Project Title: Quantifying lock and dam passage, habitat use, and survival rates of invasive carps in the Ohio River Basin

Geographic Location: The Ohio River basin from Olmsted Pool (RM 964.4) to Willow Island Locks and Dam (RM 161.7), including tributaries. The Wabash River from Terre Haute, IN downstream to the confluence with the Ohio River. White River from Indianapolis, IN downstream to the confluence with the Wabash River.

Lead Agency: U.S. Fish and Wildlife Service **(**USFWS)

Participating Agencies: Southern Illinois University (SIU), Eastern Illinois University (EIU), Indiana Department of Natural Resources (INDNR), Illinois Department of Natural Resources (ILDNR), Kentucky Department of Fish and Wildlife Resources (KDFWR), Ohio Division of Wildlife (ODOW), West Virginia Division of Natural Resources (WVDNR), Ecosystem Connections Institute (ECI)

Statement of Need: Silver and Bighead Carp (*Hypophthalmichthys molitrix* and *H. nobilis*, respectively), herein referred to as "invasive carps", are invasive fishes within the Mississippi River Basin. Since they were first detected within the Mississippi River Basin in the early 1980's (Freeze and Henderson 1982; Jennings 1988; Robison and Buchanan 1988; Burr et al. 1996), the range of invasive carps has expanded to include much of the mainstem of the Mississippi River as well as other large rivers within the Mississippi River Basin (e.g., the Ohio, Missouri, and Illinois rivers) (Burr et al. 1996; Garvey et al. 2006; Camacho et al. 2020; Schaick et al. 2020). This rapid expansion throughout the Mississippi River Basin is likely due, at least in part, to rapid population growth resulting from high individual growth rates, short generation times, high fecundity, a protracted spawning period, and long-distance dispersal capabilities (Garvey et al. 2006; Peters et al. 2006; DeGrandchamp et al. 2008; Lenaerts et al. 2021).

Invasive carp populations are established throughout the lower and middle reaches of the mainstem Ohio River as well as many of its tributaries and successful reproduction is suspected as far upstream as Louisville, Kentucky. The establishment of these populations and the potential for invasive carp populations to expand their range into the upper Ohio River has led to concern among natural resource managers that invasive carps might gain access to the Great Lakes Basin through tributaries of the Ohio River. If invasive carps were to gain entry to the Great Lakes, they could cause substantial ecological and economic damage by disrupting food webs (Sass et al. 2014; Collins and Wahl 2017) and commercial and recreational fisheries (Pimentel et al. 2000, 2005). Because of the ability of invasive carps to cause extensive economic and ecological damage, limiting the expansion of invasive carp populations into novel habitats is of the utmost concern.

To prevent the spread of invasive carps into the upper portions of the Ohio River basin and potentially into the Great Lakes, we must understand their propensity for upstream movement, habitat use, and the probability of among-pool transitions. These monitoring efforts will reveal the timing and conditions most likely associated with pool transitions and entry into novel habitats. Additionally, mass movements to "preferred" habitats may reveal the timing and locations of spawning aggregations. Knowledge of these movements will be used to create management strategies designed to limit population expansion and inform management actions such as mass removal efforts.

Project Objectives:

1) Understand tributary use by invasive carps and the role of tributaries as potential sources for recruitment and routes of invasion into adjacent basins.
2) Delineate the upstream population distribution of invasive carps.
3) Quantify passage of invasive carps through Ohio River locks and dams.
4) Quantify movement patterns of invasive carps within the Wabash River basin including assessing movement between the Wabash and Ohio rivers (i.e., the contribution of Wabash River populations to those of the Ohio River) and between the White and Wabash rivers.
5) Inform invasive carp removal efforts by quantifying fine-scale habitat use and how habitat use changes through time in the Wabash and White rivers.

Project Highlights:

- Eighty-three Silver Carps were tagged during 2023 in Markland and Meldahl pools.
- During the course of this study, ~85% of Silver Carps have inhabited tributaries compared with ~53% of Silver Carps detected in mainstem habitats.
- Tributaries of high occupancy (≥25% of Silver Carps detected in a pool detected within that tributary) were identified for each pool.
- Monthly survival probability of Silver Carps during June 2013 – July 2023 was estimated between 0.96 and 1.
- Estimated mean pool-to-pool transition probabilities were generally low (< 0.2) for Silver Carps, suggesting that most of these fish remain within the pool in which they were tagged.
- Silver Carps in the Wabash River appear to select for outside bend habitats as well as logjams and areas of rip rap.

Methods:

Ohio River

Acoustic telemetry was used to determine the probabilities of survival, detection, lock and dam passage, and movement between tributary and mainstem habitats of invasive carps in the lower to middle Ohio River (Olmsted to R.C. Byrd pools but primarily focused from J.T. Myers to R.C. Byrd pools). To do this, the locations of individual invasive carps tagged with VEMCO, Model V16 acoustic tags were recorded using a stationary array of VR2 receivers. Receivers were placed either within the mainstem Ohio River, the lower reaches of select tributaries, or lock and dam (L&D) structures. Within some tributaries, a pair of receivers was deployed, one near the mouth of the tributary and the second further upstream. This arrangement of receivers allows for the interpretation of upstream and downstream movement of tagged carps and improves our ability to assess tributary use as well as the timing of entry into and exit from tributaries throughout the year. For L&Ds, at least four VR2 receivers were deployed at each L&D to record pool-to-pool transitions through the lock chambers with the exception of Markland and R.C. Byrd L&Ds. During 2023, three receivers were deployed at Markland L&D, one at the downstream approach and two in the lock chamber. For R.C. Byrd L&D one receiver was deployed at the upstream approach and two were deployed in the lock chamber. For all other L&Ds, two receivers were placed within the lock chamber and at least one receiver was placed on each of the downstream and upstream approach walls. These receivers provide consistent spatial coverage across L&Ds to ensure detection capabilities are similar at each location and increase confidence in interpretation of detection data.

Acoustic Receiver Array: During August 2022 – July 2023, the receiver array extended from river mile 937.0 in Olmsted Pool, ~20 miles downstream of the Smithland L&D, upstream to Willow Island Pool (river mile 159.3) (Figure 1). During non-winter months, detection data were downloaded from receivers monthly or as often as possible.

Acoustic Transmitter Tagging: Adult invasive carps were collected via boat electrofishing. Efforts were concentrated in areas where invasive carps are known to congregate such as side channels, backwaters, and tributaries. Fish were measured for total length (mm) and weight (g), and visually or manually sexed (if possible). Following these measurements, an acoustic transmitter (Vemco, Model V16-6H; 69 kHz) was implanted into the peritoneal cavity via a ~3 cm incision in the ventral musculature. The incision was closed with two or three sutures. The V16-6H transmitters provide individual identification and are nominally programmed to transmit a signal every 40 seconds yielding an expected battery life of ~1,460 days (4 years). Fish implanted with acoustic transmitters were also tagged externally using a lock-on tag inserted posterior to the dorsal fin (Floy Tag & Manufacturing, Inc. FT-4 Lock-on tag with clear over-tubing).

Active Tracking: To supplement detections from the acoustic receiver array, active tracking took place in select areas of the Ohio River. A VR100 omnidirectional hydrophone was used to detect fish during these sampling trips.

Tributary Use: To assess tributary use by Silver Carps (Bighead Carps were omitted due to a paucity of data), the proportion of detected Silver Carp in each habitat was determined by dividing the number of individual Silver Carps in each habitat by the total number of detected individuals June 2013 – July 2023. Additionally, to determine if specific tributaries may be of increased importance to Silver Carps, the number of individual Silver Carp detected in a tributary was divided by the total number of Silver Carps detected in that pool. Lastly, the time spent between transitions from tributary to mainstem habitat and vice versa was determined for each species as the mean number of days between detections in these two habitat types.

Pool-to-Pool Transition Analysis: To determine the probabilities of transitions among pools, survival, and detection of Silver Carps in the Ohio and Wabash rivers, a Multi-state with Live Recaptures analysis was conducted in Program Mark (Cooch and White 2008) using the RMark package (Laake 2013) in R version 4.1.2 (R Core Team 2021). In this analysis, the Wabash River and each navigation pool of the Ohio River are considered “states”. Because environmental data (e.g., temperature and gage height) were included in this analysis and were collected from January 2014 to July 2023, detection data prior to January 2014 were omitted. Encounter histories were constructed for each individual by determining the pool of the last detection for each month (January 2014 – July 2023). Because tagging took place at various times throughout the duration of the study period and the expected battery life of the acoustic transmitters is ~4 years, not all individuals have a complete encounter history (maximum of 115 possible time periods). Encounter histories of tagged carps that were harvested during the study period were right-censored. This process removes these individuals from the estimation procedures for the times following harvest. Additionally, transition probabilities were estimated only for adjacent pools because there were very few detected movements among non-adjacent pools. Transitions among non-adjacent pools were fixed to 0. Due to the small number of fish tagged (n = 46) and tags currently active in the Ohio River (n = 2), Bighead Carps were not included in these analyses.

To examine the effects of environmental conditions on the survival, detection, and movement of Silver Carps in the Ohio River, daily water temperature, discharge, and gage height data were collected from U.S. Geological Survey gage stations from Olmsted to R.C. Byrd pools as well as the Wabash River (Table 1). Data were collected for January 1, 2014 – July 31, 2022. Because the focus of this analysis was on pool-to-pool transitions, only data from mainstem gage stations were used. Although three variables were examined [i.e., temperature (°C), discharge (ft^3 sec^{-1}), and gage height (ft)], only eight gage stations collected discharge data and collections were inconsistent temporally resulting in many gaps in these time series. Because discharge is also highly variable among gage stations, it was omitted from this analysis. Temperature data were only collected at four gage stations in the sampling area but were consistent among these gage stations. An overall mean monthly temperature was, therefore, calculated for the mainstem Ohio and Wabash rivers using data from these gage stations. In contrast, all selected gage stations collected gage height data (ft) during the study period allowing pool-specific monthly mean gage height data to be calculated. To do this, gage heights were first converted to meters then the monthly mean gage height was calculated using all gages within a pool. Because monthly mean gage heights were highly variable among pools, these values were standardized within each pool by subtracting the mean and dividing by the standard deviation. Standardizing these data effectively places gage heights for all pools on the same scale, making comparisons more meaningful. After calculating standardized monthly mean gage heights, the time series for J.T. Myers, and R.C. Byrd pools were still incomplete. The methods used to complete the time series varied for each of the pool as a result of where in the time series gaps occurred and each pool's location in the river. For R.C. Byrd Pool (the farthest upstream pool for which data were collected), there were no gage height data collected during April 2017. To complete this time series, linear interpolation was conducted between March and May 2017. For J.T. Myers Pool, there were no gage height data from January – September 2014. Because this is the beginning of the time series, temporal interpolation within J.T. Myers Pool was not possible. Data from the pools directly upstream and downstream (Newburgh and Smithland pools, respectively) of J.T. Myers Pool were, therefore, used to spatially interpolate the missing data for each month using linear interpolation.

These time series of temperature and gage height as well as the encounter histories of individual Silver Carps were used to inform transition, survival, and detection estimates in multi-state models. Potential model structures included spatially and temporally invariant parameters, parameters that varied temporally (by month or season) and/or spatially (by pool), and parameters that varied with environmental conditions (e.g., mean temperature and standardized mean gage height). In addition, additive and interactive effects of covariates were considered. Due to the large number of potential model structures, a hierarchical model selection approach was used (Doherty et al. 2012). In this approach, detection and transition probabilities were held constant while the effects of month, season, mean temperature, and pool on survival probability were evaluated (Table 2). After determining the best supported structure for survival probability, it was retained while evaluating the effects of month, season, standardized mean gage height, pool, the number of receivers per pool and the number of receivers per river mile in each pool on detection probabilities (Table 3). Lastly, the best supported structures for survival and detection probabilities were held constant while evaluating the effects of month, season, standardized mean gage height, and pool as well as a linear and quadratic effect of temperature on transition probabilities (Table 4). Models were compared using Akaike's information criterion corrected for small sample size (AIC_c; Burnham and Anderson 2002) to find the most parsimonious model. Akaike weights (W_i) were also calculated to examine uncertainty in model selection (Burnham and Anderson 2002).

Wabash River

Acoustic Receiver Array: Thirty-five VR2 receivers have been deployed since 2022 throughout the Wabash River from the confluence with the Ohio River to 214 river miles upstream (near Terre Haute, Indiana) and within the White River, from its confluence with the Wabash River to 50 miles upstream (Figure 2). Receiver deployments followed the methods described above and receivers were retrieved and were downloaded monthly when river conditions allowed. As in 2022, extended periods of low water during 2023 prevented portions of the receiver array from being retrieved, especially during autumn (Figure 3).

Acoustic Transmitter Tagging: Tagging of invasive carps in the Wabash River follows the methods for the Ohio River, above. A total of 537 Silver Carps have been tagged since 2021 at multiple locations in the Wabash River, with 207 tagged in spring and fall 2023 (Table 5).

Interbasin and Intrabasin Movement:

Within the Mississippi River and its tributaries, target-removal by professional fishers has shown temporary success in decreasing local densities (MacNamara et al. 2016). This harvest-control method relies on the assumption that silver carp aggregate within the river. However, two distinct movement strategies have been found in silver carp in a free-flowing system (Prechtel et al. 2018; Coulter et al. 2022), creating the need to evaluate the movement patterns of silver carp in other rivers to effectively manage their populations. Objectives were: (1) Uncover if intraspecific variation in dispersal exists among silver carp the lower Wabash River; (2) Observe if distance traveled differs across seasons. (3) Determine the level of betweenness among individuals.

Fine-Scale Habitat Selection: Fine-scale habitat selection by tagged adult Silver Carps was assessed throughout the Wabash and White Rivers from 2021-2023. Monthly active tracking events occurred throughout the 305 rkm from Terre Haute, IN to the confluence of the Ohio River and the lower 105 rkm of the White River from Maysville, IN to its confluence with the Wabash in Mt. Carmel, IL. During active tracking, the boat was maneuvered downstream while towing an omnidirectional hydrophone (Vemco VH165). Once a transmitter was detected, the fish's position was triangulated by using a submersible directional hydrophone (Vemco VH110). Habitat characteristics including macrohabitat type (channel border open, inside river bend, outside river bend) and microhabitat type (log jam, rip-rap, run, thalweg) were recorded at each fish's location.

To assess selection, available habitat within the study area was quantified using a randomized sampling regime. The study area was split into three sections: Upper Wabash, Lower Wabash and White River. The Wabash was separated at Mt. Carmel, Illinois where the confluence with the White River nearly doubles total discharge. In each of the three sections, random sites were generated based on the total length of the section. Sites spanned 1 km in length with enough sites in each section to cover roughly 5% of the total length. Availability of macro and microhabitats were estimated in each site and averaged across sections to give the proportion of available habitat for each section. Manly log-likelihood chi-squared tests (Manly et al. 2002) were used to determine if fish used habitats in different proportions than their availability, indicating selection. Manly selection ratios (Manly et al. 2002) were calculated to determine the direction and strength of selection patterns both within the entire study reach and individual river sections.

Invasive carp movement and distribution following dam removal

In November 2021, two dams were removed from the Eel River at river kilometer (RKM) 2. The largest of these two dams was 435-feet long and 9-feet tall and served as a barrier to invasive carp movement further up the Eel River. Removal of these dams created a novel opportunity to better understand invasive carp establishment in newly accessible habitat and evaluate the ecological risk of invasive carp occupancy in comparison to the ecological lift of new native species establishing in the Eel River basin.

Twenty-two sample sites were established to verify presence or absence of invasive carp species and to score each site using the Index of Biotic Integrity (IBI) and Qualitative Habitat Evaluation Index (QHEI) (Figure 4). An eDNA sample was collected at each of these 22 sites to validate presence or absence of invasive carp. Fish movement in the mainstem Eel River was tracked using a network of six antenna arrays installed from RKM 56 to RKM 121 that can detect Passive Integrated Transponder (PIT) tags and eight VR2TW and VR2Tx receivers installed from RKM 2 to RKM 121 that can detect acoustic tags. Active tracking of fish implanted with acoustic tags was conducted the entire length of the Eel River (RKM 121 to RKM 0).

Fish movement in the upper Wabash River, Tippecanoe River, Mississinewa River, and Salamonie River was tracked using a network of 12 VR2Tx receivers for detection of acoustic tags. Receivers in the Wabash River were installed upstream and downstream of the confluence of each of the four tributaries in May 2022. The remaining four receivers were installed in the mainstem channel of each tributary upstream of the confluence with the Wabash River. For this report, data was collected from May 2022 through 21 December 2023 but all 12 receivers remain operational.

Tags detected from the network of VR2Tx receivers were cross referenced with a database of known deployed tags in the Wabash River. When possible, fish species, gender, length at time of tagging, and weight at time of tagging, and tagging date were also included in the cross-referenced information. When unknown tags were detected in the upper Wabash River basin, project partners (and potentially Innovasea) were contacted to identify the source of tag. If the source of an unknown tag could not be identified, it was removed from further analysis since the species, gender, length, and weight were unknown.

Telemetry data was analyzed in the statistical software R, using the riverdist package. The riverdist package utilizes a river network line shapefile and GPS referenced detections to calculate the distance a fish traveled between detection dates and times.

Agency-Specific Accomplishments

Kentucky Department of Fish & Wildlife Resources (KDFWR)

During 2023, KDFWR maintained and regularly offloaded all tributary and mainstem receivers located in the Cannelton (from the Salt River to McAlpine L&D), McAlpine, and Markland (from Markland L&D to Cincinnati) pools. KDFWR also assisted other project partners with offloading receivers located in the most downstream pools (Olmsted, Smithland and JT Meyers) of the array. KDFWR met with USFWS and INDNR staff to identify new receiver sites in the lower Cannelton Pool that will be used to monitor invasive carp movements in response to contract fishing efforts and other environmental conditions. KDFWR staff also assisted USFWS with the tagging of additional invasive carp in the Meldahl Pool to replace several expired transmitters. KDFWR continued serving as the project's data manager by gathering receiver offloads from all other project partners and importing them into a SQL database, which also contains up-to-date records on tagged carp, receiver locations, and harvested tag reports. In 2023, KDFWR also compiled and integrated the Wabash River telemetry data that SIU staff have been collecting since 2021. Lastly, KDFWR created and maintained secondary databases with environmental data and daily receiver histories that are required by the telemetry project's modelling and analysis efforts.

Indiana Department of Natural Resources (INDNR)

INDNR deployed 8 additional VR2 receivers in the mainstem Ohio River and tributaries of Cannelton Pool to assist USFWS and KDFWR in evaluating fine-scale Silver Carp movements in response to contract fishing pressure. INDNR conducted a tagging event on the upper Wabash River, tagging an additional 72 Silver Carp. INDNR assisted USFWS in tagging fish in Markland Pool, spending a total of 14 hours electrofishing and tagging six invasive carp. Data from receivers in J.T. Myers and Newburgh pools were downloaded regularly by INDNR and sent to KDFWR for processing. INDNR maintained and downloaded the receivers station at J.T. Myers, Newburgh, and Cannelton lock and dams. Cannelton Pool receivers were downloaded by INDNR for the first six months in 2023 before being handed off to USFWS. INDNR subcontracted with ECI to complete work in the upper Wabash River to evaluate movements of invasive carps in response to a dam removal.

Ohio Division of Wildlife (ODOW)

ODOW maintained and offloaded data from mainstem and tributary receivers in the Markland (from Cincinnati to Meldahl L&D), Meldahl, and Greenup pools as well as those located at the Meldahl and Greenup L&Ds during 2023. All data were made available to KDFWR for processing.

West Virginia Division of Natural Resources (WVDNR)

WVDNR maintained and offloaded data from mainstem and tributary receivers in the R.C. Byrd Pool, including the portion of the Kanawha River within the pool. HOBO temperature loggers were deployed on four receivers within the pool in locations where tagged fish are frequently detected. The added array in the R.C. Byrd pool has informed WVDNR in targeted removal efforts (specifically the Kanawha river locations) where populations are less dense by providing additional detail on specific movement patterns, environmental cues to movement and additional locations where tagged fish frequent. All data was sent to KDFWR for processing and reporting.

US Fish and Wildlife (USFWS)

During 2023, USFWS, Carterville FWCO (with assistance from state and federal partners, tagged a total of 83 Silver Carps in Markland (n = 53) and Meldahl (n = 30) pools following the methods above. The Carterville FWCO also used the data collected by state agencies and processed by KDFWR to parameterize multistate models to better understand pool-to-pool transition probabilities for Silver Carps. These data were also used to understand tributary use of Silver and Bighead Carps (see methods above for details). Additionally, the USFWS Ohio River Substation (Lower Great Lakes FWCO) continued maintenance of 24 VR2 receivers (including replacement of 18 older VR2W with VR2Tx receivers) in R.C. Byrd, Racine, Belleville, and Willow Island pools took over the maintenance of the VR2 array on the Ohio River L&Ds during late fall 2022.

Illinois Department of Natural Resources, Southern Illinois University (ILDNR, SIU)

Southern Illinois University maintained thirty-five VR2 acoustic telemetry receivers throughout the Wabash River from the confluence with the Ohio River to 214 river miles upstream (near Terre Haute, Indiana) and within the White River, from its confluence with the Wabash River to 50 miles upstream. Receivers were retrieved and detections downloaded monthly when river conditions allowed. A new receiver stand was designed to improve retrieval of receivers in the rivers. Tagging of 207 invasive carps occurred in the Wabash River during May and September 2023. An analysis of the movement of silver carp from the Wabash River into the Ohio River during 2021 throughout 2023 suggested that only about 6% of Wabash River silver carp moved into the Ohio River.

Illinois Department of Natural Resources, Eastern Illinois University (ILDNR, EIU)

Eastern Illinois University conducted active tracking of acoustically tagged Silver Carps throughout the Wabash River during 2023 to identify patterns in fine-scale habitat use. Active tracking occurred monthly during daytime, with some additional nighttime active tracking taking place on select occasions to understand diurnal trends in fine-scale habitat use. Habitat characteristics were recorded at each fish's location, including macrohabitat type (river channel border, inside river bend, outside river bend) and microhabitat type (log jam, rip-rap, river run, thalweg). Additional microhabitat measurements, including substrate type, dissolved oxygen concentration, water velocity, water temperature, and water clarity were also measured at each fish's location. An analysis of fine-scale habitat use by silver carp showed that log jams were selected by this species and should be targeted for harvest removal.

Results and Discussion:

Ohio River

Acoustic Receiver Array: During 2023, 174 receivers were deployed from Olmsted Pool to Willow Island L&D. Of these, 43 were deployed at L&Ds, 40 at mainstem sites, and 91 at tributary sites (Figure 1, Table 6).

Fish Tagging Efforts: As of July 2023, 1556 invasive carps (1510 Silver and 46 Bighead) from J.T. Myers, Newburgh, Cannelton, McAlpine, Markland, Meldahl, and R. C. Byrd pools have been surgically implanted with acoustic transmitters (Table 10). Of the 1556 tagged carps, 34 Silver Carps have been harvested during the study (June 2013 – July 2023). During 2023, 31 invasive carps (30 Silver and 1 Bighead) had tags that were expected to expire (Table 7). To replace these tags and meet the needs of partner agencies, 83 Silver Carps were tagged in Markland (n = 53) and Meldahl (n = 30) pools. No Bighead Carps were tagged during 2023 due to a lack of availability.

Fish Detections: There were 1052 active tags deployed in invasive carps (1050 Silver and 2 Bighead) in the Ohio River during 2023, 543 (52%) of which were detected (539 Silver and 4 Bighead). Active tags included those expected to be active during 2023 (n = 1052) as well as those expected to expire prior to 2023 that were detected during 2023 (n = 65).

Fish Movement: Throughout the study area, the net movement (i.e., the difference between the most upstream and most downstream detections for an individual) ranged from 0.0 km to 379.8 km for Silver Carps and from 0.0 km to 130.8 km for Bighead Carps during August 2022 – July 2023. The longest net movement by a Silver Carp was completed by a male fish travelling from McAlpine Pool to the Hovey Lake area of J.T. Myers Pool during August – September 2022. In contrast, the longest net movement by a Bighead Carp during August 2022 – July 2023 was completed by a male fish that moved within Meldahl Pool. Long-distance movements are relatively rare for Silver Carp; ~71% of Silver Carp had a maximum distance travelled of < 30 km during August 2022 – July 2023. In contrast, 40% of Bighead Carp had a maximum distance travelled of < 30 km, however, given the small sample size (n = 5), these data should be interpreted cautiously. Additionally, although detections of invasive carps above Greenup L&D were rare (~0.1% of total detections), during 2023, the most upstream detections for both Silver and Bighead carps occurred in R.C. Byrd Pool at river miles 251.3 and 265.2, respectively.

Because there were relatively few detections of invasive carps in the pools upstream of Greenup L&D and below J.T. Myers L&D, further analysis of fish movement during August 2022 – July 2023 focused only on J.T. Myers, Newburgh, Cannelton, McAlpine, Markland, and Meldahl pools. In these pools, net movements are typically shortest during January – March and peak during late spring and summer (May – July) regardless of species or pool (Figures 5 and 6). For Silver Carp, mean net movements in Markland and Meldahl pools are typically longer than those in lower pools.

Dam Passage: Throughout the duration of this study (June 2013 – July 2023), there have been 465 dam passage events (140 upstream and 325 downstream passages) (Figure 7). Dam passages were completed by 237 Silver Carps and 11 Bighead Carps. Of the upstream passages, 11 (7.9%) were completed by five Bighead Carps, with one fish accounting for three of those passages as it moved from Meldahl Pool to Racine Pool during May 2014 – August 2015. One-hundred twenty-nine upstream passages (92.1%) were completed by 94 Silver Carps. Sixteen downstream passages (4.9%) were completed by nine Bighead Carps, whereas 316 (95.1%) were completed by 211 Silver Carps. Additionally, in only 50 of the 465 dam passages (10.8%) was the fish detected within the lock chamber, suggesting a high prevalence of passages through the dam gates. Passages where fish were detected within the lock chamber occurred at R.C. Byrd, Greenup, Markland, Cannelton, Newburgh, and J.T. Myers L&Ds during 2017 (n = 2; 1 Bighead and 1 Silver Carp), 2019 (n = 1; Silver Carp), 2021 (n = 14; Silver Carp), 2022 (n = 25; Silver

Carp), and 2023 (n = 8; Silver Carp). All but one confirmed lock chamber passage (at Greenup L&D during 2017) were in the downstream direction.

The current arrangement of VR2 receivers around most L&D structures in the study area and their year-round deployment suggests a high probability of detecting invasive carps transitioning among pools through lock chambers. However, if fish pass through the dam gates they likely will not be detected.

Tributary Use: Throughout the study period, ~85% of detected Silver Carps have been detected in tributaries of the Ohio River whereas, only ~53% of these fish have been detected in mainstem Ohio River habitats (Figure 8). In addition, when Silver Carps enter tributaries, they tend to spend more time (mean ± SE = 34.8 ± 1.1 days) there than in mainstem habitats (15.3 ± 0.7 days; Figure 9).

When examining specific tributaries that are commonly used within each pool, there is at least one tributary within each pool (J.T. Myers – Meldahl) that was visited by ≥25% of Silver Carps detected within that pool (Figure 10). In J.T. Myers, Cannelton, and Markland pools, only one tributary met this criterion in each pool, Eagle Creek (33%), the Salt River (59%), and Laughery Creek (79%). In each Newburgh and Meldahl pools, two tributaries were commonly inhabited by Silver Carps, Little Pigeon Creek (39%) and Borrow Pit 1 (26%) in Newburgh Pool and Ohio Brush Creek (78%) and the Scioto River (41%) in Meldahl Pool. Lastly, three tributaries were inhabited by ≥25% of Silver Carps detected in McAlpine Pool, Indian-Kentuck Creek (57%), the Little Kentucky River (47%), and the Kentucky River (73%; Figure 10). These data suggest that not only do tributaries provide important habitat for Silver Carps, but some tributaries may provide more suitable habitat than others be preferred over others and should, therefore, be more closely monitored to determine if these areas can be targeted for control efforts.

Pool-to-Pool Transition Results: For Silver Carps, AIC_c indicated that for each model parameter (S, p, and ψ) only one model structure was supported (Tables 2-4). Based on this hierarchical model selection process (ΔAIC_c and W_i), the final model included a survival probability (S) that varied with month, a detection probability (p) that varied with the additive effects of pool and the number of receivers, and transition probabilities (ψ) that varied with the additive effects of pool and month. The AIC weights of 1 for each part of the hierarchical model selection process indicate little to no uncertainty in model selection.

The mean probability of survival (S) of Silver Carps varied with month such that survival was highest during cooler months (Jan – April) and lowest during May and June (Figure 11). Estimated mean survival probability was, however, high (0.95 – 0.99) for all months.

Estimated mean detection probabilities (p) for Silver Carp were affected by the additive effect of pool and the number of receivers and ranged from 0.01 to 1.00. The probability of detection increases following a sigmoidal curve such that there is a rapid increase in detection probability from 0 to ~10 receivers after which the rate of increase in detection probability slows (Figure 12). Interestingly, detection probabilities in Greenup Pool remain low, despite this pool having a similar number of receivers than some more downstream pools and likely reflects the relative lack of tagged fish in this pool.

Model estimates of mean transition probabilities (ψ) varied with the additive effect of pool and month and indicate that Silver Carps are most likely to move from one pool to another in April and October and are least likely to move among pools in August (Table 11, Figure 13). This was also true for movements between the Wabash River and the Smithland Pool (Table 11). Interestingly, transition probabilities from the Wabash River to the Smithland Pool were consistently higher than those from the Smithland Pool to the Wabash River supporting the idea that the Wabash River Silver Carp population may act as a source population to the Ohio River. Furthermore, transition probabilities among pools were typically low (< 0.2) with some exceptions (e.g., Greenup to Meldahl and J.T. Myers to Smithland during April and October) indicating that the probability of Silver Carps remaining within a pool was typically high (>0.8). Lastly, transition probabilities from upstream to downstream pools tend to higher than those from downstream to upstream pools regardless of month.

Wabash River

Fish Movement: The retriever array in the Wabash River was difficult to reach and download during 2023 due to prolonged periods of low water levels, where most receivers were either inaccessible by boat or buried under sand in the riverbed. Only two receivers were able to be retrieved and downloaded in 2023, although a crew (with shovels and a winch) will be deployed in early spring 2024 to locate and unbury receivers. To improve receiver retrievals in the future, SIU will be experimenting with different deployment designs that cater to the rapidly changing hydrology and riverbed of the Wabash River. The "Swiss Sled" prototype (Figure 14) has been designed to improve the ability to pull receivers from the riverbed using a onshore tether. The sled is sufficiently large and heavy to remain upright on the river bottom but contains holes that reduce weight and allow the sled to be pulled out of sand. This prototype will be tested in the Wabash River in spring 2024.

Interbasin and Intrabasin Movement: An analysis of available silver carp movement data collected during 2021 through 2023 in the Wabash River revealed that greater detections and higher average distance moved occurred in spring than other months (Figure 15). Consistent with other research on movement in the Wabash River, the majority of silver carp remained near the location of release although a few moved greater than 60 km (Figure 16). A network graph was used to visualize the connectivity among tagged individuals within the Wabash River (Figure 17). Nodes depict individual fish and lines connect fish that cross within 2 km of each other within a 24-hour period. In the Wabash River, connectivity degree ranged from 0 to 19 with most fish remaining between Vincennes, IN and Grayville, IL (approximately a 65 km range; Figure 17).

Between 2021 and 2023, 537 silver carp were tagged in the Wabash and White Rivers. Of these 537 fish, only 33 fish transitioned from the Wabash River system to the Ohio River (Table 9). On average it was 300 days from tagging in the Wabash River for an individual fish to be detected in the Ohio River. Fish tagged in the Mt. Carmel site were the most often detected in the Ohio River (15/33 detected fish), followed by those tagged in Hutsonville (7/33). Interestingly, while the New Harmony, Illinois site had the most intensive tagging (139 fish) and was the closest to the confluence of the Wabash and the Ohio River, only 5 fish tagged there were later detected in the Ohio River. Hazelton, Indiana was the only tagging site on the White River, and only 2 of the 55 fish tagged were detected in the Ohio River. No fish tagged in Merom, Indiana were detected in the Ohio River, likely because this site is relatively far from the confluence and had the fewest tagged fish (42). In the Ohio River, fish were most commonly detected at the Smithland lock and dam (15 unique fish), Brookport Bridge (8 unique fish) and the J.T. Meyers lock and dam (7 unique fish). This indicates that carp originating from the Wabash River tend to go downstream in the Ohio River, towards the Mississippi River (Figure 18).

Movement data are very limited at this juncture, but patterns of silver carp movement in the Wabash River appear to differ substantially from other highly studied rivers such as the Illinois River. In the Illinois River, patterns of movement are restricted, perhaps by structures such as locks and dams and limited suitable habitat. Analysis of the network movement of silver carp suggests that fish more freely move among receiver locations in the Wabash River. A converse explanation is that the rapidly changing flow and geomorphology of the Wabash River cause silver carp to move more frequently. Further analyses of these patterns will aid commercial harvest operations to more efficiently remove silver carp. The apparent lack of silver carp moving (only about 6%) from the Wabash River into the Ohio River mainstem is surprising. However, the mouth of the Wabash River feeding into the Ohio River is often blocked by aggradation of Ohio River bed material during periods of low flow, perhaps reducing the connectivity into the river, especially during years of low discharge such as 2022 through 2023. Identifying conditions (e.g., high flow) when populations in the Ohio and Wabash Rivers become connected may aid in identifying times to direct harvest near the confluence.

Fine-Scale Habitat Selection (Eastern Illinois University):

Silver Carps detected in the Wabash and White Rivers selected for both macro- ($\chi^2 = 376.72$, df = 216, $p < 0.05$) and micro-habitats ($\chi^2 = 442.78$, df = 336, $p < 0.05$) disproportionately to available habitat. Fish were not randomly distributed across habitats, but actively selected for specific habitat types. Throughout the entire study area, outside bends were positively selected while both channel border open and inside bends were slightly avoided (Figure 19). Outside bend areas are generally deeper than the other macro habitats, which likely contributes to individuals selecting for these areas. Logjam and rip-rap micro-habitats were selected for while run and thalweg areas were avoided (Figure 20). Micro-habitat selection patterns can likely be attributed to differences in flow across available habitats. Logjam and rip-rap areas generally have slower flow and provide a velocity refuge that allows silver carp to limit energetic output. Run and thalweg areas have much higher flow which requires individuals to constantly swim to maintain position.

Although habitat selection was apparent throughout the entire study area, longitudinal variation influenced how individuals used habitat in each river section. In the lower portion of the Wabash, Silver Carps selected for outside bends much more than any other macro-habitat type (Figure 21). This was not the case in the upper Wabash where there were no obvious patterns in macro-habitat selection. Additionally, individuals in the White River selected for channel border open areas and did not select for or avoided other habitat types (Figure 21). Compared to the other sections of the study area, the lower Wabash is much wider and dominated by sandy substrates so outside bends are likely the only deep areas available to silver carp. Micro-habitat use between sections was more similar with fish selecting for logjams across all sections (Figure 22). Run and thalweg habitats were generally avoided in in all sections, although in the lower Wabash, individuals slightly selected for thalweg habitats (Figure 22). Rip-rap areas had less clear patterns of habitat selection with high variability in the lower Wabash and slightly positive selection in the upper Wabash (Figure 22). Logjams seem to be universally selected for throughout the study area and may be useful areas to target for large-scale removals or commercial harvest. However, most habitat selection patterns are not uniform throughout the study area so, depending on where removal efforts occur, different habitats may need to be targeted to maximize harvest.

Invasive carp movement and distribution following dam removal

Results from the Eel River Basin in 2023 showed IBI scores ranged from “Poor” to “Very Good” in Eel River tributaries and “Fair” to “Exceptional” in the mainstem Eel River (Table 10). QHEI scores at the Eel River tributary sites were geographically clustered with the lowest scores occurring at headwater sample sites. It should be noted that IBI scores at these headwater sites were lower in 2023 than in 2022. These sites had accumulated high organic mucks in-channel between the two years.

Approximately fifteen Silver Carp were observed in the Eel River on 5 July 2023 at RKM 56 (Stockdale Dam). This is the first recorded instance of Silver Carp in the Eel River above RKM 2. Boat electrofishing resulted in three male Silver Carp being collected (Table 11). These three carp were tagged with a PIT Tag and acoustical transmitter and then released. One of the fish tagged at Stockdale Dam was detected going down the Eel River, into the Wabash River, and was last detected in the Wabash River, Upstream of the confluence with the Tippecanoe River. No new species were found in the Eel River in the 2023 sampling. However, it was documented that several new species have moved further up the river. For example, Freshwater Drum were found at RM 35 and Bluebreast Darter and Tippecanoe Darter were documented at RKM 16. Grass Carp were only found at Logansport, RKM 2. This was the most upstream extent of Grass Carp in 2022 as well.

Environmental DNA (eDNA) samples detected Grass Carp DNA in 100% of replicates at Logansport (RKM 2) and 33% of replicates at Adamsboro (RKM 12), Hoover (RKM 20), Mexico (RKM 30), and Collamer Dam (RKM 103) (Table 12). Grass Carp DNA was also detected in 33% of replicates at Paw Paw Creek Upper and 67% of replicates at Beargrass Creek Upper. Checking for Grass Carp will be a point of emphasis in 2024 given the impact Grass Carp could have on the rooted plants of the Eel River (e.g. Eelgrass (*Vallisneria americana*)).Silver Carp DNA was detected in 33% of replicates at Squirrel Creek Upper. Caution should be taken when reviewing eDNA results with low detection rates (e.g., 33%) since false positives are common at this detection rate. For example, 2023 was a dry year and Squirrel Creek Upper was dry through most of the summer, so it is likely that the detection of Silver Carp DNA at Squirrel Creek Upper was a false positive.

A total of 68 Silver Carp were detected and able to be cross-referenced with tagging information using the network of 12 receivers established throughout the Upper Wabash River Basin. Detected fish were tagged in seven separate tagging events (Table 13). Of note are Silver Carp that were tagged in the Cumberland River, near Chetham Dam but were then detected 862 River Kilometers (RKM) away from their tagging location on multiple different receivers in the upper Wabash River basin. There was also seven Silver Carp detected in the upper Wabash River basin that were tagged near Hutsonville, Illinois, 159 RKM downstream from the closest receiver used for this project.

It was found that Silver Carp movement was seasonally dependent with the most movement occurring in May, June, and July (Figure 23). Females had a higher average distance traveled than males in these three months. The Silver Carp that migrated from the Cumberland River were outliers in this analysis as they traveled over 5 times further than any other fish. The gender of the Cumberland River Silver Carp was not reported, and they were first detected in the upper

Wabash River on 19 May 2022 and 31 May 2022. Additional years of data will allow a more powerful analysis on Silver Carp movement in small tributaries of the upper Wabash River, including the refinement of Eel River utilization after low head dam removal.

Recommendations:

Despite the expansion of the receiver array in Cannelton Pool to better understand tributary vs mainstem habitat use, there are still gaps in the receiver array that, if filled, could further improve our understanding of invasive carp movement and habitat use. For instance, receiver coverage in Smithland and Olmsted pools is poor with only two mainstem receivers near in the upper portion of Olmsted Pool and eight receivers at the locks and dams at the lower and upper ends of Smithland pool. Increasing receiver coverage in these pools would not only improve our understanding of movement and habitat use of invasive carps in the Ohio River, but would also inform movement between the Ohio River and three other large rivers with established invasive carp populations, the Wabash River (Smithland Pool) and the Tennessee and Cumberland Rivers (Olmsted Pool). Furthermore, deploying recievers at the downstream end of Olmsted Pool and in the open river between Olmsted Lock and Dam and the confluence of the Mississippi River would improve our understanding of movements between the Mississippi and Ohio rivers. Because all of these areas host large populations of invasive carps, understanding the movements of fish among these systems is critical to understanding source-sink dynamics and to effective management of these fishes. Specifically, understanding the movement of invasive carps between the Tennessee-Cumberland system and the Ohio River may elucidate movement patterns of invasive carps as they relate to deterrent technologies at Barkley Lock (e.g., do fish move away from the barrier at Barkley Lock and instead move upstream within the mainstem Ohio River?). In addition, broader spatial coverage in areas of low invasive carp density (i.e., upstream of Meldahl Pool) would help agencies understand the distribution of invasive carps in these areas and allocate removal efforts more efficiently. Accomplishing this may require the reallocation of some receivers in the upper pools to increase spatial coverage.

Although, current receiver deployments provide consistent year-round coverage of the lock chambers of all L&Ds between Smithland and Willow Island L&Ds, coverage near the gates of dams is lacking. Improving receiver coverage near dam gates could enhance our knowledge of pool-to-pool transitions (including the timing of these transitions as it relates to open-water conditions) as well as improve our ability to determine if L&D passages are primarily occurring through the lock chambers or through the dam gates. However, site selection near dam gates requires careful consideration because deploying stationary receivers in these areas is logistically challenging and raises concerns for the safety of agency personnel that would be tasked with downloading and maintaining the receivers.

There are currently 35 receivers deployed in the Wabash River. However, low waters and siltation has resulted in difficulties retrieving these receivers. These difficulties retrieving receivers mean that less information is being gathered in that system. Improving retrieval success is critical to understanding invasive carp movement within the Wabash River as well as among the Wabash and Ohio rivers. SIU is currently working to retrieve additional receivers and test different receiver deployments in the hopes of improving retrieval success.

In addition to adding receivers in specific areas to improve coverage, understanding the true coverage provided by those receivers currently deployed is critical to our understanding of fish movements and habitat use. The current combination of VR2W receivers and V16 transmitters used for invasive carp telemetry in the Ohio River ostensibly provides a detection range of 800 – 1200 m. Ambient conditions (e.g., turbidity, flow, receiver orientation) can, however, drastically affect detection ranges. It is, therefore, recommended that receivers be range-tested during a variety of conditions to determine reasonable expectations for the detection range of receivers in the Ohio River system.

Lastly, data management will continue to be vital as the telemetry program adds to the existing data set. Increases in the number of invasive carp detections are anticipated, especially within the lower pools of the Ohio River where the array and tagging efforts were expanded during 2021. Due to the expected increase in detections, front-end data management and data processing capability will become increasingly important to ensure that data are available for analysis in a timely manner. Furthermore, to accommodate the likely increase in time necessary to process and analyze these larger quantities of data, it is recommended that, as in 2022, each agency perform a download of all receivers in their areas of management and transfer the downloaded data to KDFWR by July 31 of each year. This will allow ample time for data processing, analysis, and reporting, and increase time for discussion of the results and potential improvements to analyses prior to reporting in March of the following year.

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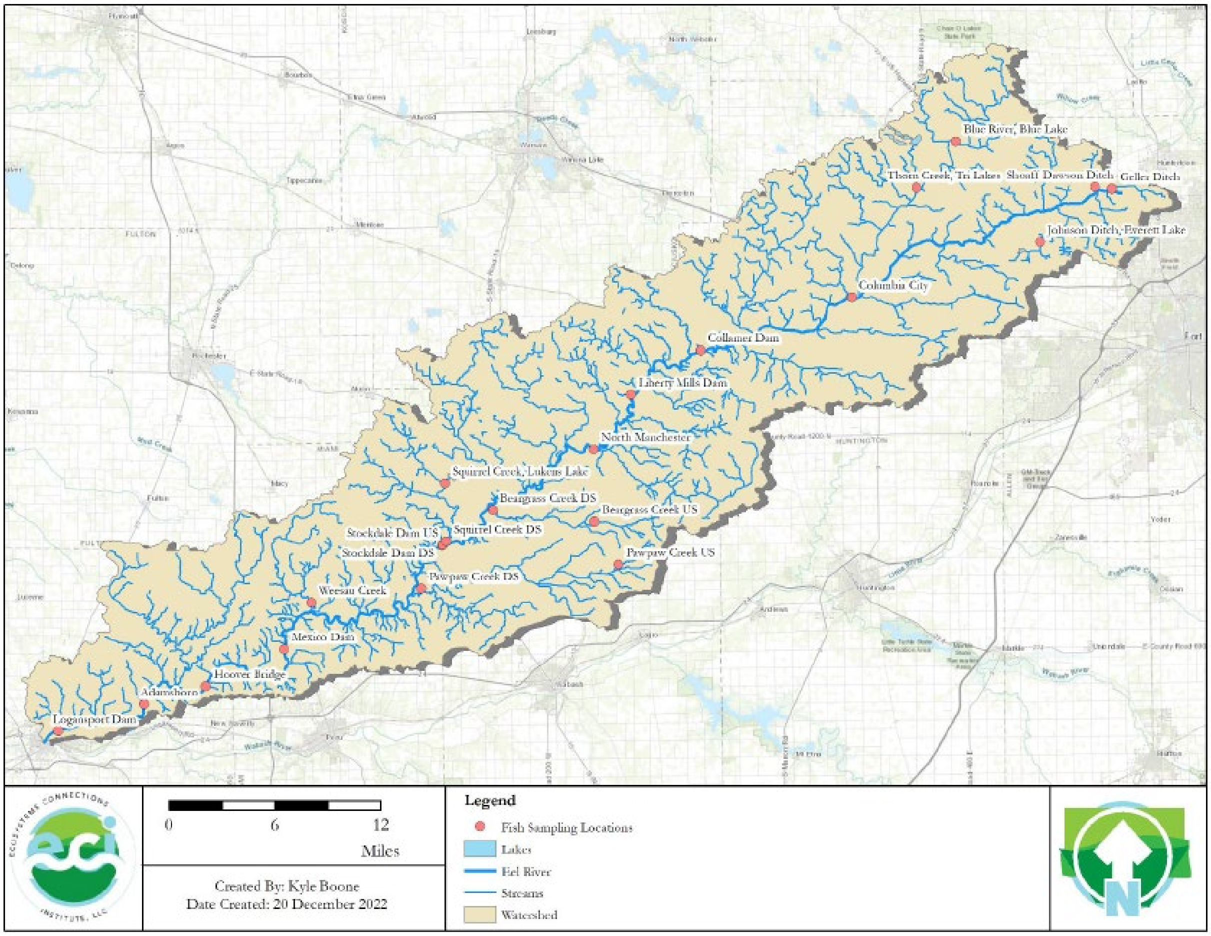

Figure 4. Locations of 22 fish sampling sites in the Eel River Watershed.

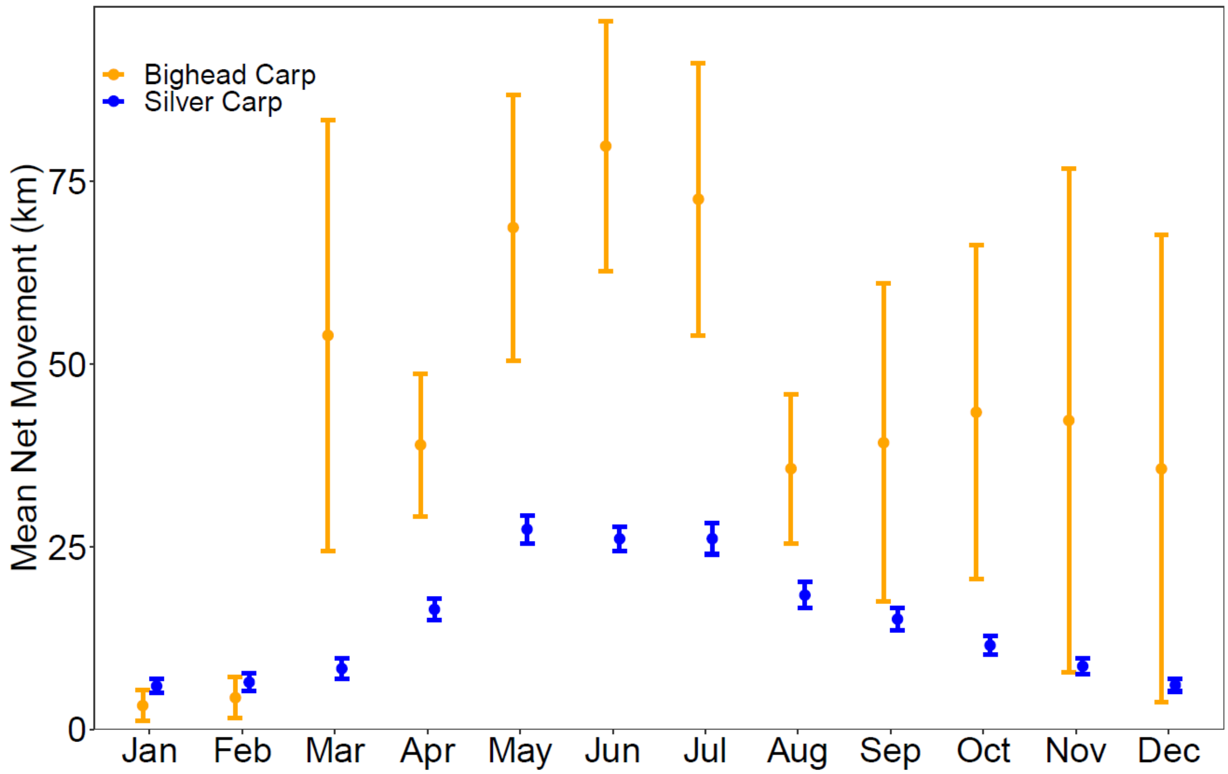

Figure 5. The mean monthly net movements (river kilometers) between the most upstream and downstream detections for tagged Silver Carp (blue) and Bighead Carp (orange) in J.T. Myers, Newburgh, Cannelton, McAlpine, Markland, and Meldahl pools during June 2013 – July 2023. Error bars represent standard error. Only tagged carp detected ≥ 2 times during a month were included in the distance calculations.

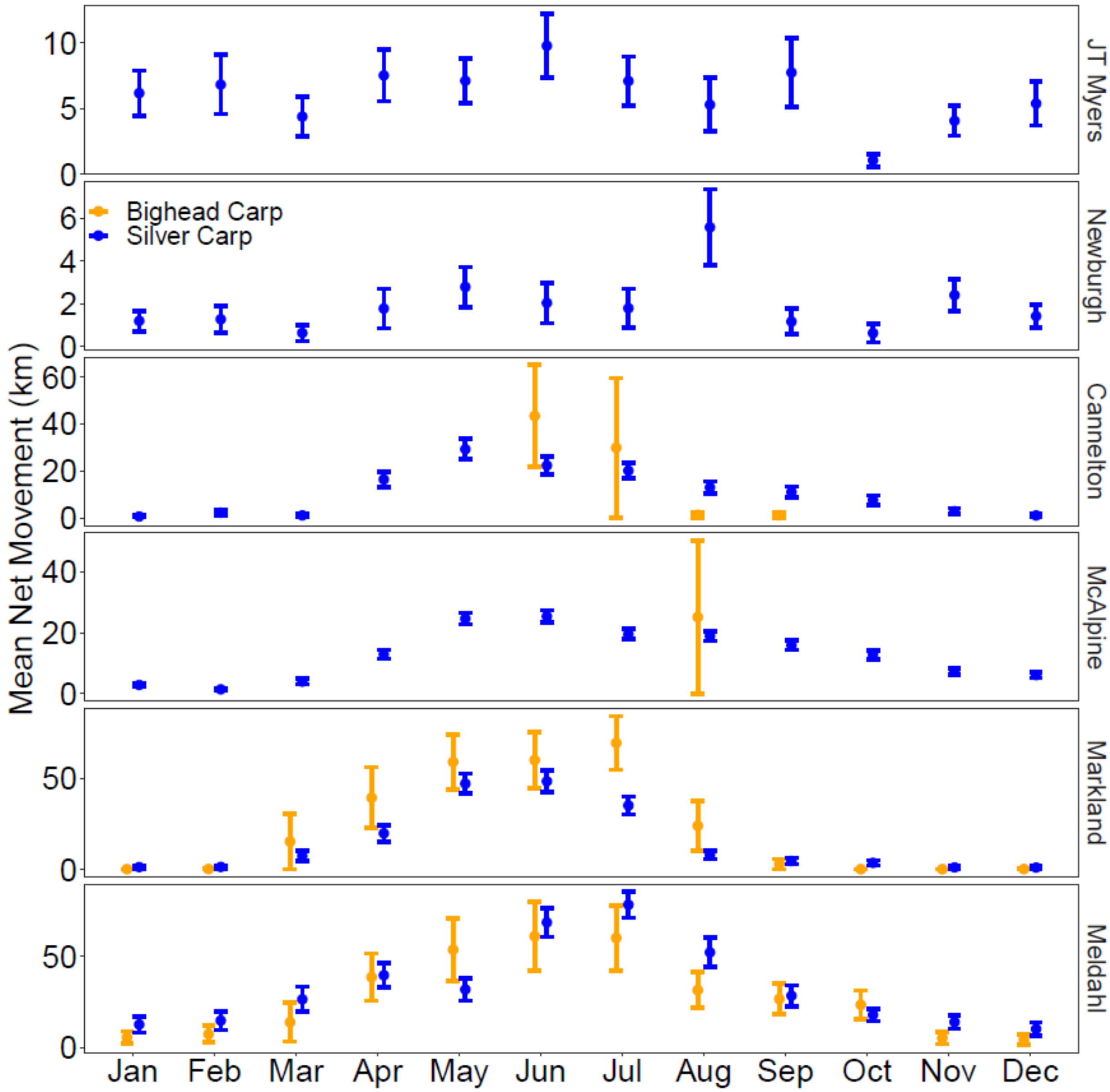

Figure 6. The mean monthly net movements (river kilometers) between the most upstream and downstream detections for tagged Silver Carp (blue) and Bighead Carp (orange) by pool in the six most active pools of the telemetry project (J.T. Myers, Newburgh, Cannelton, McAlpine, Markland, and Meldahl pools) during June 2013 – July 2023. Error bars represent standard error. Only tagged carp detected ≥ 2 times within a single pool each month were included in the distance calculations.

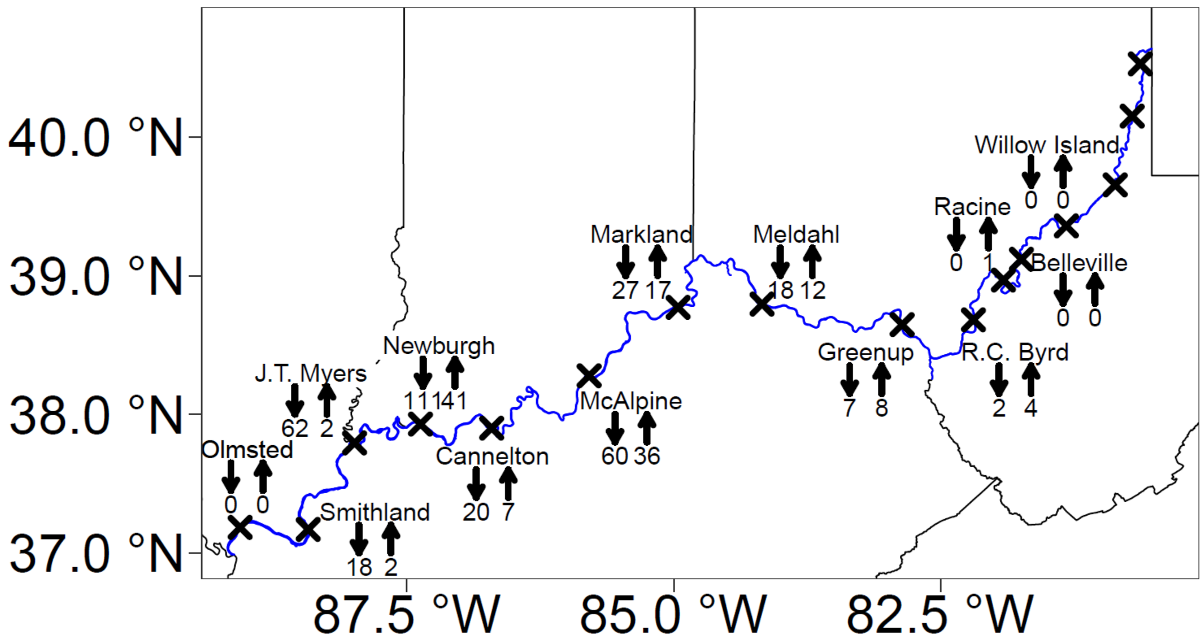

Figure 7. Total number of downstream (↓) and upstream (↑) lock and dam (L&D) passages by invasive carps during June 2013 – July 2022. Map shows passages from Olmsted L&D (river mile 964.4) near the confluence of the Ohio and Mississippi rivers to Willow Island L&D (river mile 161.7) which is the most upstream location at which acoustic receivers were deployed.

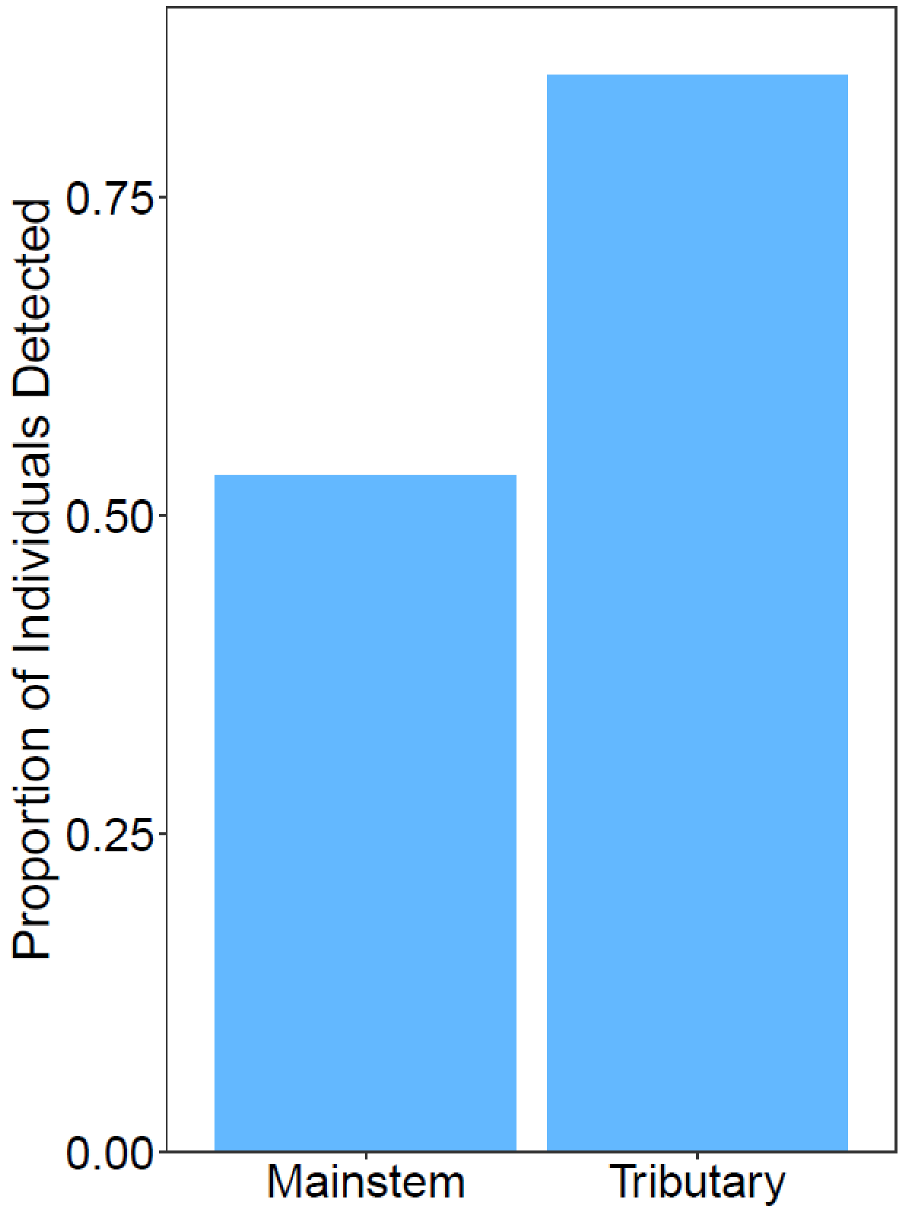

Figure 8. The proportion of individual Silver Carp detected in mainstem and tributary habitats during June 2013 – July 2023.

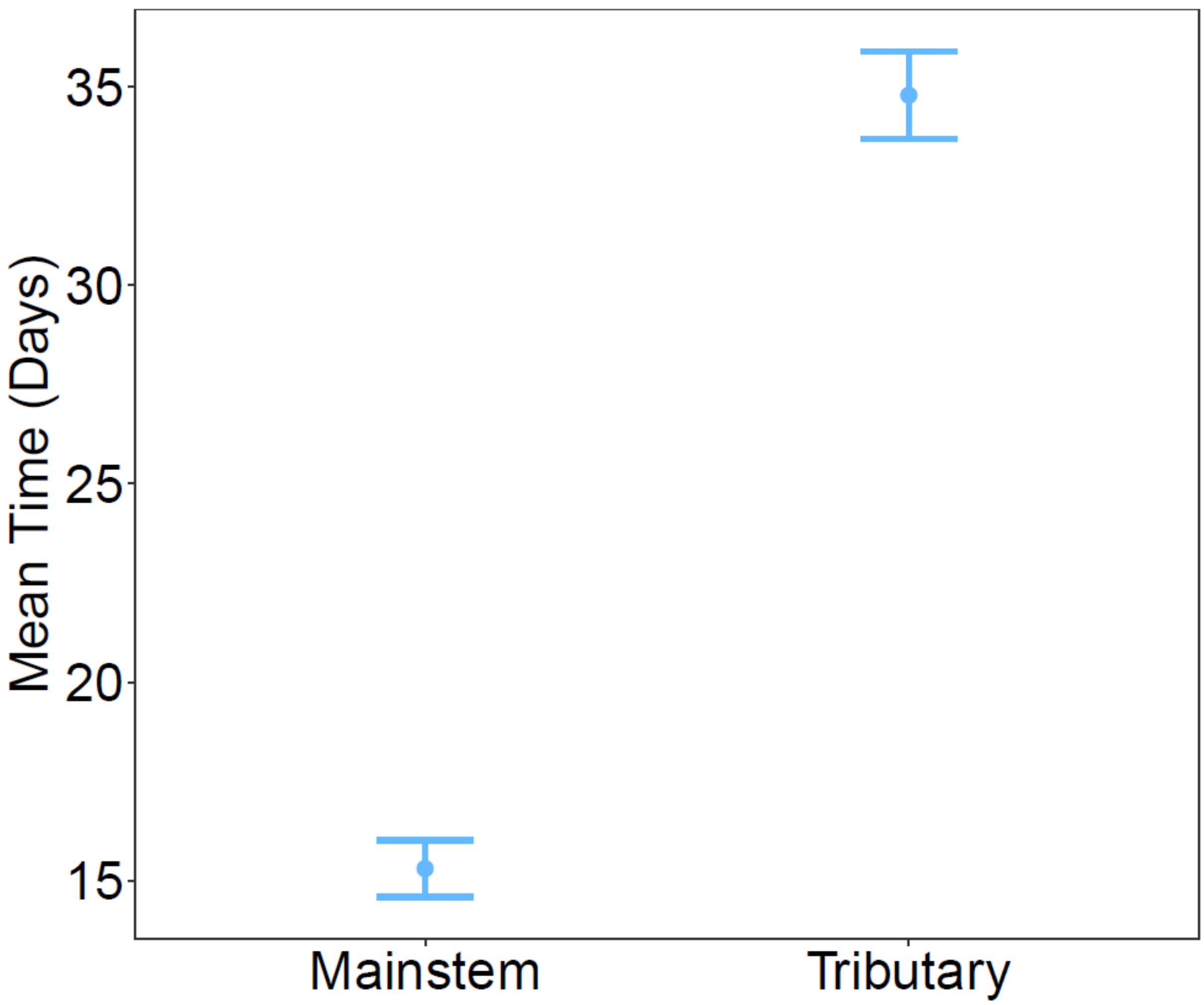

Figure 9. The mean time (days) spent in mainstem or tributary habitat for Silver Carps during June 2013 – July 2022. The number of days represents the time from the first detection of an individual in either the mainstem of the Ohio River or one of its tributaries to the first detection outside of that habitat.

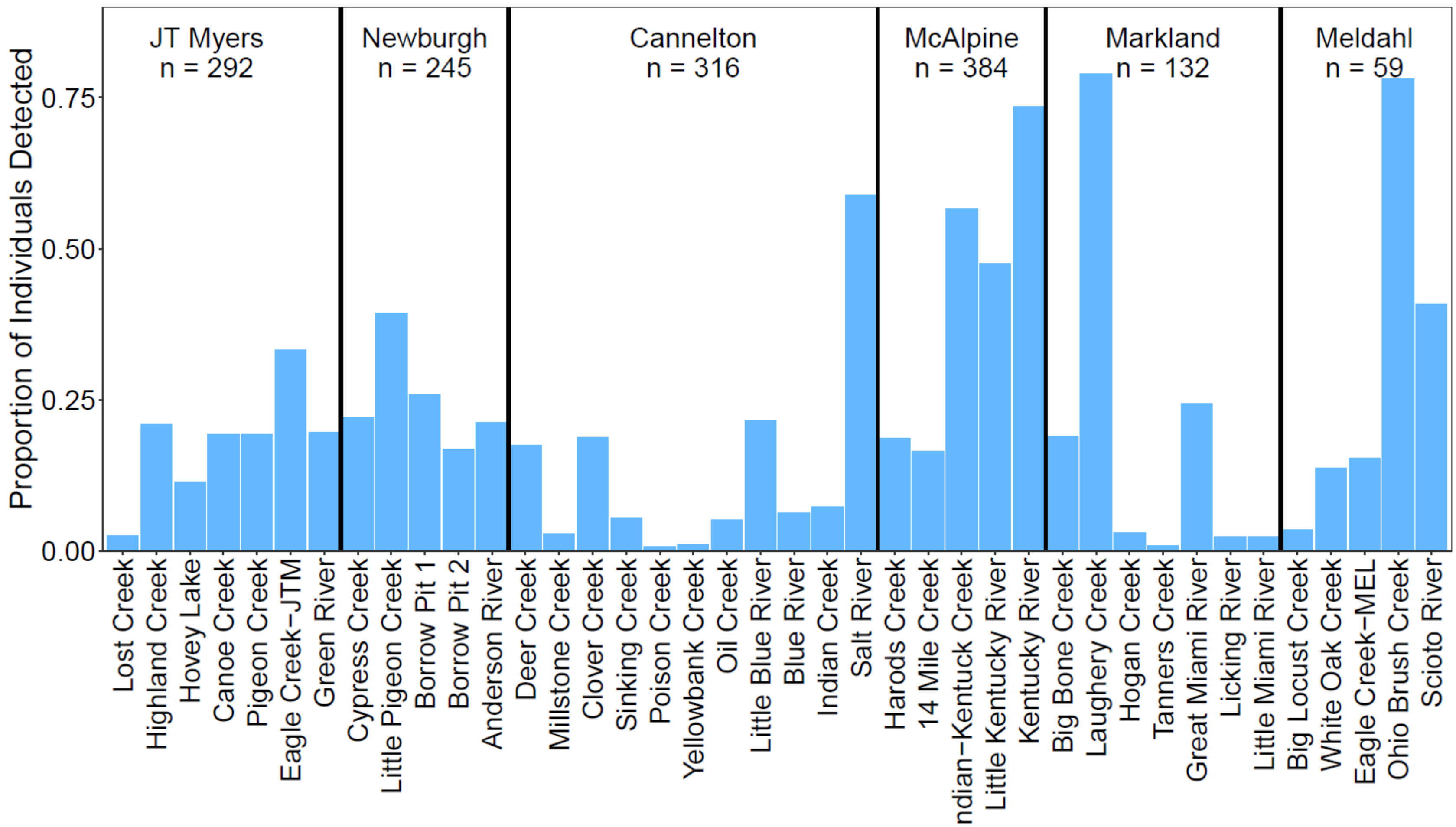

Figure 10. The proportion of individual Silver Carp in each pool that were detected in tributaries of those pools during June 2013 – July 2023. Numbers represent individual fish detected within that pool and the vertical lines are used to separate pools from most downstream to most upstream.

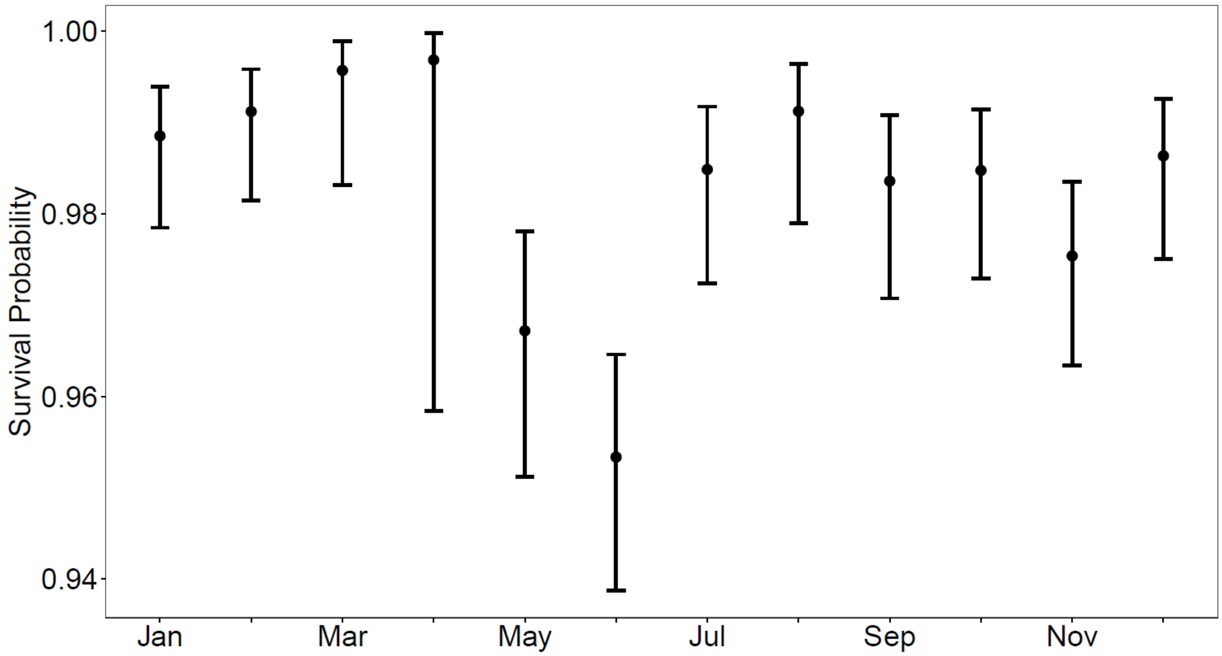

Figure 11. The effect of month probability of survival (S) of Silver Carps during January 2014 – July 2023. Plot shows mean probability of survival ± 95% confidence intervals for each month.

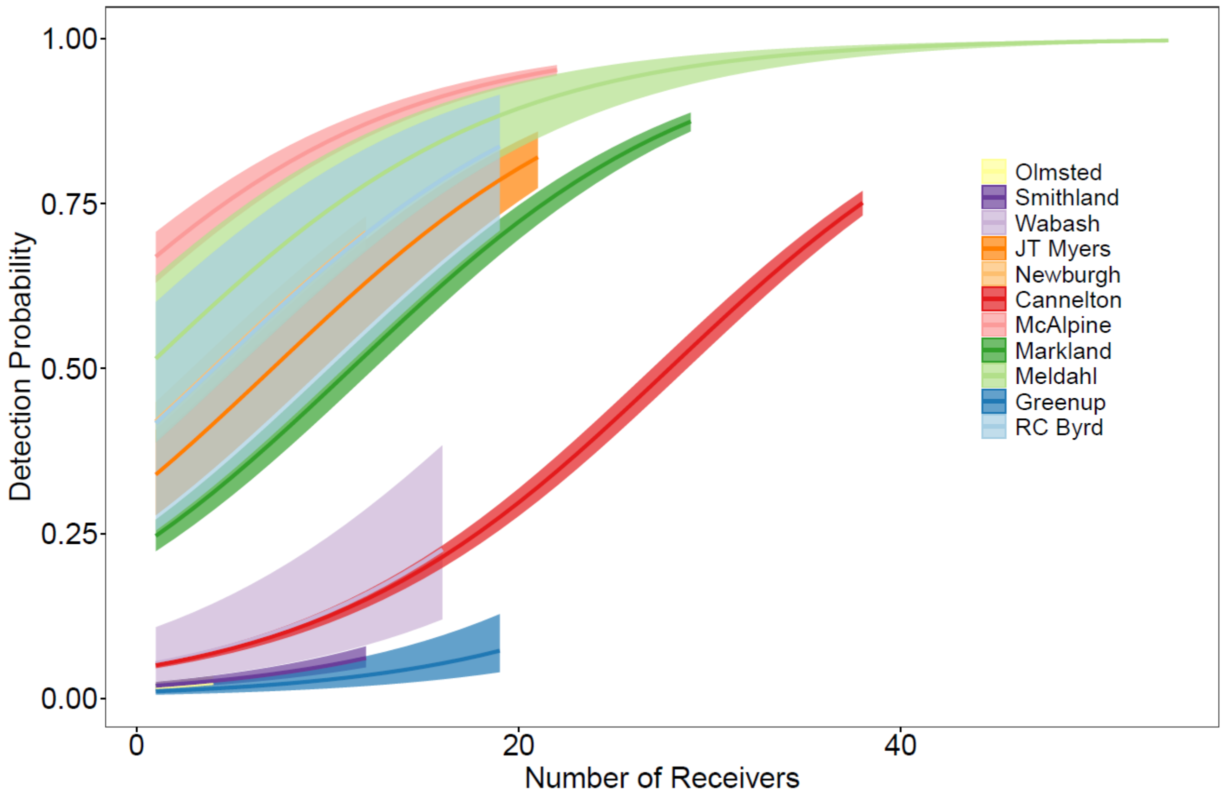

Figure 12. The effect of the number of receivers on the probability of detection (p) of Silver Carps in ten Ohio River pools and the Wabash River. The number of receivers ranged from 1 to 54 to reflect the number of receivers deployed in each pool during January 2014 – July 2023. The solid lines represent the mean probabilities of detection for each pool, whereas shaded areas represent the 95% confidence intervals surrounding those mean detection probabilities.

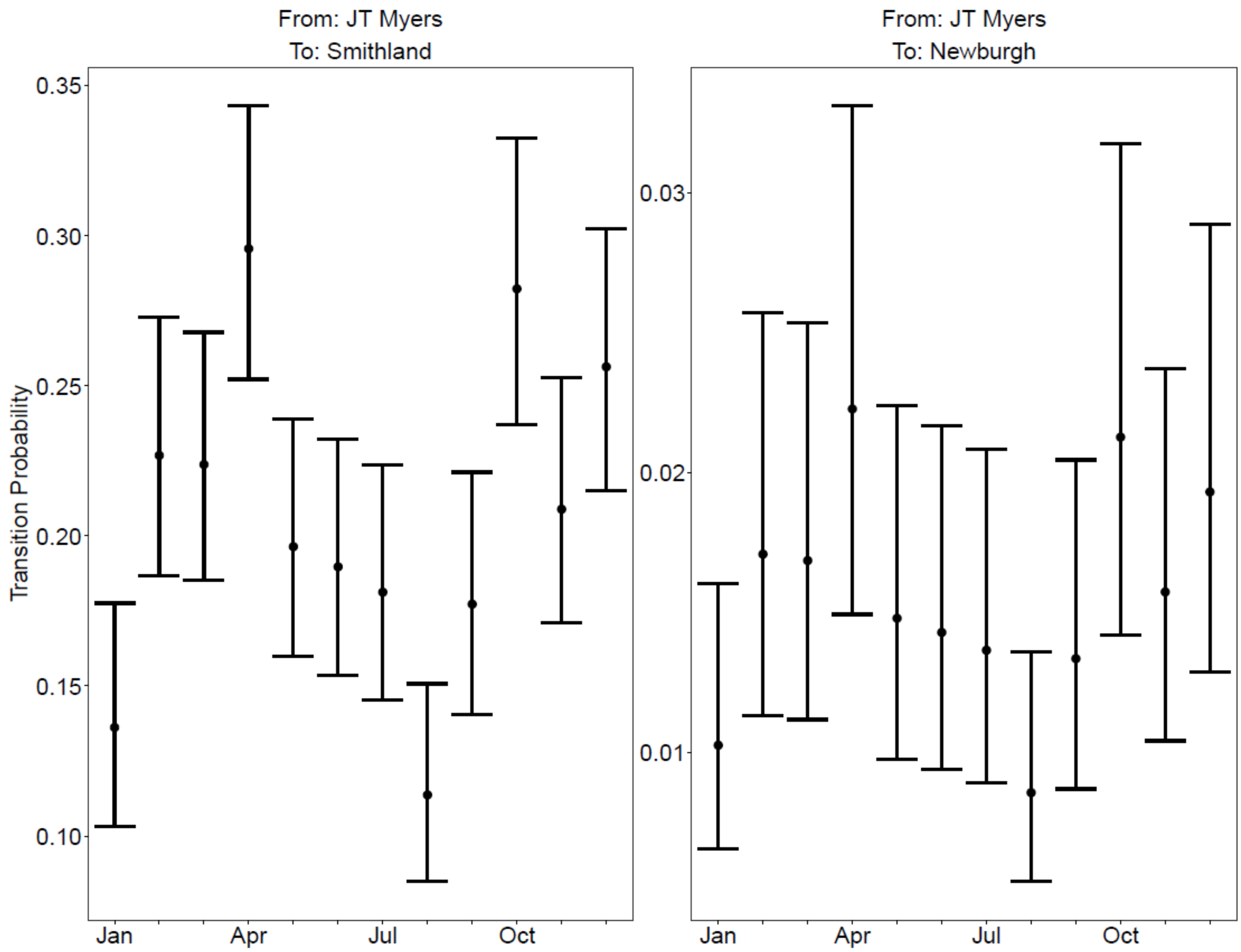

Figure 13. Monthly estimated transition probabilities (ψ) from J.T. Myers Pool downstream to Smithland Pool (left) and from J.T. Myers Pool upstream to Newburgh Pool (right). Plots for other pools are available from USFWS, CAR FWCO.

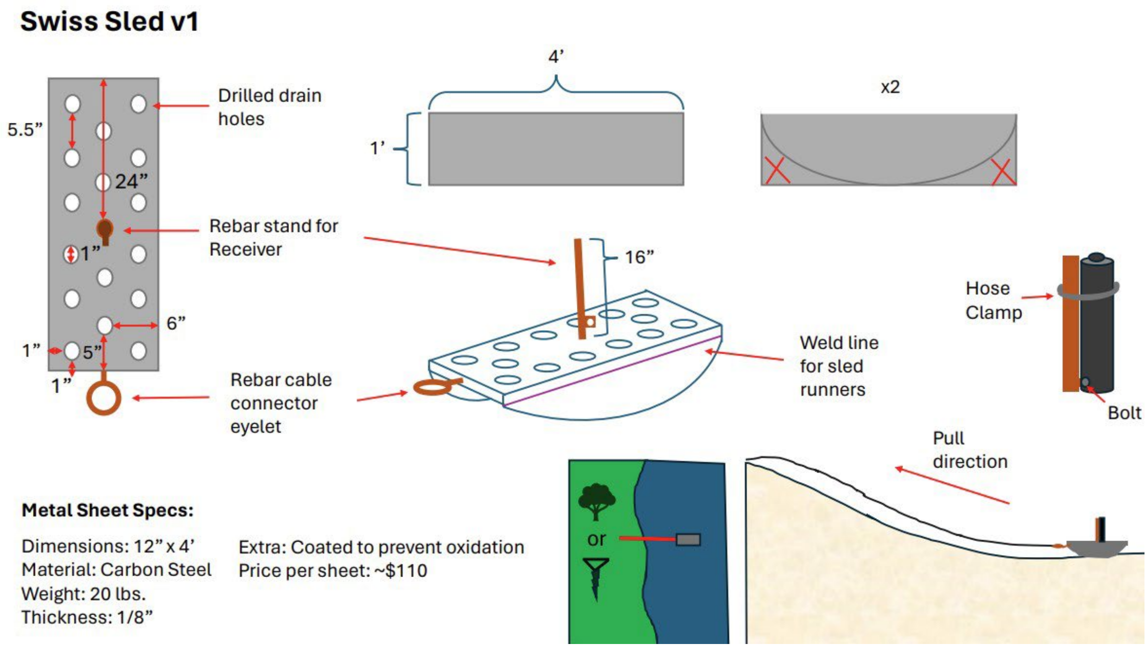

Figure 14. New "Swiss sled" design for deploying stationary VR receivers for fish acoustic telemetry in the Wabash and White Rivers. This prototype will be tested in the Wabash River to determine whether receivers can be better retrieved from the shifting sand bed of the river.

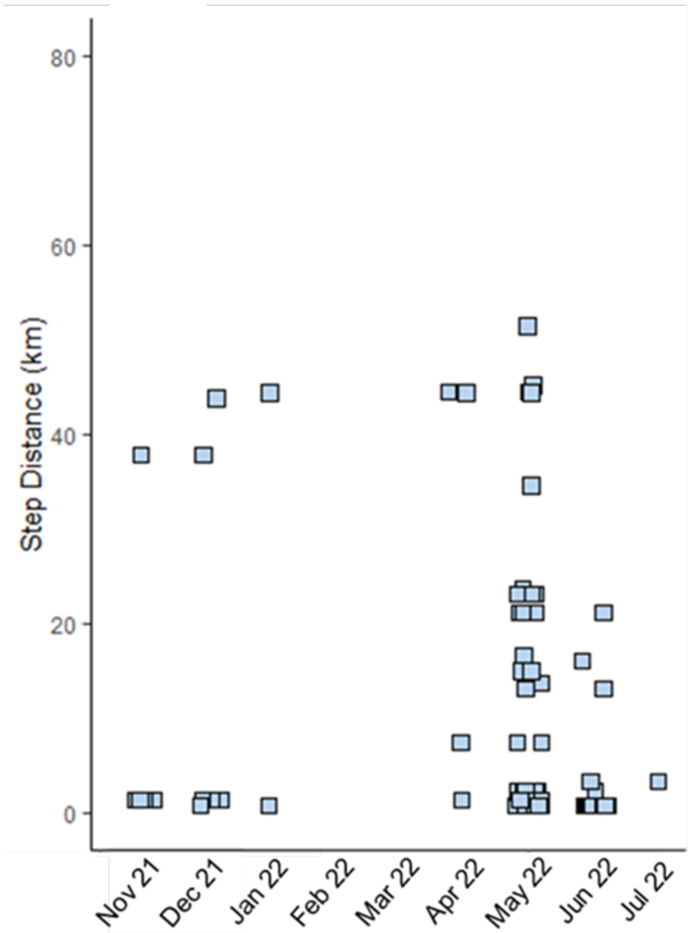

Figure 15. Net movement of silver carp in the Wabash River as a function of season and year as detected on the acoustic receiver network. Silver carp moved more during May 2022 perhaps as a function of elevated discharge and spawning.

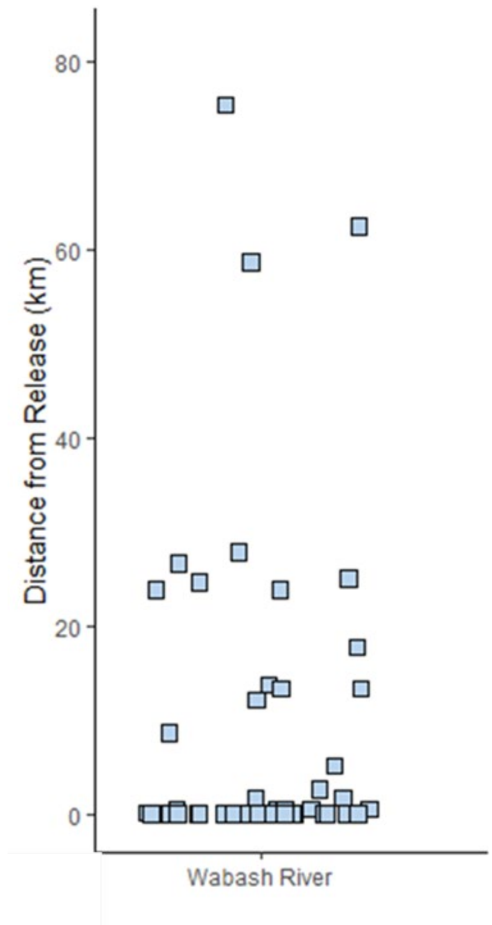

Figure 16. Farthest distance moved by silver carp as detected by the acoustic receiver array within the Wabash River during 2022 through 2023.

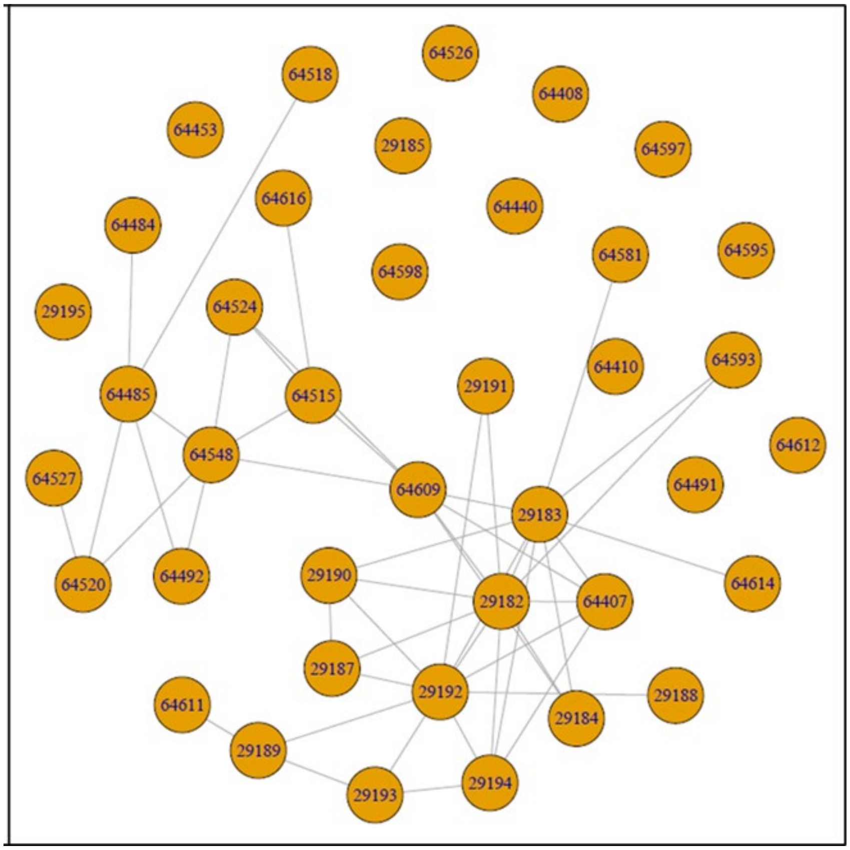

Figure 17. Network analysis of silver carp movement in the Wabash River. Each circle with number is an individually tagged silver carp. Proximity of silver carp movement to each other is depicted by connectors and proximity of circles. If all fish moved similarly, the nodes would be highly connected and circles clustered. An interpretation of this analysis is that silver carp move freely within the river, perhaps due to a lack of barriers.

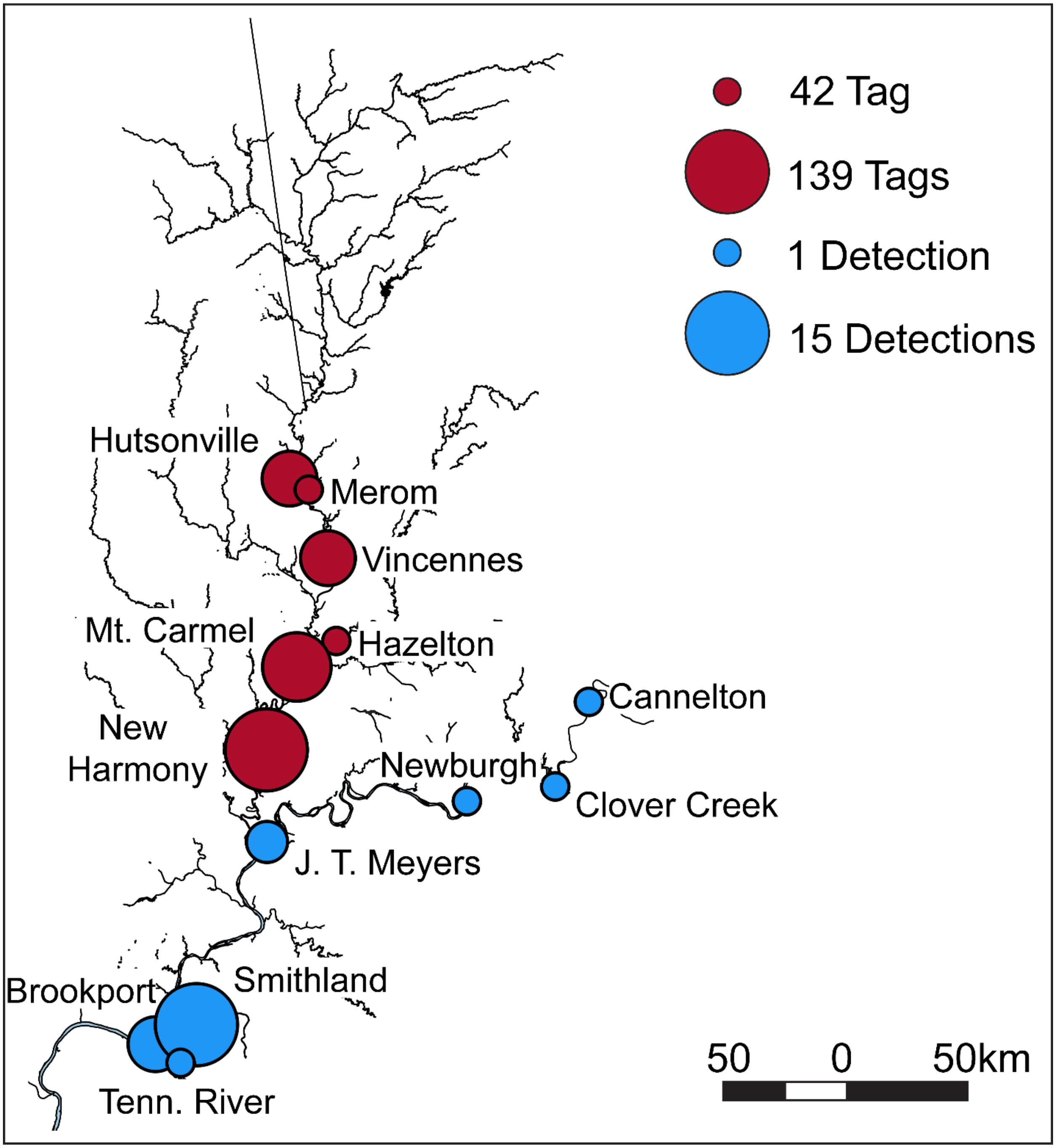

Figure 18: Map of tagging sites in the White and Wabash Rivers (Red) and receiver locations (blue) in the Ohio River from 2021-2023. For locations with multiple receivers (e.g. lock and dam structures) detections from all receivers were pooled, and the number of unique fish are reported.

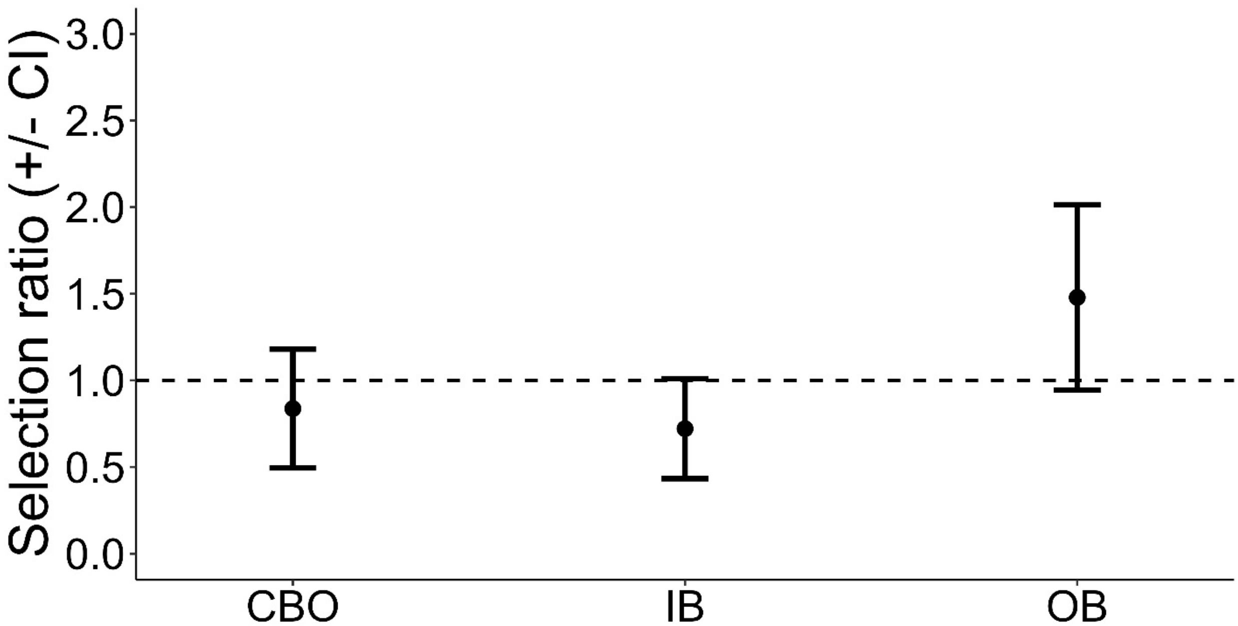

Figure 19. Selection ratios with 95% confidence intervals for macro-habitat [channel border open (CBO), inside bend (IB), and outside bend (OB)] in the Wabash and White rivers. Values greater than one indicate positive selection while values less than one indicate avoidance. These ratios were calculated using 305 detections of 108 unique individuals from 2021 to 2023.

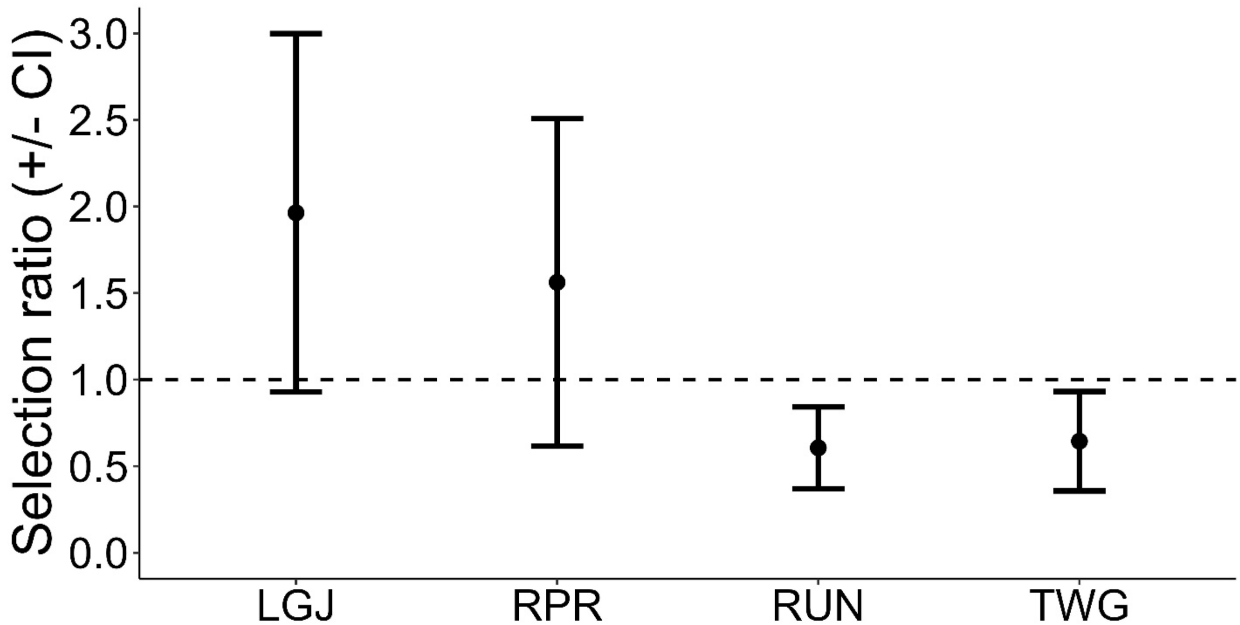

Figure 20. Selection ratios with 95% confidence intervals for micro-habitat [logjam (LGJ), rip-rap (RPR), run, and thalweg (TWG)] in the Wabash and White rivers. Values greater than one indicate positive selection while values less than one indicate avoidance. These ratios were calculated using 322 detections of 112 unique individuals from 2021 to 2023.

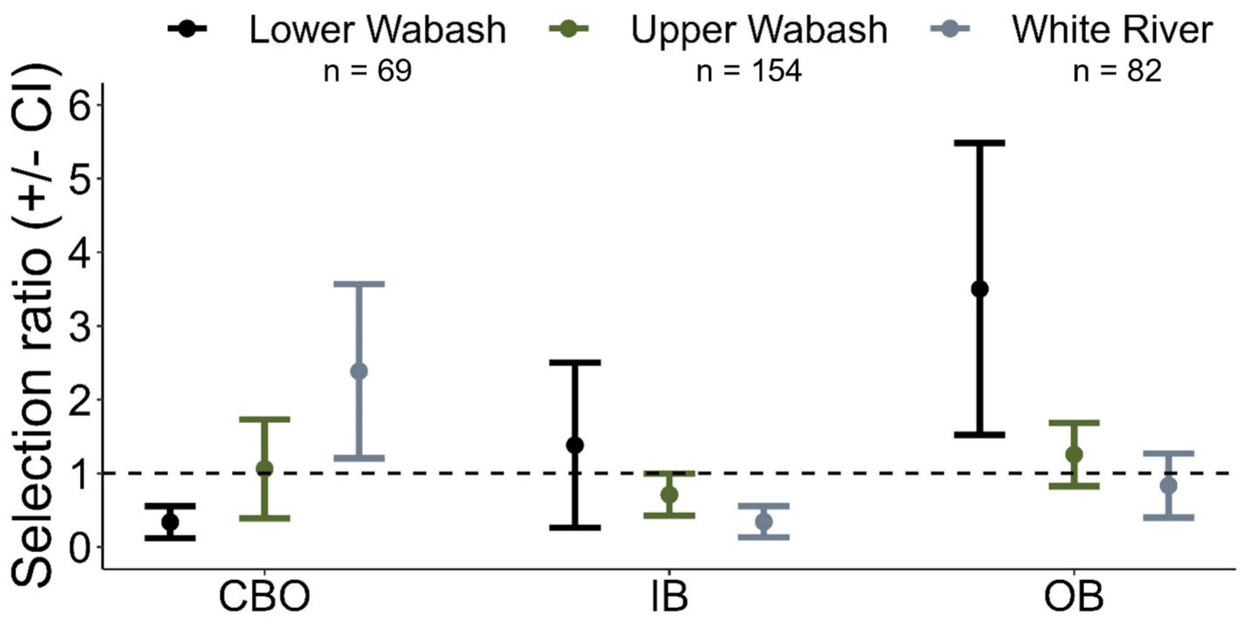

Figure 21. Selection ratios with 95% confidence intervals for macro-habitat [channel border open (CBO), inside bend (IB), and outside bend (OB)] within the Lower Wabash (Mt. Carmel, IL to Ohio River confluence), Upper Wabash (Terre Haute, IN to Mt. Carmel, IL) and White River (Maysville, IN to confluence with Wabash). Values greater than one indicated positive selection while values less than one indicate avoidance. These ratios were calculated using 305 detections of 108 unique individuals from 2021 to 2023.

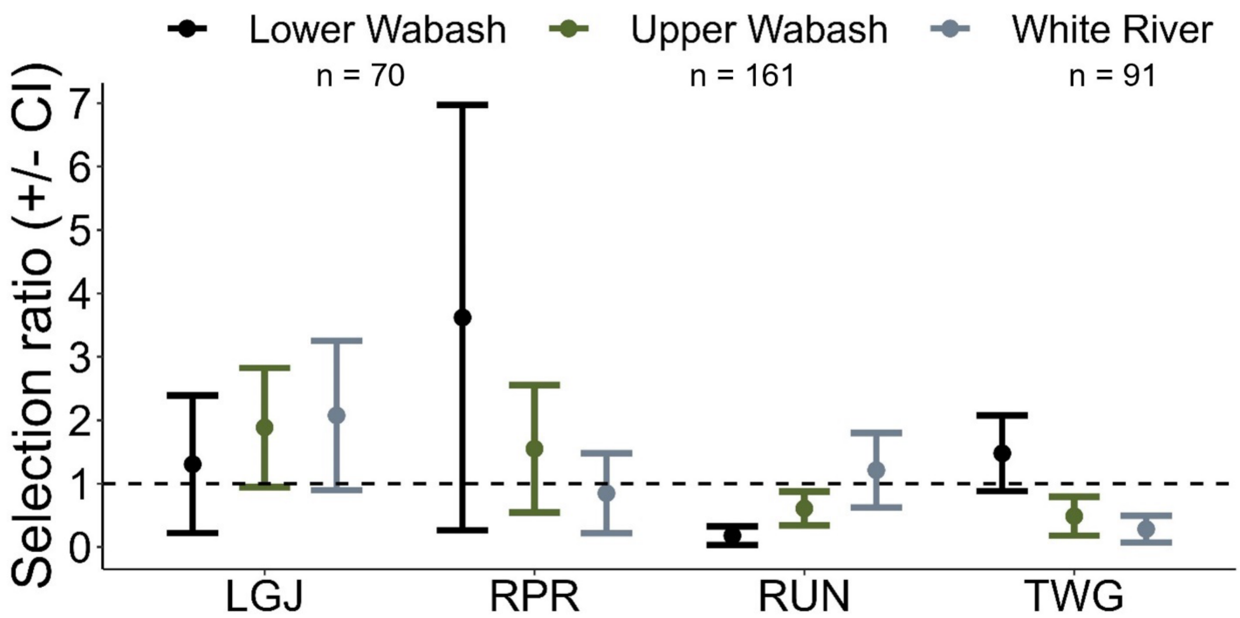

Figure 22. Selection ratios with 95% confidence intervals for micro-habitat [logjam (LGJ), rip-rap (RPR), run, and thalweg (TWG)] within the Lower Wabash (Mt. Carmel, IL to Ohio River confluence), Upper Wabash (Terre Haute, IN to Mt. Carmel, IL) and White River (Maysville, IN to confluence with Wabash). Values greater than one indicated positive selection while values less than one indicate aviodance. These ratios were calculated using 322 detections of 112 unique individuals from 2021 to 2023.

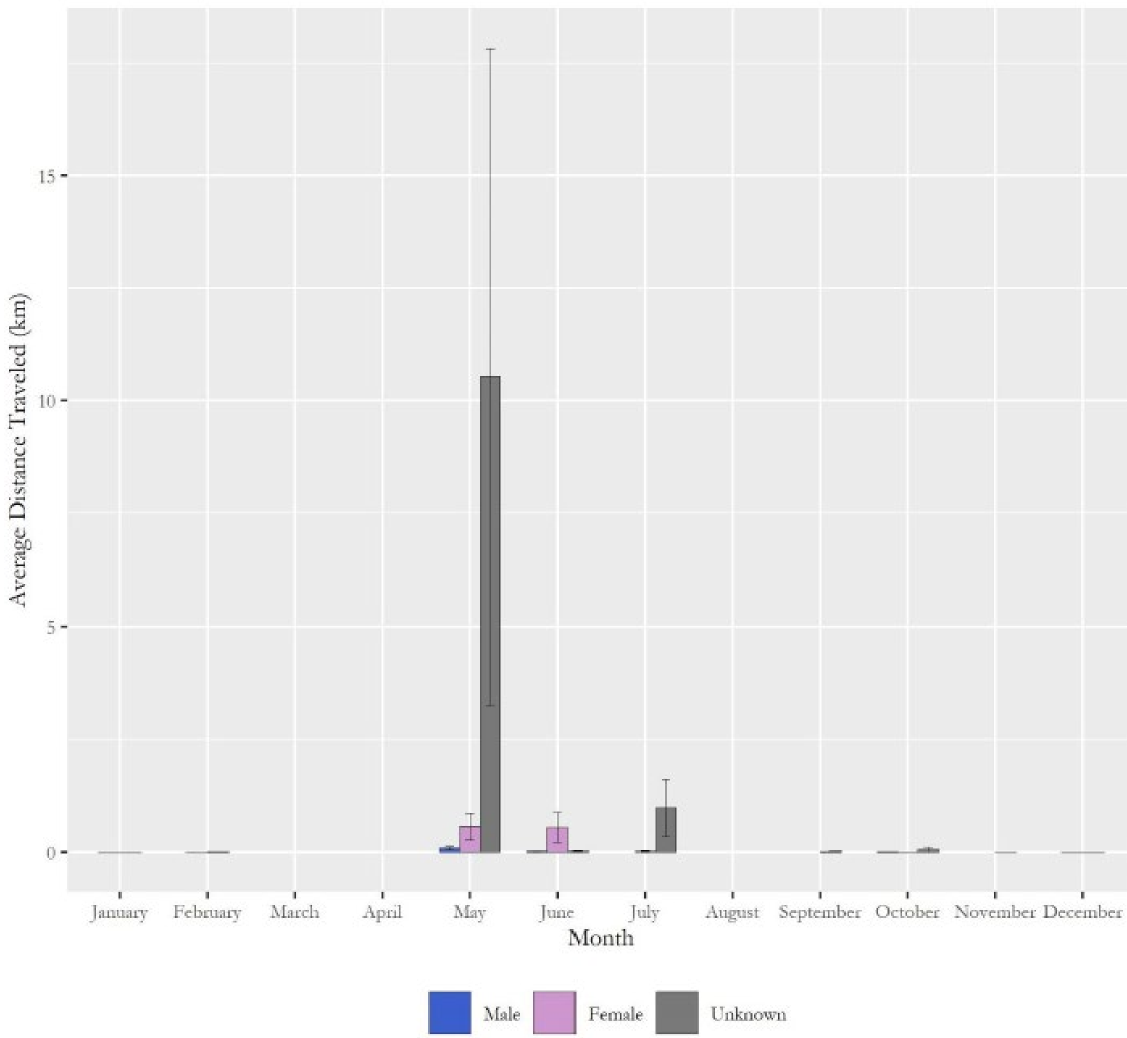

Figure 23. Average distance traveled per month for male, female, and fish where gender was unknown, for Silver Carp that were detected in the Upper Wabash River Basin network of acoustic receivers. A total of 68 Silver Carp were detected up to 21 December 2023. Months where no bars are showing indicate months where no movements were recorded for any fish. Error bars represent ± the standard error of the mean.

Table 1. The ID number, pool, and available data for US Geological Survey gage stations used in the pool-to-pool multistate model.

Gage ID	Pool	Gage Height	Temperature	Discharge
3399800	Olmsted	X		X
3611000	Olmsted	X		
3612600	Olmsted	X	X	X
3381700	Smithland	X		X
3384500	Smithland	X		
3377500	Wabash	X		X
3378500	Wabash	X	X	X
3304300	J.T. Myers	X		
3322000	J.T. Myers	X		
3322190	J.T. Myers	X		
3322420	J.T. Myers	X		
3303280	Newburgh	X	X	X
3294500	Cannelton	X		
3294600	Cannelton	X		
3292494	McAlpine	X		X
3293551	McAlpine	X		
3255000	Markland	X		
3217200	Meldahl	X		
3238000	Meldahl	X		
3206000	Greenup	X		
3216000	Greenup	X		
3216070	Greenup	X	X	X
3201500	R.C. Byrd	X		

Table 2. Model selection results for survival probability (*S*) of the multi-state with live recaptures model for Silver Carp pool-to-pool movements. The table shows the model structure, number of parameters in the model (npar), AIC_c, ΔAIC_c, and the AIC weight (W_i) for all model structures that converged for survival probability. The covariates affecting estimates of the survival probability are shown in parentheses and include temperature (temp), month, season, and pool. The "." notation indicates an invariant survival probability. The model structures for detection (*p*) and transition (ψ) probabilities were held constant and included only a pool effect for both parameters.

Model	npar	AIC_c	ΔAIC_c	W_i
S(month)p(pool)ψ(pool)	43	57457.89	0	1
S(season)p(pool)ψ(pool)	35	57495.89	38.0	0
S(.)p(pool)ψ(pool)	32	57529.52	71.63	0
S(temp)p(pool)ψ(pool)	33	57541.83	83.93	0

Table 3. Model selection results for detection probability (*p*) of the multi-state with live recaptures model for Silver Carp pool-to-pool movements. The table shows the model structure, number of parameters in the model (npar), AIC_c, ΔAIC_c, and the AIC weight (W_i) for all model structures for detection probability. The covariates affecting estimates of the detection probability are shown in parentheses and include the number of receivers (num_rec), the number of receivers per river mile (rprm), standardized gage height (std.height), month, season, and pool. The "." notation indicates an invariant detection probability. The model structures for survival (*S*) and transition (ψ) probabilities were held constant and included only a month effect for *S* (the best supported model structure) and a pool effect for ψ.

Model	npar	AIC_c	ΔAIC_c	W_i
S(month)p(pool + num_rec)ψ(pool)	44	55261.9	0	1
S(month)p(pool + rprm)ψ(pool)	44	55295.56	33.66	0
*S(month)p(pool*season)ψ(pool)*	76	56951	1689.10	0
S(month)p(pool month)ψ(pool)*	164	57008.25	1746.35	0
S(month)p(pool + month)ψ(pool)	54	57033.66	1771.76	0
S(month)p(pool + season)ψ(pool)	46	57200.13	1938.23	0
S(month)p(pool + std.height)ψ(pool)	44	57240.63	1978.73	0
S(month)p(pool)ψ(pool)	43	57457.89	2195.99	0
S(month)p(rprm)ψ(pool)	34	57750.51	2488.61	0
S(month)p(num_rec)ψ(pool)	34	58921.61	3659.71	0
S(month)p(month)ψ(pool)	44	61439.97	6178.07	0
S(month)p(season)ψ(pool)	36	61687.33	6425.43	0
S(month)p(std.height)ψ(pool)	34	61911.3	6649.39	0
S(month)p(.)ψ(pool)	33	62185.36	6923.46	0

Table 4. Model selection results for transition probabilities (ψ) of the multi-state with live recaptures model for Silver Carp pool-to-pool movements. The table shows the model structure, number of parameters in the model (npar), AIC_c, ΔAIC_c, and the AIC weight (W_i) for all model structures that converged for transition probabilities. The covariates affecting estimates of the transition probabilities are shown in parentheses and include standardized gage height (std.height), linear and quadratic effects of temperature (temp), month, season, and pool. The "." notation indicates an invariant transition probability. The model structures for survival (*S*) and detection (*p*) probabilities were held constant and included only a temperature effect for *S* and the additive effect of pool and receivers per river mile for *p*.

Model	npar	AIC_c	ΔAIC_c	W_i
S(month)p(pool + num_rec)ψ(pool + month)	56	55144.77	0	1
S(month)p(pool + num_rec)ψ(pool + season)	48	55219.49	74.72	0
S(month)p(pool + num_rec)ψ(pool + std.height)	45	55245.95	101.18	0
S(month)p(pool + num_rec)ψ(pool + temp)	45	55247.33	102.57	0
S(month)p(pool + num_rec)ψ(pool + temp + temp²)	45	55247.33	102.57	0
S(month)p(pool + num_rec)ψ(pool)	44	55259.58	114.81	0
S(month)p(pool + num_rec)ψ(month)	36	57275.96	2131.19	0
S(month)p(pool + num_rec)ψ(pool + std.height + temp + temp²)	46	58517.64	3372.87	0
S(temp)p(pool + rprm)ψ(pool + std.height + temp)	46	58519.85	3375.08	0

Table 5: Number of silver carp tagged at each location in the Wabash River system 2021-2023.

Tagging Location	No. Fish	Latitude	Longitude
Hazelton	55	38.49	-87.54
Hutsonville	98	39.11	-87.65
Merom	42	39.06	-87.57
Mt. Carmel	109	38.42	-87.74
New Harmony	139	38.13	-87.94
Vincennes	94	38.80	-87.53

Table 6. Number and distribution of VR2 receivers in the Ohio River during 2023. One-hundred sixty-two receivers were deployed from Olmsted pool, downstream of the Smithland lock and dam, to Willow Island lock and dam.

Ohio River Pool	Pool Length (km)	Lock and Dam Receivers (N)	Mainstem Receivers (N)	Tributary Receivers (N)	Total Receivers (N)
Olmsted	73.9	0	2	1	3
Smithland	116.7	7	0	2	9
J.T. Myers	112.5	4	1	14	19
Newburgh	89.1	4	0	8	12
Cannelton	183.3	1	10	34	45
McAlpine	121.2	3	3	5	11
Markland	153.3	0	2	6	8
Meldahl	153.2	7	9	8	24
Greenup	99.4	3	6	3	12
R.C. Byrd	67.1	4	5	8	16
Racine	54.1	4	1	2	7
Belleville	67.9	5	1	1	7
Willow Island	56.8	1	0	0	1
Total	1348.3	43	40	91	174

Table 7. The number of Silver and Bighead Carps tagged with acoustic transmitters by year and pool during June 2013 – December 2023. Numbers in parenthesis are fish with tags that have been reported as harvested before expected tag expiration and, therefore, are no longer active. Tags deployed for > 5 years are expected to be expired (inactive). Also included are species composition calculations for the tags expected to be active in each pool and the mean total length (mm) of all tagged fish by pool.

Year(s)	Status after 2023	Species	Ohio River Pool								Total
			J.T. Myers	Newburgh	Cannelton	McAlpine	Markland	Meldahl	Greenup	R.C. Byrd	
2013	Inactive	SVCP	-	-	-	-	-	6	-	-	6
		BHCP	-	-	-	-	-	13	-	-	13
2014	Inactive	SVCP	-	-	-	111	6	10	-	-	127
		BHCP	-	-	-	4	4	-	-	-	8
2015	Inactive	SVCP	-	-	-	23	3	5	-	-	30
		BHCP	-	-	-	1	1	5	-	-	7
2016	Inactive	SVCP	-	-	92	94	6	-	-	-	192
		BHCP	-	-	4	1	4	2	-	3	14
2017	Inactive	SVCP	-	-	90	-	12	3	-	-	105
		BHCP	-	-	-	-	2	-	-	-	2
2018	Inactive	SVCP	-	-	-	-	21	10	-	-	31
		BHCP	-	-	-	-	-	1	-	-	1
2019	Inactive	SVCP	-	-	-	30	-	-	-	-	30
		BHCP	-	-	-	1	-	-	-	-	1
2020	Active	SVCP	-	-	-	100 (1)	18	-	-	-	118
2021	Active	SVCP	226 (1)	230	92	97	3	-	-	-	648
2022	Active	SVCP	-	-	108 (1)	-	29	-	-	-	137
2023	Active	SVCP	-	-	-	-	53	30	-	-	83
2020-2023	Active	SVCP	225	230	199	197	103	30	-	-	985
2013-2019 (Including harvested)	Inactive	SVCP	1	-	182	259	48	34	-	-	524
		BHCP	-	-	4	6	11	21	-	3	45
		Overall	-	-	186	265	59	55	-	3	569

% Species Composition	Active	SVCP	22.9	23.4	20.0	23.4	10.5	3.0	0.0	0.0	100
Mean TL (mm)	Combined	SVCP	699.7	708.5	787.7	818.7	896.0	949.0	-	-	799.5
		BHCP	-	-	1139.8	1169.0	1175.1	1154.5	-	1210	1160.1

Table 8. Model-estimated mean (95% confidence intervals) pool-to-pool transition probabilities (ψ) of Silver Carps in the Ohio River derived from acoustic telemetry during January 2014 – July 2023. The highest-ranked model for Silver Carp included the additive effect of pool and month on transition probabilities. Black-shaded cells represent transitions among non-adjacent pools for which transition probabilities were not estimated. These transition probabilities were fixed to 0 and are, therefore, not reported in the table below. The probability of fish remaining within a pool is given in the gray shaded cells; upstream transition probabilities are to the right of gray-shaded cells and downstream transition probabilities are to the left of gray-shaded cells. No Silver Carps were detected above Racine Lock and Dam. Therefore, transition probabilities were not estimated for pools upstream of R.C. Byrd Pool. Shown here are the estimated transition probabilities during April and August, the months of the highest and lowest estimated pool-to-pool transition probabilities, respectively. Tables for other months are available from USFWS, CAR FWCO.

April											
Departure Pool	Destination Pool										
	Olmsted	Smithland	Wabash	J.T. Myers	Newburgh	Cannelton	McAlpine	Markland	Meldahl	Greenup	R.C. Byrd
Olmsted	0.945	0.055 (0.026 - 0.113)									
Smithland	0.175 (0.124 - 0.242)	0.647	0.025 (0.014 - 0.047)	0.153 (0.121 - 0.191)							
Wabash		0.121 (0.037 - 0.329)	0.879								
J.T. Myers		0.296 (0.252 - 0.343)		0.682	0.022 (0.015 - 0.033)						
Newburgh				0.055 (0.043 -0.070)	0.941	0.004 (0.002 - 0.009)					
Cannelton					0.003 (0.002 - 0.004)	0.899	0.098 (0.085 - 0.112)				
McAlpine						0.162 (0.142 - 0.184)	0.835	0.003 (0.002 - 0.005)			
Markland							0.018 (0.012 -0.028)	0.977	0.005 (0.002 - 0.010)		
Meldahl								0.012 (0.006 - 0.025)	0.898	0.090 (0.065 - 0.122)	
Greenup									0.294 (0.217 - 0.384)	0.664	0.042 (0.019 -0.093)
R.C. Byrd										0.125 (0.051 - 0.277)	0.875
August											
Olmsted	0.983	0.017 (0.008 - 0.038)									
Smithland	0.070 (0.044 - 0.109)	0.860	0.010 (0.005 - 0.020)	0.061 (0.042 - 0.086)							
Wabash		0.040 (0.011 - 0.130)	0.960								
J.T. Myers		0.114 (0.085 - 0.151)		0.878	0.009 (0.005 -0.014)						
Newburgh				0.017 (0.012 - 0.024)	0.982	0.001 (0.000 - 0.003)					

Cannelton					0.001 (0.000 - 0.001)	0.968	0.031 (0.024 - 0.041)				
McAlpine						0.055 (0.042 - 0.071)	0.944	0.001 (0.001 - 0.002)			
Markland							0.005 (0.003 - 0.009)	0.993	0.001 (0.000 - 0.003)		
Meldahl								0.004 (0.002 - 0.008)	0.967	0.029 (0.020 - 0.043)	
Greenup									0.115 (0.075 - 0.173)	0.869	0.017 (0.007 - 0.039)
R.C. Byrd										0.041 (0.015 - 0.105)	0.959

Table 9: Number of unique fish detected at each receiver location in the Ohio River 2021-2023. For locations with multiple receivers (e.g. lock and dam structures) detections from all receivers were pooled, and the number of unique fish are reported.

Receiver Location	No. Fish	Latitude	Longitude
Brookport	8	37.11	-88.63
Cannelton	2	38.12	-86.41
Clover Creek	1	37.84	-86.63
J.T. Meyers	7	37.80	-87.99
Newburgh	3	37.83	-87.04
Smithland	15	37.16	-88.43
Tennessee River	2	37.03	-88.53

Table 10. Index of Biotic Integrity (IBI) and Qualitative Habitat Evaluation Index (QHEI) scores at 22 sites that were sampled in 2022 and 2023. An IBI score could not be calculated for Squirrel Creek Upper either year due to low catch rates of fish during electrofishing sampling.

System	Site	IBI Score 2022	IBI Score 2023	IBI Ranking 2023	QHEI Score 2022	QHEI Score 2023
Mainstem Eel River	Columbia City	40	42	Very Good	54	51.5
	Collamer	42	50	Exceptional	70.5	70
	Liberty Mills	48	38	Good	75	73.5
	North Manchester	44	46	Very Good	74	75.5
	Above Stockdale Dam	36	30	Fair	54	49.5
	Below Stockdale Dam	46	54	Exceptional	73	78.5
	Mexico	32	46	Very Good	76	69.75
	Hoover	48	44	Very Good	78	75
	Adamsboro	46	44	Very Good	75	73.25
	Logansport	44	44	Very Good	76	78
Tributaries	Geller Ditch	32	14	Poor	19	26.5
	Johnson Ditch	30	14	Poor	28	29.5
	Shoaff Ditch	30	24	Poor	35	32.5
	Thorn Creek	28	28	Fair	62	46
	Blue River	32	14	Poor	35.5	34
	Beargrass Creek Upper	40	42	Very Good	64	47
	Beargrass Creek Lower	46	24	Poor	78.5	71
	Squirrel Creek Upper	NA	NA	NA	28	25
	Squirrel Creek Lower	38	40	Good	65.5	65
	Pawpaw Creek Upper	50	46	Very Good	42	46.5
	Pawpaw Creek Lower	46	46	Very Good	79.5	76.5
	Weesau Creek	46	44	Very Good	82	71

Table 11. Information and tag number for the three Silver Carp that were tagged at River Kilometer 56 of the Eel River on 5 July 2023. River discharge was 326 ft^3/s at the time of sampling.

Species	Date Tagged	Sex	Length (mm)	Weight (g)	Acoustic Tag Number	PIT Tag Number
Silver Carp	7/5/2023	Male	610	2502.5	A69-1602-23552	989001040400156
Silver Carp	7/5/2023	Male	630	2765	A69-1602-23553	989001040400151
Silver Carp	7/5/2023	Male	580	2800	A69-1602-23525	989001040400088

Table 12. Percent of replicates that were above detection limits at 24 sampled sites in the Eel River Watershed and Wabash River Watershed.

					Percent of Replicates that Detected DNA		
Site Type	Site Name	River Kilometer	Latitude	Longitude	Bighead Carp	Silver Carp	Grass Carp
Mainstem Eel River	Columbia City	121	41.118	-85.499	0	0	0
	Collamer	103	41.074	-85.664	0	0	33.33
	Liberty Mills	92	41.038	-85.739	0	0	0
	North Manchester	82	40.995	-85.781	0	0	0
	Above Stockdale Dam	59	40.914	-85.941	0	0	0
	Below Stockdale Dam	58	40.912	-85.951	0	0	0
	Mexico	30	40.818	-86.108	0	0	33.33
	Hoover	20	40.797	-86.198	0	0	33.33
	Adamsboro	12	40.783	-86.264	0	0	33.33
	Logansport	2	40.759	-86.364	0	0	100
Tributary of the Eel River	Thorn Creek		41.207	-85.429	0	0	0
	Blue River		41.245	-85.386	0	0	0
	Geller Ditch		41.206	-85.217	0	0	0
	Everett Lake Ditch		41.162	-85.296	0	0	0
	Shoaff Ditch		41.207	-85.235	0	0	0
	Pawpaw Creek Upper		40.898	-85.753	0	0	33.33
	Pawpaw Creek Lower		40.878	-85.966	0	0	0
	Squirrel Creek Upper		40.965	-85.940	33.33	0	0
	Squirrel Creek Lower		40.917	-85.939	0	0	0
	Beargrass Creek Upper		40.932	-85.779	0	0	66.67
	Beargrass Creek Lower		40.943	-85.890	0	0	0
	Wesau Creek		40.867	-86.086	0	0	0
Mainstem Wabash River	Wabash River Downstream Eel River	566	40.747	-86.407	0	0	0
	Wabash River Upstream Eel River	576	40.751	-86.301	66.67	100	100

Table 13. River name, site name, date of tagging, and number of individuals detected in the Upper Wabash River Basin network of receivers from the identified tagging event.

River Fish was Tagged In	Site Name	Date of Tagging	Number of Individual Detected from Tagging Event
Wabash River	Lafayette	4/1/2011	2
Cumberland River	Chetham Dam	3/2/2021	2
Eel River	Stockdale Dam	7/5/2022	1
Wabash River	Hutsonville	11/1/2021 and 4/18/2022	7
Wabash River	Lafayette	3/29/2023 and 3/30/2023	29
Wabash River	Omer Cole Ramp	8/2/2022 and 8/3/2022	20
Wabash River	Above Lafayette	9/14/2021 and 9/15/2021	7