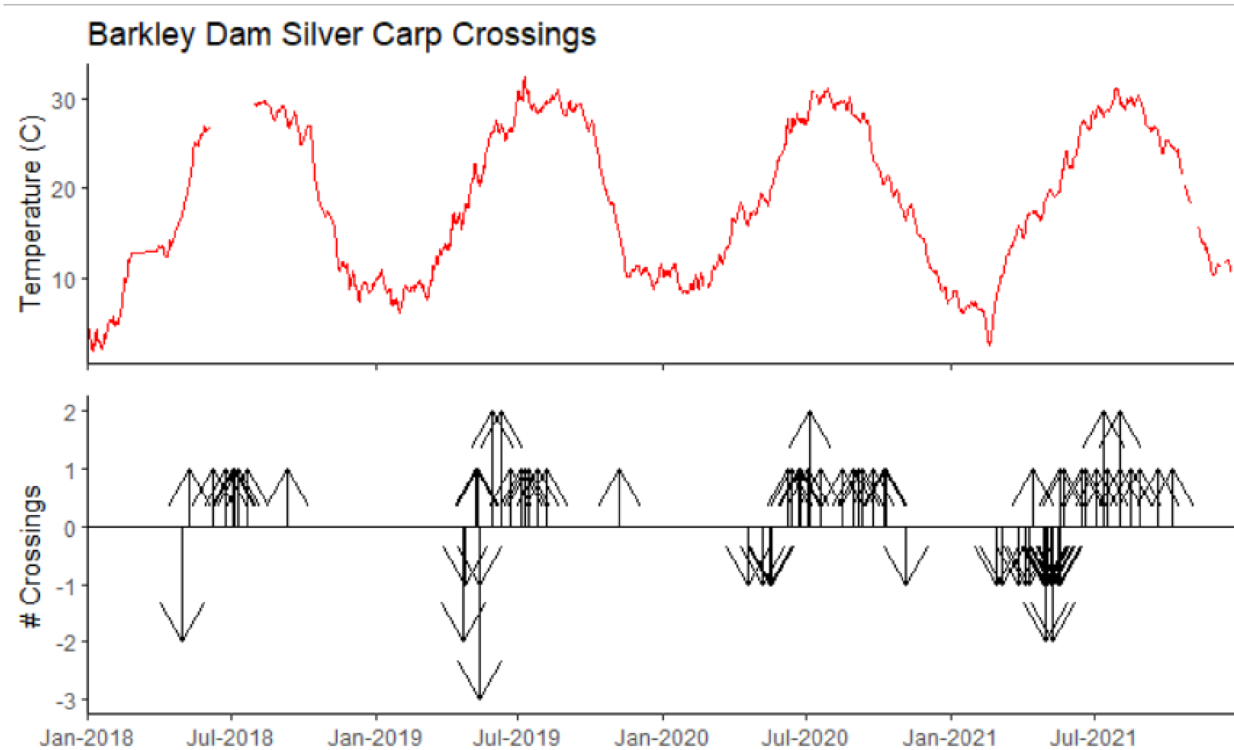


Figure 7. Silver Carp crossing Lake Barkley Dam compared to temperature (C).

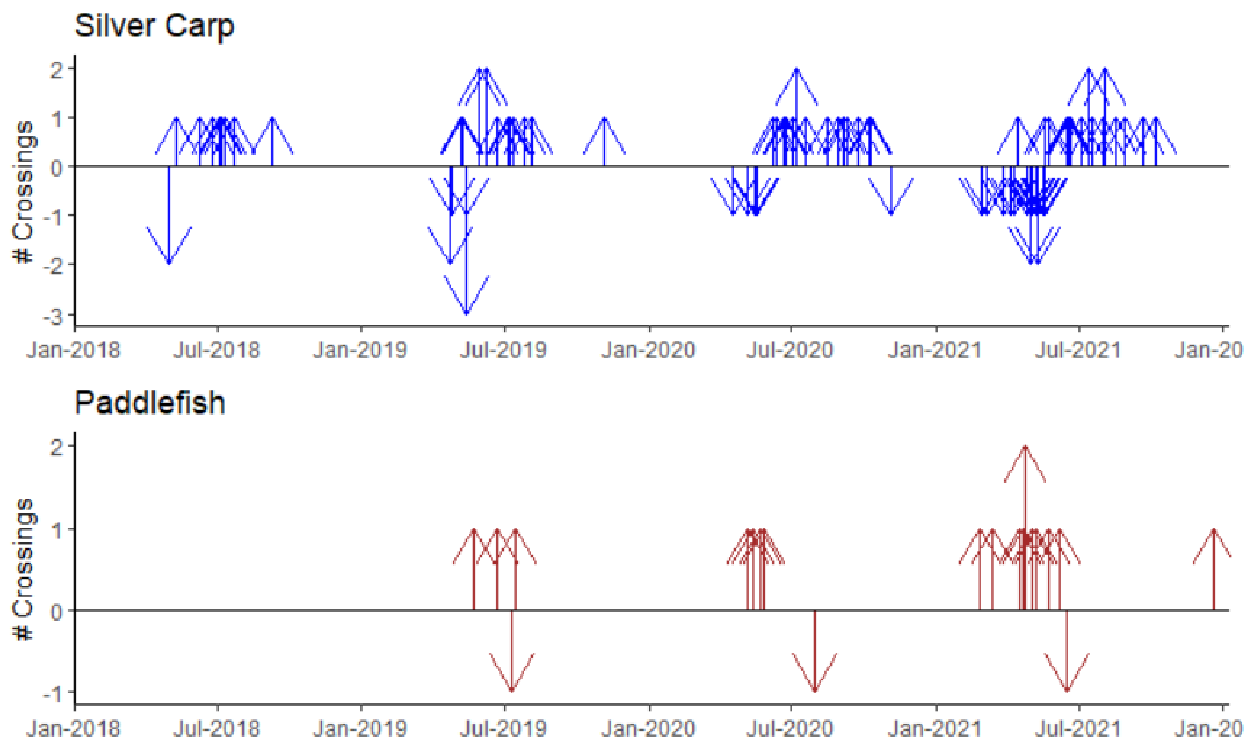


Figure 8. Timing of Silver Carp and Paddlefish crossing Lake Barkley Dam compared to each other.

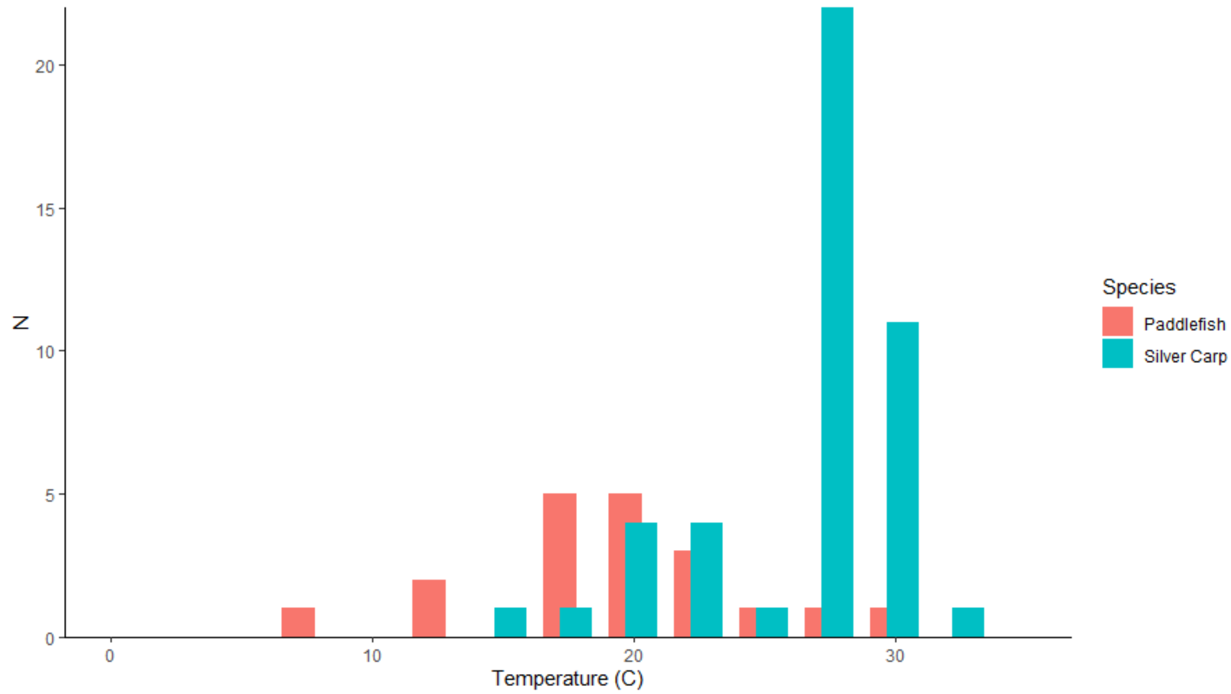


Figure 9. Frequency distribution of upstream crossing of the Lake Barkley Dam by Silver Carp and Paddlefish.

Table 1. Summary of fish captured, tagged, and released in the Lake Barkley tailwaters by KDFWR in 2021.

Species	N	TL (mm) Mean ± SE	W(g) Mean ± SE
Freshwater Drum	41	495 ± 13	1,693 ± 129
Paddlefish	24	782 ± 25	6,680 ± 607
Silver Carp	149	664 ± 7	2,866 ± 82
Smallmouth Buffalo	40	548 ± 18	2,342 ± 198

Table 2. Number of fish tagged by KDFWR in Lake Barkley, Kentucky Lake, and their tailwaters since 2016.

Species	2016	2017	2018	2019	2020	2021	Total
Freshwater Drum				20	32	41	93
Paddlefish				16	22	24	62
Silver Carp*	69	66	44	169	150	149	647
Smallmouth Buffalo				41	40	40	121

* 134 resident, 513 nonresident-near; resident fish were tagged and released in Kentucky Lake, nonresident-near fish were tagged and released below Barkley or Kentucky dams

Table 3. Number of fish which moved between the lakes and the Ohio River in a short period of purposeful, directed movement.

		Species	Residency*	N
Downstream Crossings	Turned Upstream	Silver Carp	Nonresident-far	32
		Silver Carp	Resident	3
	Turned Downstream	Silver Carp	Nonresident-far	4
		Freshwater Drum	Nonresident-near	1
		Paddlefish	Nonresident-far	1
		Smallmouth Buffalo	Nonresident-near	1
Upstream Crossings		Silver Carp	Nonresident-far	6
		Silver Carp	Nonresident-near	1
		Unknown		1

*resident fish were tagged and released in Kentucky Lake, nonresident-near fish were tagged and released below Barkley or Kentucky dams, nonresident-far fish were tagged and released outside the study area for this section.

Table 4. Number of Silver Carp crossing a dam by direction and residency.

	Lake Barkley		Kentucky Lake	
	Upstream	Downstream	Upstream	Downstream
Resident	3	1	2	1
Nonresident – near	21	1	13	-
Nonresident – far	32	33	13	12

Table 5. Number of native species and unknown species crossing a dam by direction.

	Lake Barkley		Kentucky Lake	
	Upstream	Downstream	Upstream	Downstream
Freshwater Drum	7	-	-	1
Paddlefish	21	3	1	1
Smallmouth Buffalo	6	-	1	-
Unknown	6	-	2	-

Table 6. Frequency distribution of number of crossings by individual Silver Carp.

	Number of Crossings			
	1	2	3	4
Resident	5	1	-	-
Nonresident – near	33	1	-	-
Nonresident – far	47	18	1	1

Table 7. Frequency distribution of number of crossings by individual native species.

	Number of Crossings			
	1	2	3	4
Freshwater Drum	6	1	-	-
Paddlefish	16	2	2	-
Smallmouth Buffalo	7	-	-	-
Unknown	8	-	-	-

Table 8. Number of dam crossings detected in the lock by direction and species.

	Upstream		Downstream	
	Used Lock	Did not use Lock	Used Lock	Did not use Lock
Silver Carp	84	-	4	44
Freshwater Drum	7	-	1	-
Paddlefish	22	-	1	3
Smallmouth Buffalo	7	-	-	-
Unknown	8	-	-	-

Table 9. Mean (with SE) spill discharge (cms) for native species crossing the Lake Barkley Dam.

	Downstream		Upstream	
	Mean	SE	Mean	SE
Freshwater Drum	-	-	234.1	136.2
Paddlefish	101.9	101.9	213.4	84.6
Smallmouth Buffalo	-	-	0.0	0.0
Unknown	-	-	29.0	29.0

Table 10. Mean (with SE) water temperature (C) for native species crossing the Lake Barkley Dam.

	Downstream		Upstream	
	Mean	SE	Mean	SE
Freshwater Drum	-	-	22.7	1.5
Paddlefish	29.4	1.1	19.2	1.2
Smallmouth Buffalo	-	-	25.7	1.0
Unknown	-	-	28.0	0.5

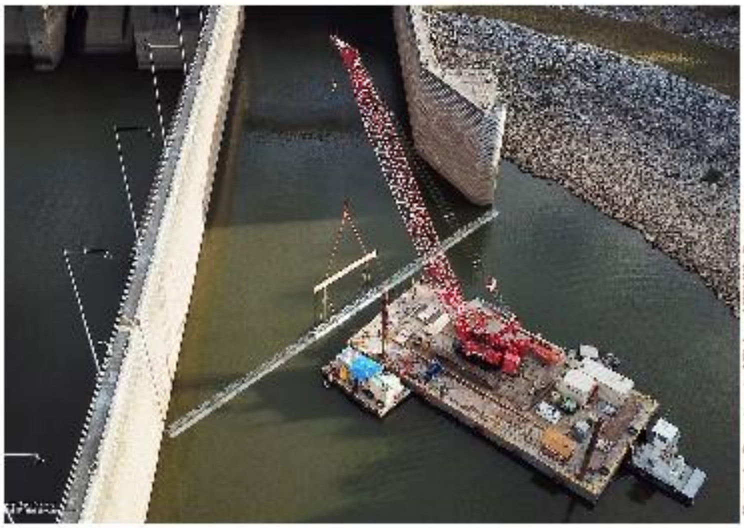
Appendix C. 'Lake Barkley BioAcoustic Fish Fence Effectiveness Study' document from USFWS

U.S. Fish & Wildlife Service

Lake Barkley BioAcoustic Fish Fence Effectiveness Study

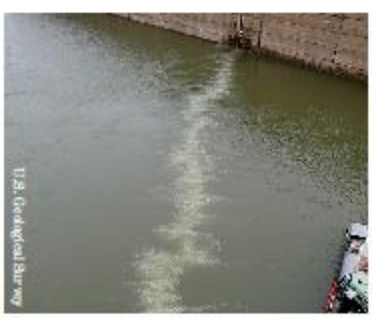
Questions and Answers

Four species of non-native invasive carp—bighead, black, grass and silver—can be found within the waters of the United States. The surge of invasive carp threatens the country's renowned aquatic biodiversity, outdoor economies and way of life. Federal, state, university and industry partners have joined together to test a new and innovative fish deterrent technology to slow the carps' upstream push. A BioAcoustic Fish Fence, or BAFF, has been deployed on the downstream side of Barkley Lock in Kentucky to determine its effectiveness at reducing the movement of invasive carp through a lock chamber.



Kentucky Department of Fish and Wildlife Resources

The BAFF, or BioAcoustic Fish Fence, being installed at Lake Barkley Lock and Dam.



U.S. Geological Survey

The air-bubble curtain, visible when the BAFF is turned on.

What is a BioAcoustic Fish Fence, or BAFF? How does it work?

Developed by Fish Guidance Systems, the BAFF is designed to deter or guide fish using sound, strobe lights, and air bubbles. The BAFF in the downstream approach channel at Barkley Lock may deter invasive carp from using the lock to move into Lake Barkley.

A line of bubbles runs diagonally across the lock approach channel between the walls. Sound is projected within the air bubbles where it is amplified and trapped. Some sound and light may escape the water and be detected by boaters. At night, flashing white lights can be visible, especially when water levels are low.

The BAFF has the potential to deter the movement of fish without impeding navigation.

How long will the BAFF be in place?

Currently, the BAFF is scheduled for removal in fall 2023 and the study will conclude after three years of data collection. The BAFF may remain in place longer to evaluate additional BAFF settings or to collect additional fish behavior data. If effective, partners may also pursue a permanent installation.

How effective is a BAFF at stopping invasive carp?

Tests conducted by the University of Minnesota found that a BAFF-like device was 97% effective at blocking bighead carp without habituation in a lab setting. The purpose of this project is to evaluate the BAFF's effectiveness in a field setting, which may differ.

Why isn't an electric dispersal barrier being used at Lake Barkley?

Electric dispersal barriers have been installed and tested in the Chicago Area Waterway System. This project is specifically designed to field test the BAFF as an alternative type of deterrent for deterring invasive carp passage through a lock chamber.