**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 J.T. Myers Locks and Dam (RM 846.0) to Willow Island Locks and Dam (RM 167.7), 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), U.S. Army Corps of Engineers (USACE), and U.S. Geological Survey (USGS)

**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:**

- During 2021, 30 receivers were added to the downstream portion of the array, improving coverage in three areas known to have high densities of invasive carps (J.T. Myers, Newburgh, and Cannelton pools).
- Six-hundred forty-eight Silver Carp were tagged during 2021 from J.T. Myers Pool to Markland Pool, dramatically increasing the number of tagged fish in the Ohio River.
- During 2021, 92% of Silver Carp detections occurred in tributaries compared with 62% of Bighead Carp detections
- The estimated annual survival rate for Silver Carp during June 2013 – December 2021 was 0.74
- Estimated mean pool-to-pool transition probabilities were generally low (< 0.2) for Silver Carp, suggesting that most of these fish remain within the pool in which they were tagged

**Methods:**

**Ohio River**

Acoustic telemetry was used to determine the probabilities of survival, detection, and lock and dam passage of invasive carps in the lower to middle Ohio River (Olmsted to Willow Island 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 most 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, four VR2 receivers were deployed at each L&D to record pool-to-pool transitions through the lock chambers with the exception of R.C. Byrd L&D. During 2021, three receivers were deployed at R.C. Byrd L&D, two at the downstream approach and one at the upstream approach. For all other L&Ds, two receivers were placed within the lock chamber and 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 2021, the receiver array extended from river mile 937.0 in Olmsted Pool, ~20 miles downstream of the Smithland L&D, upstream to Willow Island L&D (river mile 161.7). Most VR2 receivers deployed in the mainstem of the Ohio River were retrieved in November 2020 to avoid loss of equipment to ice flows, high water and barge collisions during winter. During April 2021, the mainstem VR2 receivers were redeployed, and downloads and maintenance performed for L&D and tributary receivers. Because receiver loss at tributary and L&D sites is low, most receivers deployed in these locations remained in the system throughout the year. 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 and gill nets set to block or trap fish. 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 ~1,825 days (5 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 will take place in select areas of the Ohio River. A VR100 omnidirectional hydrophone will be used to detect fish during these sampling trips.

*Tributary Use*: To assess tributary use by invasive carps, the proportion of detections by month and habitat type (tributary or mainstem) was determined for each species by dividing the number of detections for that species in each habitat within a month by the total number of detections for that species during June 2013 – December 2021. The proportion of transitions from mainstem to tributary and from tributary to mainstem habitats each month was also assessed for both Silver and Bighead Carps species. To do this, the number of transitions in each direction were summed and divided by the total number of transitions made during June 2013 – December 2021 for each species. 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.

*Statistical Analyses*: To determine the probabilities of transitions among pools, survival, and detection of Silver Carps in the Ohio River, 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, each navigation pools of the Ohio River is considered a “state”. Encounter histories were constructed for each individual by determining the pool of the last detection for each month (June 2013 – December 2021). Because receiver coverage was poor for much of 2021 below McAlpine L&D, all pools below this point were considered a single stratum in the model (Below McAlpine). Additionally, because tagging took place at various times throughout the duration of the study period and the expected battery life of the acoustic transmitters is ~5 years, not all individuals have a complete encounter history (maximum of 103 possible time periods). Encounter histories of tagged carp whose tag battery expired or that were harvested were right-censored. This process removes these individuals from the estimation procedures for the times following tag expiration or harvest. Additionally, the probability of transitions among non-adjacent pools were only estimated if they occurred in the data. Transitions among non-adjacent pools that were not observed were fixed to 0. Due to the small number of fish tagged (n = 46) and tags currently active in the Ohio River (n = 10), Bighead Carp were not included in these analyses.

Encounter histories of individual Silver Carp were used to inform transition, survival, and detection estimates in multi-state models. More than 400 models were developed. Models included temporally and spatially invariant parameters, as well as those that varied temporally (by month or season) and/or spatially (by pool). Additive and interactive effects of covariates were also considered. Models were compared using Akaike’s information criterion corrected for small sample size ($AIC_c$) to find the most parsimonious model; a lower $AIC_c$ value indicates greater support for that model. However, models that are within two AIC points of one another are considered to have equal support from the data. A variance inflation factor ($\hat{c}$) was also calculated for the most parameterized model in the model set [S(pool * month)p(pool * month)$\psi$(pool * month)] using the median $\hat{c}$ procedure in Program Mark, to assess overdispersion in the models (Cooch and White 2008). If $\hat{c}$ differed substantially from one, the $AIC_c$ values for all models were adjusted by $\hat{c}$ and the most parsimonious model was assessed using the quasi-Akaike’s information criterion ($QAIC_c$). Values of $\hat{c}$ between one and three are considered acceptable (Lebreton et al. 1992).

**Wabash River**

*Acoustic Receiver Array*: VR2 receivers were deployed during August 2021 throughout the Wabash River from the confluence with the Ohio River upstream 214 river miles (near Terre Haute, Indiana) and within the White River, from its confluence with the Wabash River to 50 miles upstream. Receiver deployments followed the methods described above. In the Wabash River, 12 receivers were retrieved during November to avoid loss to ice flows. All other receivers remained in the system throughout the winter. Data from all receivers were downloaded prior to winter.

*Acoustic Transmitter Tagging*: Tagging of invasive carps in the Wabash and White Rivers occurred during May and October and followed the methods for the Ohio River, above.

*Fine-Scale Habitat Use*: Fine-scale habitat use by tagged adult invasive carp was assessed throughout the Wabash River. Monthly active tracking events occurred throughout 214 river miles from Terre Haute, IN to the Ohio River. Habitat characteristics including substrate type, dissolved oxygen concentration, water velocity, water temperature, and water clarity were measured at locations where tagged fish were detected.

**Agency-Specific Accomplishments**

*Kentucky Department of Fish & Wildlife Resources (KDFWR)*

During 2021, KDFWR maintained and offloaded receivers from the Cannelton (from the Salt River to McAlpine L&D), McAlpine, and Markland (from Markland L&D to Cincinnati). KDFWR also continued active tracking efforts to determine if invasive carps are moving between McAlpine and Markland pools without being detected by stationary receivers deployed at the lock, which would bias estimates of pool-to-pool transitions. KDFWR also assisted USFWS tagging efforts in McAlpine Pool and INDNR efforts to expand the receiver array in J.T. Myers, Newburgh, and Cannelton pools. Lastly, KDFWR compiled and processed all receiver data offloaded by partner agencies in the Ohio River.

*Indiana Department of Natural Resources (INDNR)*

During 2021, INDNR deployed a total of 30 new VR2 receivers in J.T. Myers (n = 13), Newburgh (n = 8), and Cannelton (n = 5) pools as well as at Cannelton L&D (n = 4). INDNR also tagged 300 Silver Carp in J.T. Myers (n = 118) and Newburgh (n = 182) pools. Data from receivers in J.T. Myers, Newburgh, and Cannelton pools were downloaded regularly by INDNR and sent to KDFWR for processing. All methods followed those described above.

*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 2021. 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, Racine, and Belleville pools as well as those located at the Willow Island, Belleville, Racine, and R.C. Byrd L&Ds during 2021. All data were sent to KDFWR for processing.

*US Fish and Wildlife (USFWS)*

During 2021, USFWS, Carterville FWCO, tagged a total of 317 Silver Carp in J.T. Myers (n = 108), Newburgh (n = 48), Cannelton (n = 92), McAlpine (n = 97), and Markland (n = 3) pools following the methods above. Additionally, the Carterville FWCO tagged 54 Silver Carp in the upper Wabash River to assist INDNR with understanding Silver Carp movement in the Wabash River Basin. The Carterville FWCO also used the data collected by state agencies and processed by KDFWR to parameterize a multistate model to better understand pool-to-pool transition probabilities for Silver Carps and tributary use for Silver and Bighead Carps (see methods above for details).

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

As described above, SIU deployed acoustic receivers throughout the Wabash and White rivers and tagged 282 Silver Carp in these areas during 2021.

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

During 2021, EIU conducted active tracking of acoustically tagged Silver Carp in the Wabash River during 2021 (see above for details).

**Results and Discussion:**

**Ohio River**

*Acoustic Receiver Array:* During 2021, 144 receivers were deployed from Olmsted Pool to Willow Island L&D (Figure 1, Table 1). Of these, 43 were deployed at L&Ds, 37 at mainstem sites, and 64 at tributary sites. The expansion of the receiver array into downstream pools where invasive carps are more abundant will improve our understanding of fish movements within and among pools and improve the ability of management agencies to understand the best times and areas for removal efforts to maximize efficiency of these management actions. Additionally, concurrent catfish telemetry studies led by the Ohio Department of Natural Resources and the West Virginia Division of Natural Resources in Meldahl and R.C. Byrd pools, respectively have led to increases in receiver coverage in these upstream pools, demonstrating the utility of maintaining a robust receiver array that can serve the needs of multiple natural resource management agencies.

*Fish Tagging Efforts:* As of December 2021, 1334 invasive carps (1288 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 2). Of the 1334 tagged carps, 16 Silver Carps have been harvested during the study (2013 – 2021). During 2021, 204 invasive carps (190 Silver and 14 Bighead) had tags that were expected to expire. To replace these tags (Table 2) and meet the needs of partner agencies, 192 Silver Carp were tagged in Cannelton (n = 92), McAlpine (n = 97), and Markland (n = 3) pools. No Bighead Carp were tagged during 2021 due to a lack of availability.

*Fish Detections:* There were 995 active tags deployed in invasive carps (985 Silver and 10 Bighead) in the Ohio River during 2021, 665 (67%) of which were detected (656 Silver and 9 Bighead). Active tags included those expected to be active during 2021 (n = 920) as well as those expected to expire prior to 2021 that were detected during 2021 (n = 75). Included in these 665 detected fish were 399 Silver Carp tagged in J.T. Myers, Newburgh, and Cannelton pools during 2021 indicating that the expansion of the receiver array and additional transmitter deployments in these high-density areas will result in a substantial amount of additional information about invasive carp movements and habitat use that will benefit managers by improving our knowledge of where and when these fish congregate and their propensity for moving among pools.

*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 228.7 km for Silver Carp and from 0.0 km to 226.9 km for Bighead Carp during 2021. The longest net movement by a Silver Carp was completed by a female fish travelling from Newburgh Pool to Smithland Pool during January – May. In contrast, the longest net movement by a Bighead Carp during 2021 was completed by a male fish that moved from Markland Pool to Meldahl Pool during July – August. Long-distance movements are relatively rare for Silver Carp; ~84% of Silver Carp had a maximum distance travelled of < 30 km during 2021. In contrast, only ~25% of Bighead Carp had a maximum distance travelled of < 30 km. Additionally, although detections of invasive carps above Greenup L&D were rare (~1% of total detections), the most upstream detections for Silver and Bighead Carp during 2021 occurred at river miles 247.9 and 258.2 in R.C. Byrd Pool, respectively.

Because there were relatively few detections of invasive carps in the pools upstream of Greenup L&D and most fish and receivers downstream of McAlpine L&D were either tagged or deployed during 2021, further analysis of fish movement during 2021 focused only on McAlpine, Markland, and Meldahl pools. In these pools, net movements are typically shortest during October – February and peak during summer (May – August) regardless of species or pool (Figures 2 and 3). These results are similar to those reported in previous years.

*Dam Passage*: Throughout the duration of this study (June 2013 – December 2021), there have been 134 dam passage events (47 upstream and 87 downstream passages) (Figure 4). Dam passages were completed by 83 Silver Carp and seven Bighead Carp. Of the upstream passages, six (12.8%) were completed by four Bighead Carp, with one fish accounting for three of those passages as it moved from Meldahl Pool to Racine Pool during May 2014 – August 2015. Forty-one upstream passages (87.2%) were completed by 35 Silver Carp. Six downstream passages (6.9%) were completed by five Bighead Carp, whereas 81 (93.1%) were completed by 69 Silver Carp. Additionally, in only 17 of the 134 dam passages (12.7%) 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 Meldahl, Markland, Newburgh, and J.T. Myers L&Ds during 2016 (n = 1; Silver Carp), 2017 (n = 1; Bighead Carp), 2019 (n = 1; Silver Carp), and 2021 (n = 14; Silver Carp). All confirmed lock chamber passages 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 may not be detected.

*Tributary Use*: During 2021, 92.3% of Silver Carp detections occurred in tributaries of the Ohio River, whereas 61.7% of detections of Bighead Carp occurred in these areas. Throughout the duration of this study (2013 – 2021), 81.4% of Silver Carp detections and 69.6% of Bighead Carp detections occurred in tributaries.

During June 2013 – December 2021, mainstem and tributary habitat use appeared to differ by species. For Silver Carp, the proportion of detections in tributaries far exceeded those in mainstem habitats, regardless of month. In contrast, a higher proportion of Bighead Carp detections occurred in mainstem habitat during August and September, but the proportion of tributary detections exceeded those in the mainstem Ohio River during all other months. The proportion of detections that occurred in mainstem habitat peaked during September – November for Silver Carp and during August – October for Bighead Carp (Figure 5). This is consistent with a greater proportion of transitions between tributary and mainstem habitat occurring during summer and autumn for both species. The proportion of transitions from mainstem to tributary habitats and vice versa are similar within months (Figure 6). Interestingly, the data also suggest that when Silver Carp enter tributaries, they reside there for a mean of 24.6 days (SE = 0.9 days) before returning to mainstem habitat. In contrast, Silver Carp reside in the mainstem Ohio River for a mean of 14.5 days (SE = 0.8 days) before returning to tributary habitat. Bighead Carp spend a similar amount of time between transitions in tributary (mean ± SE = 21.4 ± 4.2 days) and mainstem (18.9 ± 3.8 days) habitats (Figure 7). These data suggest that tributaries provide important habitat for invasive carps, especially Silver Carp.

*Model Results*: For Silver Carp, the variance inflation factor ($\hat{c}$) was 2.13. Model results were, therefore, adjusted to account for overdispersion and $QAIC_c$ values used to determine the most parsimonious models. $QAIC_c$ indicated that only two models had $\Delta AIC_c$ values $\leq 2$ (Table 3). These models included survival probabilities (S) that varied by month or season; detection and transition probabilities (p and $\psi$, respectively) varied based on the interactions of pool and month and pool and season, respectively. The QAIC weights of 0.59 and 0.41 for these models indicates a high degree of uncertainty in model selection and indicate that the highest-ranked model [S(month)p(pool * month)$\psi$(pool * season)] is only ~1.4 times better supported than the second-ranked model.

The mean probability of survival (S) of Silver Carp varied by month (Figure 8). Estimated mean survival probability was, however, high (0.93 – 1.00) in all months. Estimated monthly mean survival probabilities yielded a mean annual survival probability of 0.74 (95% Confidence Interval (CI) = 0.59 – 0.83). Because there are few documented cases of tagged Silver Carp being harvested from the Ohio River, the annual survival probability was used to estimate annual natural mortality (mean = 0.26, 95% CI = 0.17 – 0.41).

Estimated mean detection probabilities (p) were affected by the interaction of pool and month for Silver Carp and ranged from 0.00 to 1.00 (Figure 9). Detection probabilities were typically highest among pools in warmer months and lowest in cooler months. Furthermore, these probabilities tended to be low across months below McAlpine L&D and in Greenup pools and high in Meldahl and McAlpine pools. These discrepancies are likely due to few tagged fish present above Greenup L&D. Similarly, relatively few tagged fish and few receivers were present below McAlpine L&D through December 2020. During 2021, large numbers of Silver Carp (n = 548) were tagged in J.T. Myers, Newburgh, and Cannelton pools (Table 2). An additional 30 receivers were also added throughout these pools. The additional tagged fish and receivers should improve detection probabilities below McAlpine L&D for future analyses.

Model estimates of mean transition probabilities ($\psi$) varied with the interaction of pool and season and indicate that, with the exception of transitions from Greenup Pool to Meldahl Pool, transition probabilities among pools were low (< 0.2) and probabilities of remaining within a pool were high (> 0.8; Table 4). Mean transition probabilities were highly variable and could be exceptionally high from Greenup Pool to Meldahl Pool (0.177 – 0.615). Mean transition probabilities were often highest during winter and spring and lowest during summer (Table 4).

**Wabash River**

Twenty-eight VR2 receivers were deployed in the Wabash River and ten receivers were deployed in the White River during August 2021. In addition, a total of 282 transmitters were implanted into adult invasive carps in the Wabash and White rivers during May (58 transmitters) and October 2021 (224 transmitters). Because most fish were not tagged until Autumn, 2021, a relatively small amount of data was collected, and no analyses were completed during this time. Similarly, the small number of invasive carps implanted with acoustic transmitters in the Wabash River during the majority of 2021 limited the collection of habitat use data. Additional active tracking will occur during 2022 for analyses of patterns and timing of habitat use to inform removal efforts.

**Recommendations:**

Expansion of the receiver array and tagging efforts in J.T. Myers, Newburgh, and Cannelton pools during 2021 will improve our understanding of fish movements and transition probabilities in areas with high densities of invasive carps. Despite these improvements, 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, although Cannelton Pool is known to have a high density of invasive carps and is the longest navigation pool in the Ohio River (~114 miles), it has the fewest receivers deployed (n = 9) from J.T. Myers to R.C. Byrd pools. Additionally, receiver coverage in Cannelton Pool is primarily at the upstream and downstream ends of the pool, leaving a ~80 mile stretch of this pool without any receivers. Increasing receiver coverage in this area would not only improve our understanding of movement and habitat use of invasive carps, but would also inform Ohio River contracted harvest efforts that occur primarily within Cannelton Pool.

In addition to expanding receiver coverage in Cannelton Pool, additional receivers in Smithland and Olmsted pools (including Olmsted L&D) would improve our understanding of movements within the Ohio River mainstem system as well as between the Mississippi and Ohio rivers and the Ohio River and three of its major tributaries, the Wabash, Cumberland, and Tennessee rivers. Because these areas also 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?).

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.

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), however, can 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.

Further improvements to modeling the telemetry data are also recommended. First, because few fish are detected above Greenup L&D, parameters estimated for these areas (p and ψ) are based on few detections and are likely unreliable. Combining all strata above Greenup L&D would reduce the number of parameters estimated using low numbers of detections and potentially improve estimation of all model parameters. Furthermore, due to the increase in receiver coverage and the number of Silver Carp tagged in areas below McAlpine L&D, this stratum could be expanded into its component strata (e.g., below J.T. Myers, J.T. Myers, Newburgh, and Cannelton pools). Expansion of this stratum into its component strata would allow for estimation of survival, detection, and transition probabilities in areas with high densities of invasive carps. Although this will introduce additional parameters to the model, the large number of detections likely in these areas should minimize uncertainty in these parameter estimates. In addition to these improvements to the multi-state model, inclusion of an occupancy model based on detection data would improve our understanding of the habitat use of invasive carps. This type of model may also elucidate environmental drivers of fish movements between habitats (e.g., tributary and mainstem) as well as the timing of these movements. This information could be used to improve the efficiency of targeted removals of invasive carps by improving our ability to predict the timing and location of invasive carp aggregations.

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 each agency perform a download of all receivers in their areas of management and transfer the downloaded data to KDFWR by July 31, rather than December 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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Figures and Tables

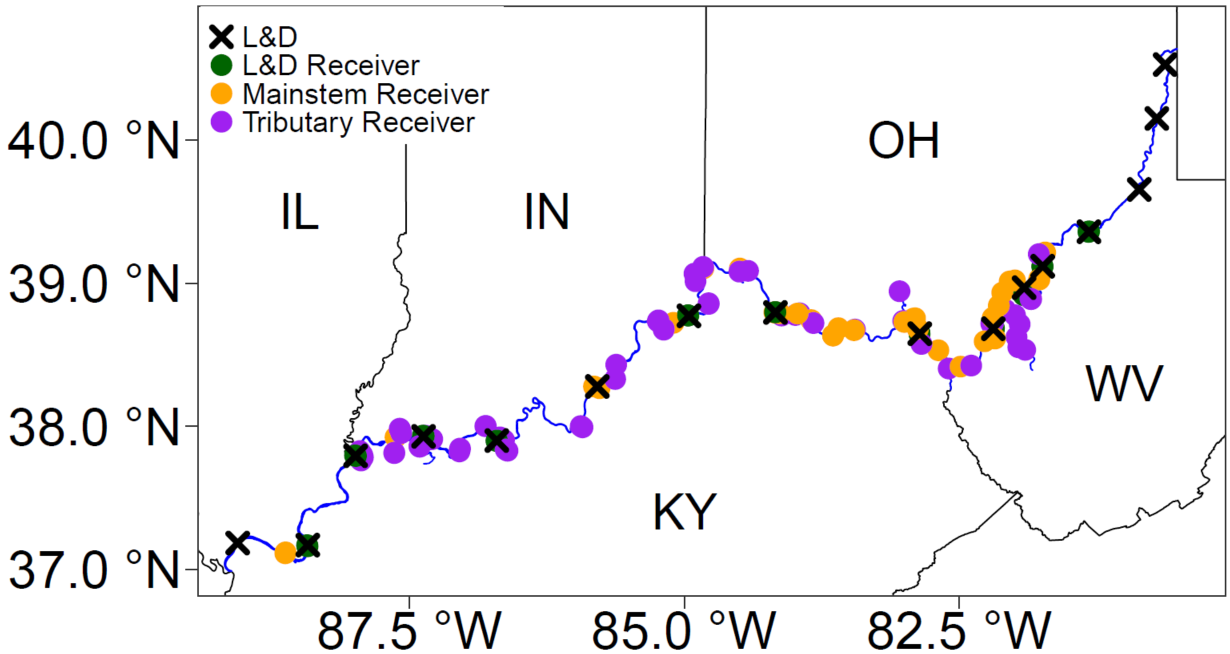


Figure 1. Locations of Lock and Dam structures (L&D; black crosses) and acoustic receivers deployed at L&D structures (green circles) and in the mainstem (orange circles) and tributaries (purple circles) of the Ohio River during 2021. Map shows the Ohio River (blue) from its confluence with the Mississippi River in the west to the Pennsylvania border in the east. Receivers were deployed from Olmsted Pool, downstream of the Smithland L&D, to the Willow Island L&D. From west to east, the L&Ds are Olmsted, Smithland, J.T. Myers, Newburgh, Cannelton, McAlpine, Markland, Meldahl, Greenup, R.C. Byrd, Racine, Belleville, Willow Island, Hannibal, Pike Island, and New Cumberland. Ohio River pools are named for the downstream L&D (e.g., Olmsted Pool begins at Olmsted L&D and ends at Smithland L&D).

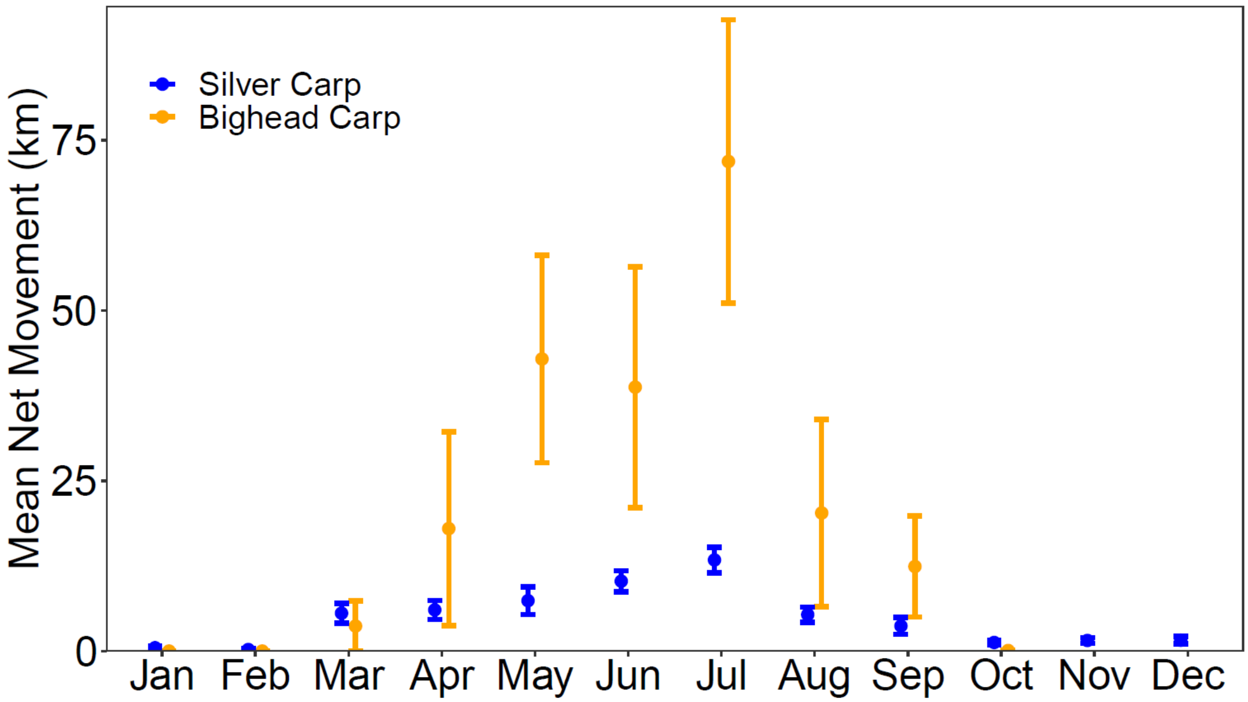


Figure 2. The mean monthly net movements (river kilometers) between the most upstream and downstream detections for tagged Silver Carp (blue) and Bighead Carp (orange) in McAlpine, Markland, and Meldahl pools during 2021. Error bars represent standard error. Only tagged carp detected ≥ 2 times during a month were included in the distance calculations.

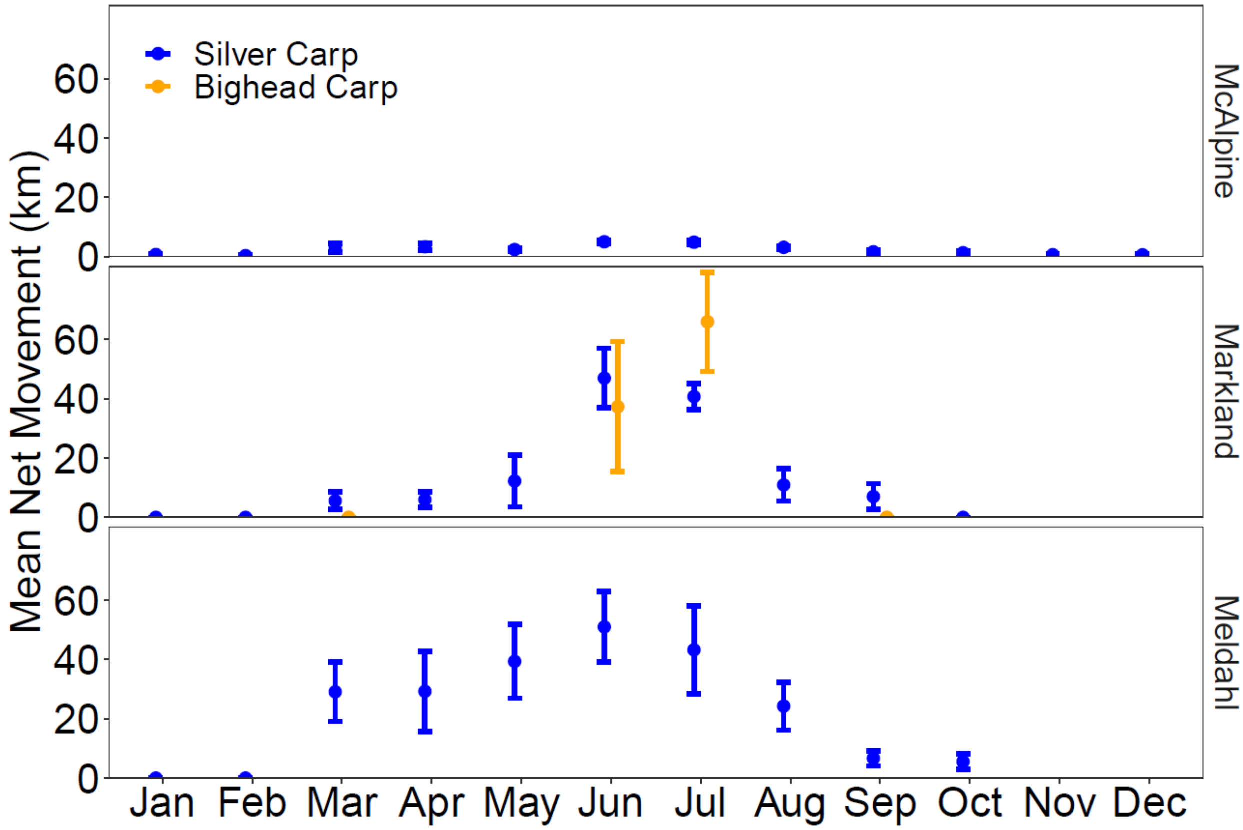


Figure 3. The mean monthly net movements (river kilometers) between the most upstream and downstream detections for tagged Silver Carp (blue) and Bighead Carp (orange) by pool in the three most active pools of the telemetry project (McAlpine, Markland, and Meldahl pools) during 2021. Error bars represent standard error. Only tagged carp detected ≥ 2 times within a single pool each month were included in the distance calculations.

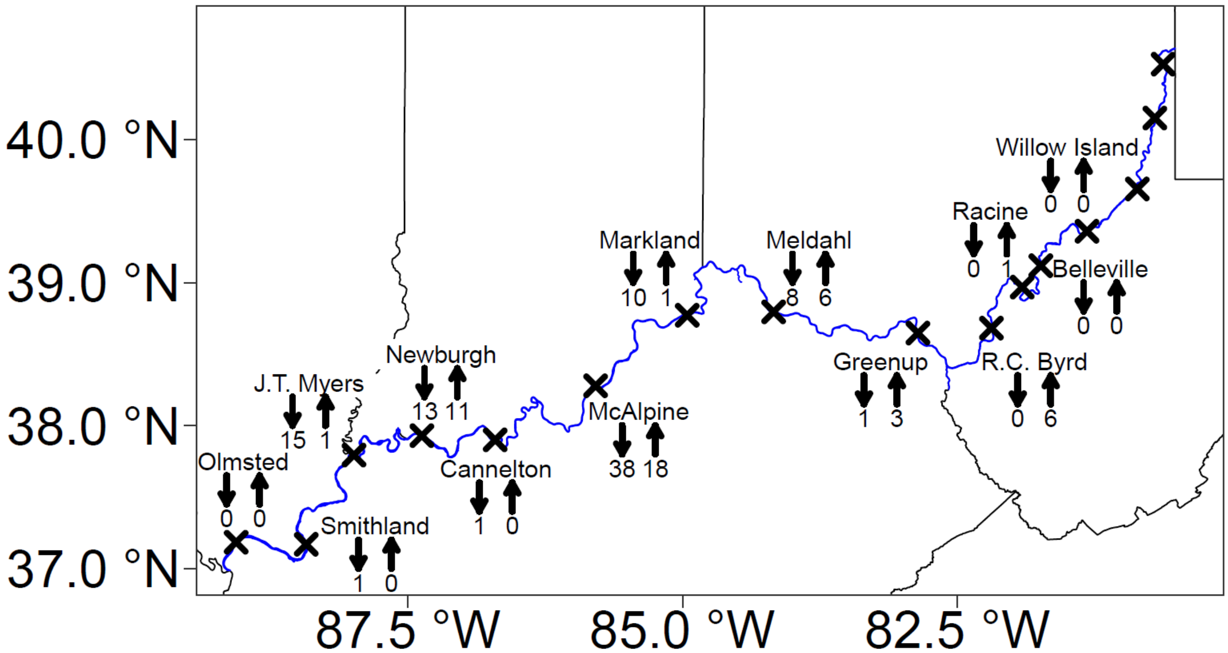


Figure 4. Total number of downstream (↓) and upstream (↑) lock and dam (L&D) passages by invasive carps during June 2013 – December 2021. Map shows passages from Olmsted L&D (river mile 964.4) near the confluence of the Ohio and Mississippi rivers to Willow Island L&D (river mile 161.7) which is the most upstream location at which acoustic receivers are deployed.

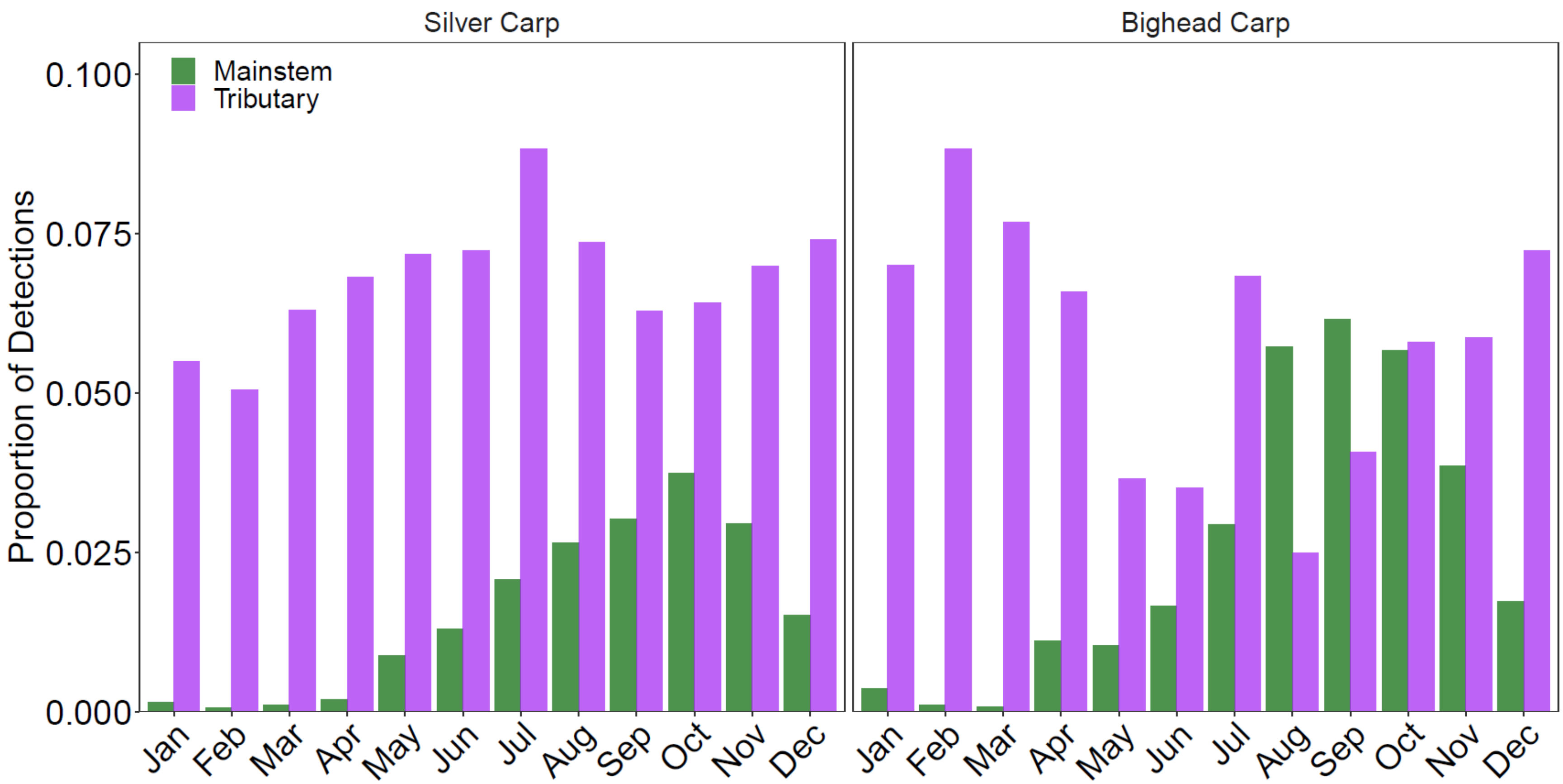


Figure 5. The proportion of detections by month for Silver (left) and Bighead (right) carps in mainstem (green) and tributary (purple) habitats of the Ohio River during June 2013 – December 2021.

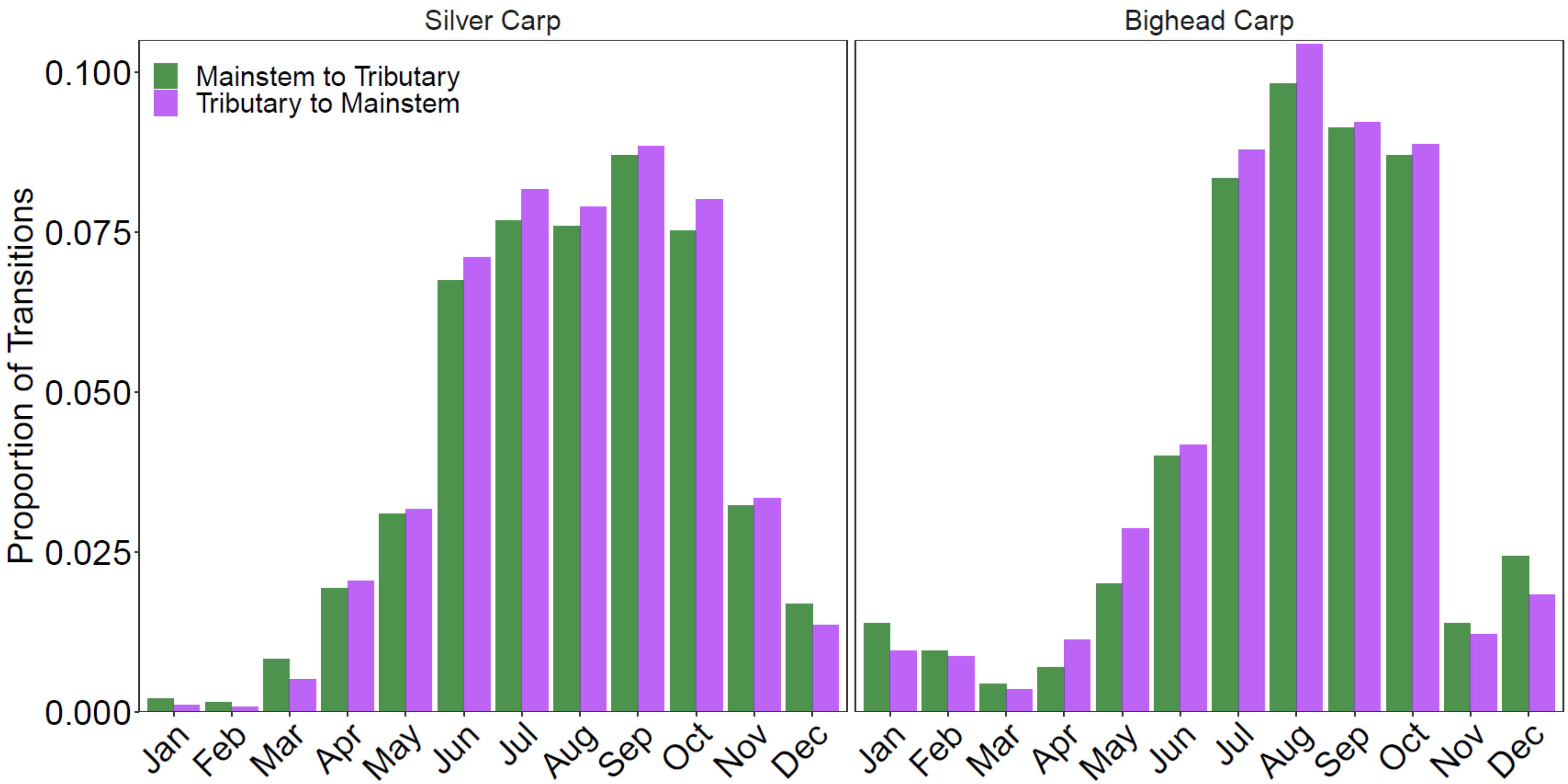


Figure 6. The proportion of transitions from mainstem to tributary (green) or from tributary to mainstem (purple) habitats by month for Silver (left) and Bighead (right) carps in the Ohio River during June 2013 – December 2021.

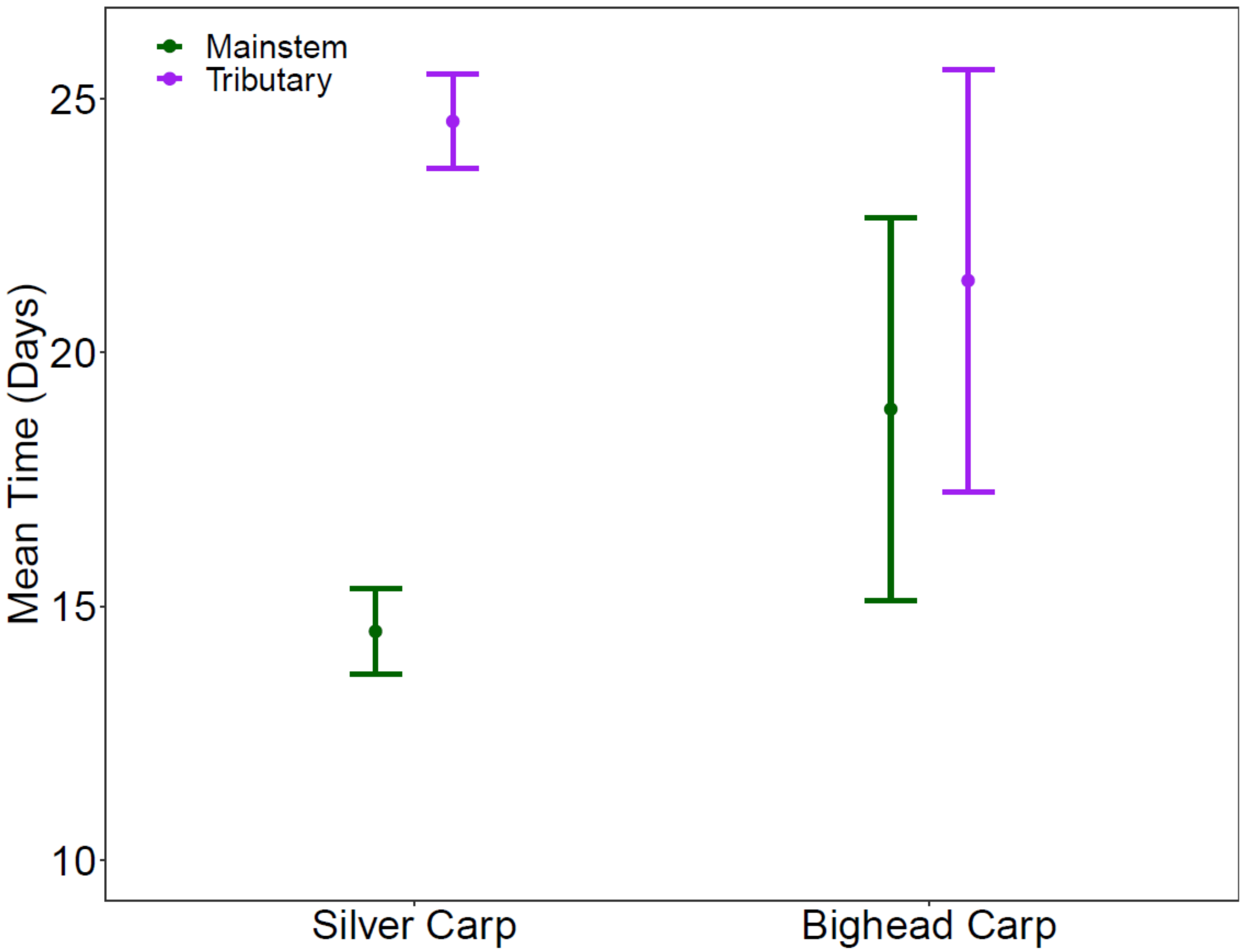


Figure 7. The mean time (days) spent in mainstem (green) or tributary (purple) habitat for Silver and Bighead Carps during June 2013 – December 2021. The number of days represents the time from the first detection of an individual in either the mainstem of the Ohio River or one of its tributaries to the first detection outside of that habitat.

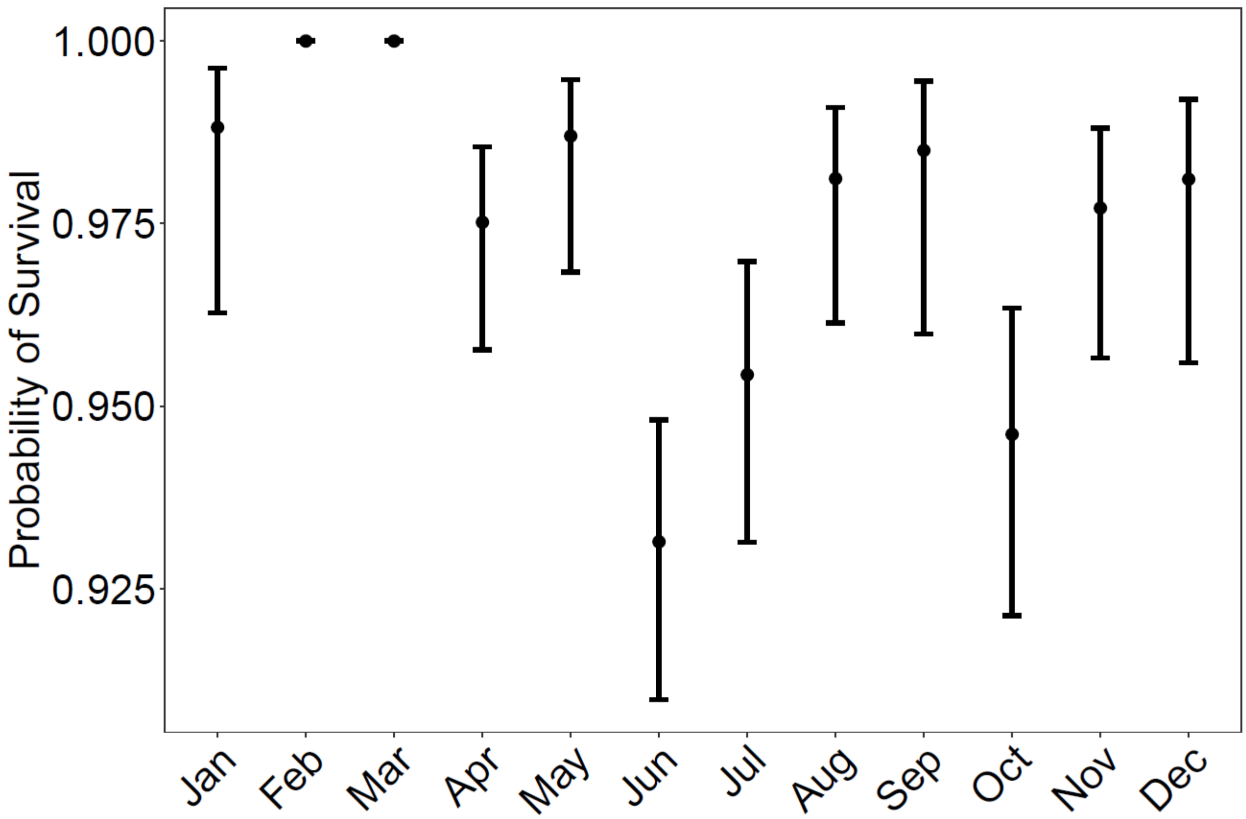


Figure 8. Mean monthly survival probabilities (S; filled circles) and 95% confidence intervals (error bars) for Silver Carp during June 2013 – December 2021.

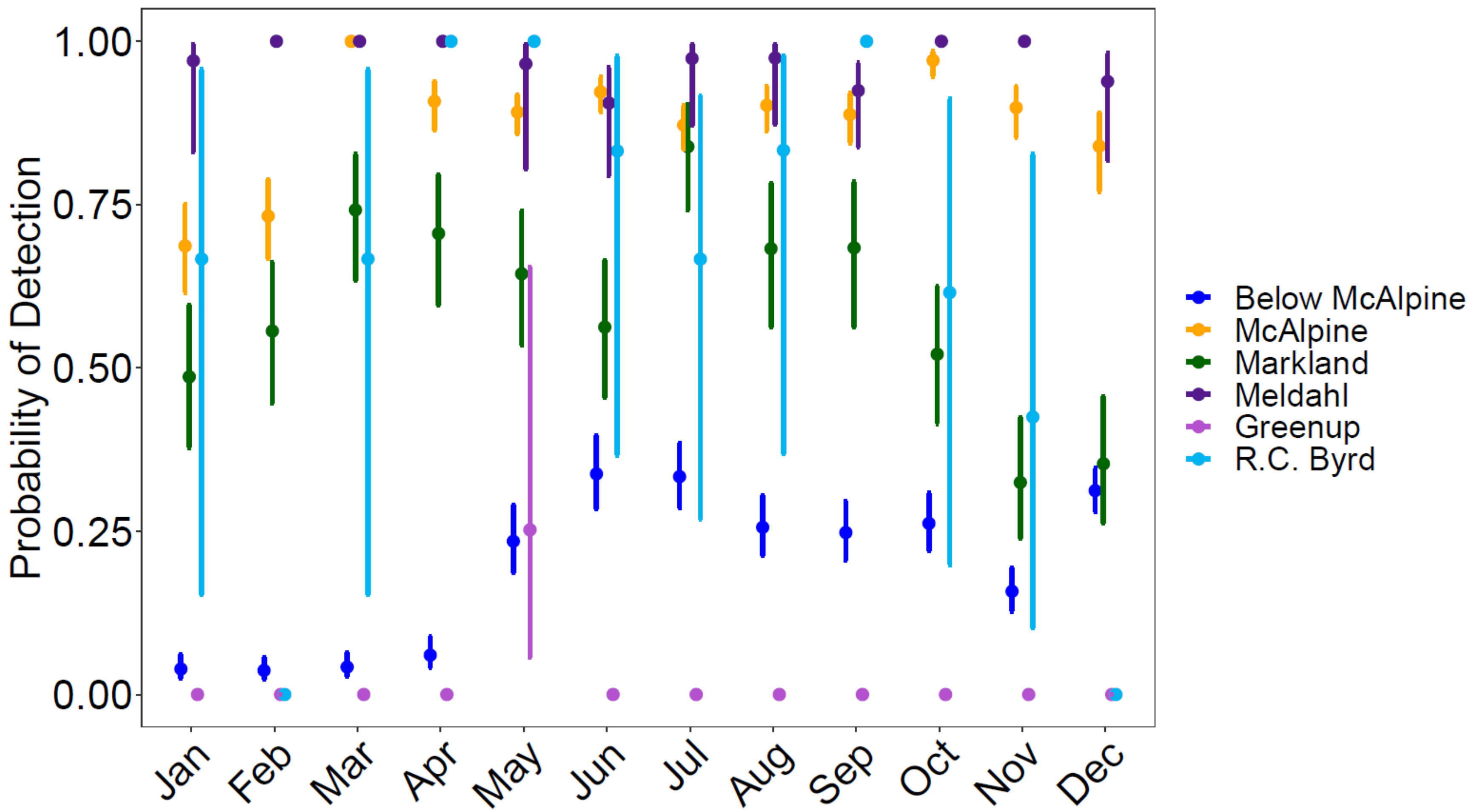


Figure 9. Model estimated monthly mean detection probabilities (p; filled circles) and 95% confidence intervals (error bars) in Ohio River navigation pools for Silver Carp tagged during June 2013 – December 2021. No Silver Carp were detected upstream of Racine Lock and Dam; therefore, detection probabilities were not estimated for pools upstream of R.C. Byrd Pool.

Table 1. Number and distribution of VR2 receivers in the Ohio River during 2021. One-hundred forty-four receivers were deployed from Olmsted pool, downstream of the Smithland lock and dam, to the Willow Island lock and dam.

| Ohio River Pool | Pool Length (km) | Lock and Dam | | Mainstem | | Tributary | | Total Sites per Pool (N) | Percent of Total Sites |
|---|---|---|---|---|---|---|---|---|---|
| | | Sites per Pool (N) | Sites per Pool (%) | Sites per Pool (N) | Sites per Pool (%) | Sites per Pool (N) | Sites per Pool (%) | | |
| Olmsted | 73.9 | 0 | 0.0 | 2 | 100.0 | 0 | 0.0 | 2 | 1.4 |
| Smithland | 116.7 | 7 | 100.0 | 0 | 0.0 | 0 | 0.0 | 7 | 4.8 |
| J.T. Myers | 112.5 | 4 | 21.1 | 1 | 5.3 | 14 | 73.7 | 19 | 13.1 |
| Newburgh | 89.2 | 4 | 33.3 | 0 | 0.0 | 8 | 66.7 | 12 | 8.3 |
| Cannelton | 183.3 | 1 | 11.1 | 1 | 11.1 | 7 | 77.8 | 9 | 6.2 |
| McAlpine | 121.2 | 3 | 27.3 | 2 | 18.2 | 6 | 54.5 | 11 | 7.6 |
| Markland | 153.4 | 4 | 26.7 | 4 | 26.7 | 7 | 46.7 | 15 | 10.3 |
| Meldahl | 153.2 | 4 | 16.0 | 14 | 56.0 | 7 | 28.0 | 25 | 17.2 |
| Greenup | 99.5 | 3 | 25.0 | 5 | 41.7 | 3 | 33.3 | 11 | 8.3 |
| R.C. Byrd | 67.1 | 4 | 23.5 | 5 | 29.4 | 8 | 47.1 | 17 | 11.7 |
| Racine | 54.1 | 4 | 50.0 | 2 | 25.0 | 2 | 25.0 | 8 | 5.5 |
| Belleville | 67.9 | 4 | 57.1 | 1 | 14.3 | 2 | 28.6 | 7 | 4.8 |
| Willow Island | 56.8 | 1 | 100.0 | 0 | 0.0 | 0 | 0.0 | 1 | 0.7 |
| Total | | 43 | | 37 | | 64 | | 144 | 100.0 |

Table 2: The number of Silver and Bighead Carp tagged with acoustic transmitters by year and pool during June 2013 – December 2021. 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) | Expected Status after 2021 | Species | Ohio River Pool | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | JT Myers | Newburgh | Cannelton | McAlpine | Markland | Meldahl | Greenup | RC Byrd | |
| 2013 | Inactive | SVC | - | - | - | - | - | 6 | - | - | 6 |
| | | BHC | - | - | - | - | - | 13 | - | - | 13 |
| 2014 | Inactive | SVC | - | - | - | 111 | 6 | 10 | - | - | 127 |
| | | BHC | - | - | - | 4 | 4 | - | - | - | 8 |
| 2015 | Inactive | SVC | - | - | - | 23 | 3 | 5 | - | - | 30 |
| | | BHC | - | - | - | 1 | 1 | 5 | - | - | 7 |
| 2016 | Inactive | SVC | - | - | 92 | 92 | 6 | - | - | - | 190 |
| | | BHC | - | - | 4 | 1 | 4 | 2 | - | 3 | 14 |
| 2017 | Active | SVC | - | - | 90 (14) | - | 12 (1) | 3 | - | - | 105 |
| | | BHC | - | - | - | - | 2 | - | - | - | 2 |
| 2018 | Active | SVC | - | - | - | - | 21 | 10 | - | - | 31 |
| | | BHC | - | - | - | - | - | 1 | - | - | 1 |
| 2019 | Active | SVC | - | - | - | 30 | - | - | - | - | 30 |
| | | BHC | - | - | - | 1 | - | - | - | - | 1 |
| 2020 | Active | SVC | - | - | - | 100 (1) | 18 | - | - | - | 118 |
| | | BHC | - | - | - | - | - | - | - | - | 0 |
| 2021 | Active | SVC | 226 | 230 | 92 | 97 | 3 | - | - | - | 648 |
| | | BHC | - | - | - | - | - | - | - | - | 0 |
| 2017-2021 | Active | SVC | 226 | 230 | 168 | 226 | 53 | 13 | - | - | 916 |
| | | BHC | - | - | - | 1 | 2 | 1 | - | - | 4 |
| | | Overall | 226 | 230 | 168 | 227 | 55 | 14 | - | - | 920 |
| 2013-2016 (Including harvested) | Inactive | SVC | - | - | 106 | 227 | 16 | 21 | - | - | 370 |
| | | BHC | - | - | 4 | 6 | 9 | 20 | - | 3 | 42 |
| | | Overall | - | - | 110 | 235 | 25 | 41 | - | 3 | 414 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| % Species Composition (2017-2021) | Active | SVC | 24.6 | 25.0 | 18.3 | 24.6 | 5.8 | 1.4 | 0.0 | 0.0 | 99.6 |
| | | BHC | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.1 | 0.0 | 0.0 | 0.4 |
| | | Overall | 24.6 | 25.0 | 18.3 | 24.7 | 6.0 | 1.5 | 0.0 | 0.0 | 100.0 |
| Mean Total Length (mm) (2013-2021) | Combined | SVC | 699.7 | 708.5 | 796.9 | 818.7 | 894.9 | 952.5 | - | - | 782.8 |
| | | BHC | - | - | 1139.8 | 1169.0 | 1175.1 | 1154.5 | - | 1210 | 1160.1 |

Table 3. Model selection results for the multi-state with live recaptures model for Silver Carp. The table shows the model structure, $QAIC_c$, $\Delta QAIC_c$, and the QAIC weight for two best-supported models. The covariates affecting estimates of the probabilities of survival (S), detection (p) and transition (ψ) are shown in parentheses for each model.

| **Model** | **$QAIC_c$** | **$\Delta QAIC_c$** | **QAIC weight** |
|---|---|---|---|
| $S(month)p(pool * month)\psi(pool * season)$ | 9143.90 | 0.00 | 0.59 |
| $S(season)p(pool * month)\psi(pool * season)$ | 9144.62 | 0.71 | 0.41 |

Table 4. Model-estimated mean (95% confidence intervals) pool-to-pool transition probabilities (ψ) of Silver Carp in the Ohio River derived from acoustic telemetry during June 2013 – December 2021. The highest-ranked model for Silver Carp included the interactive effect of pool and season on transition rates. Black-shaded cells represent transitions among non-adjacent pools for which there were no observations. 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 Carp were detected above Racine Lock and Dam. Therefore, transition probabilities were not estimated for pools upstream of R.C. Byrd Pool.

| | Destination Pool | | | | | |
|---|---|---|---|---|---|---|
| **Departure Pool** | Below McAlpine | McAlpine | Markland | Meldahl | Greenup | R.C. Byrd |
| **Spring** | | | | | | |
| Below McAlpine | 0.765 (0.739 – 0.789) | 0.235 (0.211 – 0.261) | | | | |
| McAlpine | 0.034 (0.023 – 0.049) | 0.966 (0.945 – 0.977) | 0.000 (0.000 – 0.006) | | | |
| Markland | | 0.006 (0.001 – 0.040) | 0.986 (0.929 – 0.997) | 0.008 (0.002 – 0.031) | | |
| Meldahl | | | 0.000 (0.000 – 0.000) | 0.957 (0.900 – 0.983) | 0.043 (0.017 – 0.100) | 0.000 (0.000 – 0.000) |
| Greenup | | | | 0.615 (0.426 – 0.774) | 0.285 (0.000 – 0.542) | 0.100 (0.032 – 0.271) |
| R.C. Byrd | | | | | 0.000 (0.000 – 0.000) | 1.000 (1.000 – 1.000) |
| **Summer** | | | | | | |
| Below McAlpine | 0.977 (0.963 – 0.986) | 0.023 (0.014 – 0.037) | | | | |
| McAlpine | 0.053 (0.040 – 0.070) | 0.947 (0.925 – 0.960) | 0.000 (0.000 – 0.005) | | | |
| Markland | | 0.004 (0.000 – 0.030) | 0.996 (0.970 – 1.000) | 0.000 (0.000 – 0.000) | | |
| Meldahl | | | 0.004 (0.000 – 0.030) | 0.985 (0.907 – 0.998) | 0.011 (0.002 – 0.063) | 0.000 (0.000 – 0.000) |
| Greenup | | | | 0.313 (0.035 – 0.851) | 0.687 (0.149 – 0.965) | 0.000 (0.000 – 0.000) |
| R.C. Byrd | | | | | 0.000 (0.000 – 0.000) | 1.000 (1.000 – 1.000) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Autumn** | | | | | | |
| Below McAlpine | 0.977 (0.961 – 0.987) | 0.023 (0.013 – 0.039) | | | | |
| McAlpine | 0.128 (0.106 – 0.154) | 0.872 (0.846 – 0.894) | 0.000 (0.000 – 0.000) | | | |
| Markland | | 0.018 (0.007 – 0.045) | 0.982 (0.955 – 0.993) | 0.000 (0.000 – 0.000) | | |
| Meldahl | | | 0.000 (0.000 – 0.000) | 0.904 (0.853 – 0.939) | 0.096 (0.061 – 0.147) | 0.000 (0.000 – 0.000) |
| Greenup | | | | 0.232 (0.097 – 0.459) | 0.768 (0.541 – 0.903) | 0.000 (0.000 – 0.000) |
| R.C. Byrd | | | | | 0.000 (0.000 – 0.000) | 1.000 (1.000 – 1.000) |
| **Winter** | | | | | | |
| Below McAlpine | 0.942 (0.924 – 0.956) | 0.058 (0.044 – 0.076) | | | | |
| McAlpine | 0.140 (0.117 – 0.167) | 0.860 (0.833 – 0.883) | 0.000 (0.000 – 0.000) | | | |
| Markland | | 0.000 (0.000 – 0.000) | 1.000 (0.000 – 1.000) | 0.000 (0.000 – 1.000) | | |
| Meldahl | | | 0.010 (0.003 – 0.041) | 0.939 (0.864 – 0.971) | 0.051 (0.026 – 0.095) | 0.000 (0.000 – 0.000) |
| Greenup | | | | 0.177 (0.086 – 0.331) | 0.823 (0.669 – 0.914) | 0.000 (0.000 – 0.000) |
| R.C. Byrd | | | | | 0.000 (0.000 – 0.000) | 1.000 (1.000 – 1.000) |