Evaluating the spatial and temporal distribution and ecology of Bighead and Silver Carp and native fishes of the lower Red River basin

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Photo Credit: S. Brewer

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EXECUTIVE SUMMARY

We investigated the spatial and temporal distribution of Bighead Carp and Silver Carp (hereafter Carp) in the lower Red River basin of Arkansas. Our study objectives were: 1) determine the spatial and temporal extent of Bighead and Silver Carp in the Red River basin of Arkansas; 2) determine habitat associations of large river fish assemblages; and 3) summarize the demographics of Bighead and Silver Carp. We sampled 67 reaches in the lower Red River and its major tributaries for juvenile Carp and other small-bodied fishes (24 of the reaches were in the Arkansas portion of the Red River). We conducted repeated surveys in these reaches where the reaches were sampled 2-3 times over approximately 2 years representing 242 surveys (95 surveys in Arkansas). We completed adult Carp and native fish assemblage sampling across 61 reaches (22 reaches in Arkansas) where we also repeated surveys at these locations (245 total surveys, 100 surveys completed in Arkansas during the reporting period). We captured the most large-bodied fishes (including Carp) using gillnets and electrofishing, whereas fyke nets and seine hauls collected mainly smaller-bodied fishes. Hoop nets captured fewer fishes when compared to other gear types. We sampled 120,072 fishes, comprising 70 species and 41 genera, from the mainstem Red River in Arkansas. We used data associated with the entire catchment (including OK and TX data) to model the occupancy of adult fishes including both carp species. Carp tended to occupy reaches with the presence of slackwater habitat, that were deeper and narrower (lower habitat complexity), with higher discharge conditions, and were positively associated with chlorophyll-a concentrations. Adult and juvenile assemblage structure varied with reach scale attributes with notable differences among some taxonomically similar species. No carp under the age of 3 were sampled in the catchment. Bighead Carp and Silver Carp in the Red River catchment appear to live longer and grow larger than other populations. Silver Carp and Bighead Carp in the lower Red River had a theoretical maximum length (L_∞) of 920 and 1,348-mm TL, respectively. The oldest sampled Silver Carp and Bighead Carp were age 14 and 17, respectively. Bighead Carp growth was positively associated with warmer air temperatures and negatively associated with discharge variability. Similarly, Silver Carp growth was positively associated with warm air temperature and negatively associated with discharge variability. However, Silver Carp growth was also positively related to high discharge conditions

and the variability of air temperature. Silver Carp annual mortality was relatively low and recruitment into the population appeared steady. It appears that Carp are likely coming from another catchment, have only limited or periodic successful reproduction in the study area, or spawn downriver in LA. Continued monitoring for reproductive success would be helpful. Moreover, if the goal is to greatly reduce or eliminate carp, then strategies that prevent further immigration before reproduction occurs or becomes more successful would be ideal. Targeted removal may then be useful for reducing numbers already in the catchment; however, there are also oxbow lakes that contain carp but appear only connected to the river during major floods (i.e., possible source locations).

BACKGROUND

Freshwater ecosystems are among the most biodiverse systems on earth; however, they may also be the most endangered (Reid et al. 2019). Despite covering only 2.3% of the Earth's surface, freshwater ecosystems account for 9.5% (126,000 species) of described animal species (Balian et al. 2008). Dudgeon et al. (2006) lists over-exploitation, flow modification, water pollution, habitat-degradation, and invasive species as the five major threats to biodiversity. Invasive species, or introduced non-native species that are able to survive to recruitment, reproduce across a variety of habitats, and expand their ranges to locations outside of where they were first introduced are of particular concern (Blackburn et al. 2011). Invasive species are of concern because they alter food web interactions, compete with other species for space and resources, and can ultimately change native species assemblage structure (Carey and Wahl 2010). As such, there is a need to understand population demographics of invasive species and the spatial and temporal extent to which they occur.

Two species emblematic of the concerns caused by invasive species are Bighead Carp (BHC) *Hypopthalmichthys nobilis* and Silver Carp (SVC) *Hypopthalmichthys nobilis* (hereafter Carp). In areas where they have been introduced, Carp cause ecological (Schrank et al. 2003; Irons et al. 2007; Sampson et al. 2009), economic (Lovell et al. 2006), and safety (Vetter et al. 2015) concerns. Since their detection in the 1970's (Freeze and Henderson 1982; Kelly et al. 2011), Carp have proliferated and been reported in 23 states (Kolar et al. 2005). One of the reasons Carp have been so successful is because they are filter feeders (Williamson and Garvey

2005), and both species have been linked to declines in phytoplankton and zooplankton abundances (Irons et al. 2011; Sass et al. 2014; Cooke 2016). Carp affect fish populations through interspecific competition and depletion of resources (Schrank et al. 2003; Sampson et al. 2009). As a result, Carp are often linked to declines in native fish diversity and densities (Kolar et al. 2007) including the recruitment of native juvenile fishes (Chick et al. 2020b). In addition to their ecological effects, Carp are also projected to relate to future economic declines. For example, the Carp invasion in Lake Michigan is projected to result in a 7 billion dollar loss via commercial fisheries revenue (Buck et al. 2010). Lastly, Carp pose threats to human safety due to their penchant to launch themselves out of the water often causing serious injuries to boaters (Spacapan et al. 2016).

The climate of the Great Plains ecoregion is extreme, fluctuating between floods and droughts; thus, providing a unique opportunity to study species assemblage structure and population dynamics of both native and invasive fishes. The Red River basin is characterized by extreme floods and droughts (Matthews and Marsh-Matthews 2007), and large conductivity fluctuations (Hargrave and Taylor 2010a). Carp occur in the lower Red River basin; however, there has not been recent, extensive sampling targeting Carp or native fishes. Therefore, examining Carp population demographics and occupancy along with native fishes is an important first step to determining how best to manage the expansion of non-native fishes in the lower basin. Our specific study objectives were to determine 1) the spatial and temporal extent of Bighead and Silver Carp in the lower Red River basin, 2) habitat associations of large river fish assemblages, and 3) to summarize the population demographics of Bighead and Silver Carp in the lower Red River basin.

METHODS

Objective 1. Determine the spatial and temporal extent of Bighead Carp and Silver Carp in the lower Red River basin

Juvenile fish sampling

Of the total 67 reaches sampled for juvenile fishes in 2021 and 2022, 24 occurred in the Arkansas portion of the Red River (Table 1) with each reach being approximately 300-m in length. Although some juvenile sampling occurred in the winter, our occupancy modeling design consists of only data collected during the period that we defined as the juvenile warm-water season from May through early October 2021-2022. Our sample season was chosen to detect both juvenile fishes of Carp, if present, and to meet the closure assumption (i.e., if a species was detected, it was assumed present at that site for the duration of the season). Our sample reaches (hereafter sites) were distributed across the mainstem Red River (Figure 1) and were designed to target juvenile Carps. Sites were selected based on river access, proximity to U.S. Geological Survey (USGS) streamgages, and the likelihood of detection of the target species. Our sites were selected approximately 25-100 km downriver of major dams and confluences because this is the suggested length of river needed to allow Carp eggs to develop and hatch while in suspension (Kolar et al. 2007; Garcia et al. 2015). Our sample sites included slackwater habitats such as forewaters, backwaters, side channels, sandbars, and pool complexes. Slackwater habitats are thought to be important nursery areas for a variety of juvenile fishes including Bighead Carp and Silver Carp (Jurajda 1999; Love et al. 2017; George et al. 2018). Furthermore, discharge and temperature conditions are similar across these areas, and the areas are large enough to be considered closed to species immigrations (i.e., not individuals) during our sampling periods.

We attempted to sample age-0 Carps using three different gear types during daylight hours. Using a combination of gears diminishes some of the sample bias associated with a single gear approach (Clark et al. 2007). For example, passive gears tend to target more active individuals (Fago 1998). At each site, we set mini-fyke nets, sampled using beach seines, and conducted larval tows (see Table 2 for gear descriptions). First, we set 3 mini-fyke nets in <2 m of water at locations adjacent to the shoreline to target small-bodied fishes (Eggleton et al. 2010). Mini-fyke nets are commonly used to sample age-0 Carps (Wanner and Klumb 2009; Gibson-Reinemer et al. 2017; Williams 2020) and sometimes capture high numbers compared to other gears (Collins et al. 2017). Next, a beach seine was used to sample wadeable habitat across the reach using a modified version of the encirclement technique (Bayley and Herendeen 2000). Transects were established throughout wadeable habitat at each site and seine hauls were completed across each transect. Seine hauls were limited to 25 m to maintain the efficiency of the gear because longer hauls are less efficient (Lombardi et al. 2014).We quantified total seine distance, seine width, and maximum depth for each haul to estimate the area sampled. We completed a sub-surface larval tow at representative locations of deeper water (i.e., where we could not seine or place fyke nets). Each tow was pulled for 10 min and the volume of water sampled was quantified using a flow meter (General Oceanics Mechanical Flowmeter Model 2030R) attached to the mouth of the net. We standardized larval tows based on the volume of water filtered by the net. Any samples that could not be identified in the field were preserved in 70% ethanol and brought back to the lab for processing.

Juvenile fish habitat

We quantified the physicochemical factors that may be related to Carp or native fish distributions across multiple spatial scales (i.e., reach, segment, and catchment). The physicochemical factors are divided into detection (Table 3) and occupancy (Table 4) covariates. Stream habitat use by fishes is hierarchical where finer levels of organization are nested within coarser landscape constraints (Frissell et al. 1986; Imhof et al. 1996). Coarse scale (e.g., segment and catchment) habitat factors are applied to multiple reaches that occur within the same stream segment or catchment (i.e., nested). For example, finer-scale channel unit conditions (i.e., pH and substrate) used by fish are often influenced by coarse factors (i.e., drainage area and geology) of the surrounding watershed (Mollenhauer et al. 2019). Including coarse-scale habitat factors helps explain fish distributions and account for pseudoreplication inherent in the nested structure of sampling riverine sites (i.e., sites closer in proximity are naturally more similar than sites further away).

We measured several factors across each sample site that described the general water-quality conditions. First, we collected temperature and dissolved oxygen samples at 0.5 m below the water's surface for each site using a multi-parameter water-quality meter (YSI ProDSS). We collected salinity from a well-mixed location of each site approximately 0.5m below the surface. We also measured water clarity using a Secchi disk, because turbidity can influence resource use, foraging success, and even provide shelter from predators (Zamor and Grossman 2007; Reichert et al. 2010). To characterize the general conditions of each site, we measured all water-quality parameters three times in each site and averaged these values.

We also quantified the proportion of select channel unit features in each site. Because forewater and backwater habitat are often important nursery habitat for many large river fishes (Galat et al. 2004), we quantified the area of each using a meter tape or rangefinder (Simmons Volt 600 Laser Rangefinder) to measure length and average width. Other slackwater areas such as pools offer low-velocity areas in the main channel (Schwartz and Herricks 2005); therefore, we measured pool area using side-scan sonar (Humminbird Helix 12). The proportion of each of the slackwater channel units was expressed as a proportion of the available habitat in each site. Because age-0 Carp are associated with large woody debris in some systems (George et al. 2018), we also used side-scan sonar to quantify the percentage of large woody debris following the methods of Gordon et al. (1992).

We quantified several hydraulic variables to describe the fluvial dynamics of our sampling sites. Species often use specific depths within a water column (Lamouroux et al. 1998); therefore, we quantified the average thalweg depth by measuring depth at 10-m increments along the thalweg of the site using side-scan sonar. Further, because the shape of the channel dictates habitat availability (Thomson et al. 2001), we quantified width to depth ratios in each site. We measured three representative wetted width measurements using a rangefinder. The average thalweg depth of the site was then divided by the average widths. We also obtained discharge data from the nearest USGS streamgages to apply to sampling sites within the same stream segments to examine both detection and occupancy.

Some habitat metrics were quantified using existing geospatial data. At the reach-scale, we quantified distance to the nearest dam by measuring the distance from the most downstream point of our sites to the nearest upstream using National Hydrology Dataset (NHDplus) flowlines and ArcMap spatial analyst. We also measured the distance from our sites and the nearest upstream 5th-order tributary. Areas below dams and major tributary confluences are potential spawning locations for Carp species (Kolar et al. 2007; George et al. 2018; Camacho et al. 2020).

At the stream segment scale, we calculated stream sinuosity and slope. Sinuosity (i.e., channel migration of meandering rivers) affects fish habitat use including choice of spawning location (Fukushima 2001; Lazarus and Constantine 2013) and was calculated by dividing the thalweg length by the straight line distance of the segment. (Camana et al. 2016). We calculated river slope using ArcMap spatial analysis to determine the change in elevation between the upstream and downstream points of each stream segment and divide by the thalweg length (i.e., channel distance measured down the middle of the channel, Bain and Stevenson 1999).

We also measured several habitat variables that may affect fish distributions at the catchment scale. We measured the drainage area (km^2) upstream of each site (i.e., catchment draining to each site) using NHDplus flow lines to determine the size and relative position of sites within the network. Because catchment lithology controls many local physicochemical conditions (Frissell et al. 1986; Stevenson 1997), we quantified the dominant lithology (e.g., limestone) upstream of each site. We also quantified landscape disturbance (hereafter LDI) following Brown and Vivas (2005) using the 2021 National Land Cover Dataset (further NLCD; Dewitz 2021) and a modification of Mouser et al. (2019) (see below). Human land-use modifications can disproportionately affect the quality and quantity of riverine nursery habitat (Schlosser 1995; Rochette et al. 2010; Britton and Pegg 2011). However, land-cover types tend to be multicollinear because they sum to 100% (Ainiyah et al. 2016); thus, combining land cover into a single index is helpful when analyzing data using multiple regression scenarios (Genovese et al. 2001). Therefore, we characterized the level of LDI following a modification of Brown and Vivas (2005) provided by Mouser et al. (2019).

Adult fish sampling

Of the 61 reaches sampled throughout the catchment for adult Carp during the reporting period, 22 were in the Arkansas portion of the Red River (Table 1). A total of 245 surveys were completed in the catchment, with 100 surveys occurring in Arkansas. Although sampling was conducted year-round, our data collected during the cold-water season (October through March) were insufficient for occupancy modeling due to the limited number of repeated surveys as low water levels made access extremely difficult. As such, our occupancy modeling for adult Carp and native adult fishes included only data from surveys conducted during the adult warm-water season (April through September). Thus, for occupancy modeling we included data collected from 43 unique reaches (14 located in Arkansas), comprising 137 surveys (45 in Arkansas). Each reach was approximately 1.5 to 2.0 river km (rkm) (hereafter sites) and sampled 1-3 times. Access can be problematic on the Red River and thus, sites were selected based on accessibility (i.e., access to private lands and conditions conducive to boat launching) (Figure 2).

We sampled fishes using a combination of gillnets, hoop nets, and electrofishing because they have been shown useful for sampling. both Bighead and Silver Carps in perceived low-density environments (Norman and Whitledge 2015; Butler et al. 2019). Three experimental sinking gillnets (54.8-m long for mainstem and 30.5-m long for tributary sampling with 8.9, 10.16, and 10.8-cm bar-length mesh panels) and three hoop nets (4.88-m long with a 1.2-m diameter opening) were placed throughout each site (Table 2). Gillnets were deployed perpendicular to the shoreline with one placed near each end of the reach and the third net placed in the middle of the reach at the narrowest portion of the channel to restrict Carp movement. Hoop nets were placed parallel to the shoreline with the opening facing downstream in locations that included channel edges and channel crossovers but lacking extensive woody debris. After net placement, we electrofished using an 80-amp Midwest Lakes Electrofishing Systems shocking unit (Polo, Missouri). We used standard AFS electrofishing settings based on conductivity (though we tried several others- see below). Water conductivity in the tributaries was much lower than the mainstem Red River. As such, voltage was set to high range (pulsed DC current, >300 volts, 60Hz) for tributaries and low range (pulsed DC current, <300 volts, 60Hz) for the main stem Red River sites. Beginning at the upriver end of the site, the boat traversed downstream in a cloverleaf pattern with electrical current applied for 10-sec with 5-sec "off peddle" intervals to increase the effectiveness of capturing Silver Carp and to attempt to drive fish into the nets and shoreline (Bouska et al. 2017). Electrofishing continued until the entirety of the reach was sampled.

Before we established our electrofishing protocol, we used several electrofishing settings at sites where Carp were observed on previous occasions. During experimental electrofishing trials, we used pulsed DC current at both low and high frequencies, with Hz ranging from 15 to 60 and a target amperage of 4 and 20, respectively. Boat electrofishing was also used to drive Carp into set nets. Both gillnets and hoop nets were then removed after six hours post-placement. All Carp collected during our sampling events were euthanized. Total length (mm, +/- 1 mm), and weight (g, +/- 10 g), were recorded for captured Carp, except for a few captured while our scale was malfunctioning.

Adult fish habitat

We quantified the physicochemical factors that may be related to Carp distributions across multiple spatial scales. We quantified habitat factors at the catchment, segment, and reach scales. The habitat factors were either collected in the field or obtained using existing geospatial data (Table 5). We assessed habitat use using an occupancy modeling framework. Our warm-water season was defined as April through September where we could reasonably assume each site (sampling reach, defined as a 1.5 – 2.0 rkm section) was closed to changes in Silver Carp or Bighead Carp occupancy (i.e., if the species was present, then it was assumed present for the season, though individuals may move back and forth from the site) (Mackenzie et al. 2005). We defined the season using the species' biology and associated water temperature. Silver Carp remain relatively stationary during the summer months (Coulter et al. 2016a) and are hypothesized to spawn at water temperatures above 18 °C (Nico et al. 2022). Therefore, we established the season as April through September based on historical water temperature trends (Figure 3). We conducted repeated fish surveys (see Adult fish sampling) using multiple gears where our surveys were temporally replicated over the warm season during a two–year sampling period (2021 – 2022).

The habitat factors operating at the catchment scale that may be related to Carp occurrence were drainage area, disturbance, and lithology (Table 5). Drainage area (km^2) is a coarse scale habitat factor that influences fish distributions, assemblage structure, and species richness (Newall and Magnuson 1999; Osborne and Wiley 1992; Griffiths 2018). We used the National Hydrography Database Plus (NHDplus) (https://apps.nationalmap.gov/downloader/#/) flow lines in ArcGIS Pro (version 3.0.1, Esri, Redlands, CA) to delineate each catchment (i.e., the entire upstream area that drains to the site) using the watershed tool and quantified the area of each catchment. Disturbance can affect assemblage structure and distribution by altering nutrient flow and habitat availability, and lead to decreased diversity throughout multiple trophic levels (Scrimgeour et al. 2008; Wang et al. 2008; Johnson and Angeler 2014). We used ArcGIS Pro to quantify the area of each land use type in each catchment using the National Land Cover Database (NLCD) and previously calculated drainage areas. Each land type was assigned the corresponding disturbance value from the Landscape Development Index (LDI) (Brown and Vivas 2005). However, in instances where the land-cover type applied to multiple LDI coefficients (e.g., multiple types of agriculture land), we calculated the average of the relative LDI coefficients. We multiplied the proportion of each land type in the catchment by the assigned LDI value to quantify the overall disturbance factor for each land type. We then summed the coefficients of the disturbance factors within each catchment to characterize the disturbance level for the catchment. For example, if a catchment was 50% woodland pasture and 50% row crop then the pastureland was assigned an LDI coefficient of 2.02 and the row crop was assigned an LDI coefficient of 4.45 resulting in an overall disturbance factor of 3.23. Lastly, lithology is related to sedimentation, pH, and controls the macro and micronutrient cycling load within a catchment (Sarkar et al. 2007; Zeng et al. 2011; McDowell et al. 2013; Glaus et al. 2019). Sandstone contains high quantities of silica, which leads to predominately neutral or slightly acidic environments because soluble silica forms orthosilicate acid (Worden and Morad 2000; Belton et al. 2012). Catchments with lower percentages of sandstone will likely have higher pH than those with higher percentages of sandstone. We quantified the percentage of sandstone for the drainage area of the catchment using the U.S. Geological Survey's (USGS) National Geologic Map Database (https://mrdata.usgs.gov/geology/state/) and the identify tool in ArcGIS Pro.

Habitat factors operating at the segment scale that may be related to Carp occurrence were sinuosity, slope, and discharge (Table 5). Segments were classified by 5th-order tributary confluences. Stream sinuosity, the ratio of the straight-line segment of the river to the channel distance (Rowe et al. 2009), is associated with habitat complexity (e.g., woody debris, canopy cover) and floodplain connection (Nagayama and Nakamura 2018). Sinuous reaches in a river are important for certain species reproduction (e.g., Sakhalin Taimen *Hucho perryi*; Fukushima 2001), and Carp in the Missouri River spawned larger quantities of eggs in more sinuous river segments (Deters et al. 2013). Sinuosity was calculated by dividing the river kilometer (rkm) distance by the straight-line distance of the segment using the distance tool in ArcGIS Pro. Slope can affect species distributions by influencing water velocity, channel morphology, and substrate, which are often correlated with the stream gradient (Camana et al. 2016). Stream gradient may alter the availability of low-velocity habitat associated with Carp presence. We quantified slope using spatial analysis in ArcGIS Pro by dividing the change in elevation from the upstream to downstream end of the segment by the segment length (rkm). Lastly, discharge (m^3/s) affects fish density and occurrence, habitat associations, recruitment success, and can be altered for mitigation purposes (Valdez et al. 2001; Gillete et al. 2006; Work et al. 2017; Love et al. 2017; Bašić et al. 2018). Silver Carp in the Illinois River were positively associated with discharge but avoided main channel habitats during high discharge (Coulter et al. 2017). We obtained discharge data from the USGS streamgage of the segment or from Stream Stats (https://streamstats.usgs.gov/ss/) in instances where USGS streamgages were not available. We calculated the median discharge during the season (i.e., occupancy) and divided by the drainage area of the segment to standardize discharge across rivers for comparability (i.e., Red River, Kiamichi, Blue River, etc.).

At the reach scale, we hypothesized that distance to the nearest upstream dam, percent backwater, width-to-depth ratio, salinity, and chlorophyll-*a* were related to Carp presence. Dam construction changes both biotic and abiotic riverine attributes (Catalano et al. 2007). For example, flow alteration caused by dam construction in the Yangtze River has led to reduced recruitment for both Bighead Carp and Silver Carp (Duan et al. 2009). Bighead Carp and Silver

Carp are thought to require an estimated 100 km of free-flowing river to successfully spawn (Kolar et al. 2007). We used NHDplus flowlines and ArcPro GIS spatial analyst to quantify the distance from the downstream end of each site to the nearest upstream dam. Backwaters (i.e., a specific slackwater type) are off channel, relatively shallow, low-velocity areas, relative to the main flow thread within the channel (Vietz et al. 2013). These locations are often used as a refuge by juvenile fishes due to forage availability and growth potential (Humphries et al. 2006). Backwater habitats are also used by adult Carp as refuge areas during higher discharge conditions (Coulter et al. 2017; MacNamara et al. 2018) and may offer higher forage potential (Williamson and Garvey 2005). We calculated the percent backwater for the reach by measuring the channel width and length within each backwater using a handheld rangefinder (Simmons VLRF 600, Overland Park, KS, +/- 1 m), and then expressed backwater area as a percent of the total reach area. Width-to-depth ratios describe the general structure of a stream channel where increasing ratios describe wider and shallower channels (Gordon et al. 1992; Dunham et al. 2002). We collected 3 channel width measurements with a handheld rangefinder and three corresponding channel depths with a boat equipped depth finder (Humminbird Helix 10, Rane, WI) at three locations of each reach to determine a mean reach ratio. Fishes have different salinity tolerances and will use habitat within their salinity tolerances over appropriate dissolved oxygen and temperature conditions (e.g., Shortnose Sturgeon *Acipenser brevirostrum*; Farrae et al. 2014). Inappropriate salinity environments can hinder reproduction and in extreme instances lead to poor osmoregulation and eventual death (Oto et al. 2017; Neves et al. 2019). We collected three salinity measurements (ppt) at the upper, middle, and bottom portions of each reach using a Yellow Springs Instrument (YSI pro dds, Yellow Springs, Ohio). Chlorophyll-*a* (chl-a) concentration is widely used as a surrogate for productivity and algal biomass (Pinder et. al 1997). Carp are omnivores, consuming both zooplankton and phytoplankton (Calkins et a. 2012) and may be associated with varying chl-a densities in the catchment. A water sample was collected using an integrating tube sampler to sample the top 2-m of the water column at the most downstream end of the reach (Raikow et. al. 2004). The water was stored in containers and transferred to the laboratory. Within 24 h of water collection, three 250-mL subsamples were placed into a 47-mm diameter filter tower (PALL, Port Washington, New York) and filtered through a 1-µm glass fiber filter (PALL, Port Washington, New York). The filter was then placed into a light-proof container and frozen for later laboratory analysis. In the laboratory, chla was extracted from the filters using 90% ethanol, filtered a second time, then estimated using a Trilogy Laboratory Fluorometer (Turner Designs, San Jose, California) (Sartory and Grobbelaar 1984).

At the reach scale, we quantified water temperature, turbidity, discharge, and sampling effort to relate to Carp detection (Table 5). Sullivan et al. (2017) found that increased catchability of Silver Carp occurred at higher water temperatures during the summer months (e.g., July and August) in the Des Moines River, Iowa. We measured water temperature (°C) at a well-mixed location of the upper, middle, and bottom portions of the reach using a YSI and calculated the mean during the survey to relate water temperature to Carp detection. Turbidity can affect the visual and chemical acuity of fishes thereby reducing growth and recruitment because of reduced foraging or successful spawning (Järvenpää et al. 2019; Korman et al. 2021). Turbidity also affects detection (Figueroa-Pico et al. 2020; Bunnell et al. 2021). We collected three visibility measurements (i.e., Secchi depth, +/- 1 cm) as a surrogate for turbidity at the upper, middle, and bottom portions of the reach. Discharge can affect the detection of fishes. For example, Zentner et al. (2021) found that detection of sucker species with passive integrated transponders (PIT) in streams was negatively associated with increasing discharge. We obtained discharge data from the nearest USGS streamgage and calculated the mean discharge for the day of each survey and standardized by the drainage area of the segment to compare discharge across rivers (i.e., Red River, Kiamichi, Blue River, etc.). In instances where USGS streamgages were not available, we used the median discharge value of the segment for the month in which the survey occurred using Stream Stats (U.S. Geological Survey, 2019, The StreamStats program, online at https://streamstats.usgs.gov/ss/, accessed on April 10, 2023). Sampling effort can affect the detection of fishes (Reid and Haxton 2017), so we calculated the electrofishing effort (i.e., seconds) for the survey.

Data analyses

An occupancy model (OM) is useful for delineating factors related to occupancy probabilities while accounting for incomplete gear detection (Mackenzie et al. 2002). The four assumptions of an occupancy model are: 1) the occupancy state must be "closed" (i.e., to the species and not individuals), 2) there is no unexplained heterogeneity in detection, 3) there is no unexplained heterogeneity in occupancy, and 4) the sites are independent of each other (Bailey and Adams 2005). We met the assumption of species' closure by establishing a season (April – September) and by having a sufficient reach size (1-2 rkm). The second and third OM assumptions were met with the inclusion of both detection and occupancy covariates to explain variation in detection or occupancy probabilities (Mackenzie et al. 2002). We met the final assumption by spacing our sites at least 1.5-2 rkm apart so surveying one site did not influence detection at an adjacent site. Determining detection probability is essential because it affects our ability to infer occupancy (Benoit et al. 2021). Estimates of detection account for potential species presence at a site even if the sites were not sampled (i.e., false absence, Royle and Kery 2007; Kery et al. 2010). We quantified the probability of detection using temporally replicated surveys during our warm-water season (Mackenzie et al. 2002). The detection history (i.e., 1 if present, and 0 if absent) was modeled with covariates using a logit function to explain heterogeneity of detection because detection covariates varied across surveys (Mackenzie et al. 2002). Probability of detection was then used to estimate the probability of occupancy. The relationship between detection probability and occupancy was modeled as two Bernoulli distributions. Occupancy was modeled using covariates hypothesized to be related to species presence to explain the heterogeneity in occupancy (Mackenzie et al. 2002). However, we first had to ensure our model met the assumptions associated with regression.

Prior to model construction, we transformed our data if skewed or had natural breaks in the data, checked for multicollinearity, and standardized our remaining covariates. We log transformed percent sandstone, slope, discharge, width-to-depth, and chlorophyll-a because these data were skewed. We made drainage area categorical (where 0 was low, 1 was high, and 1 was the reference) and a natural break occurred in our data at 80,000 km^2 (34% of observations were less than this value). We also made percent backwater categorical (0 = absence, 1 = present, where 1 was the reference) and a natural break occurred in our data at 1% backwater (57% of observations less than this value). Next, we conducted a Pearson’s pairwise correlation analysis on our continuous covariates to check for correlations. If our continuous covariates were multicollinear ($|r| > 0.6$), then we selected the covariate that had the greatest number of correlations or chose continuous covariates over categorical covariates. We removed drainage area from the analysis because it was highly correlated to width-to-depth and slope. We also removed slope and percent sandstone from the analysis because they were highly correlated with width-to-depth ratio ($r = -0.63$) and discharge ($r = 0.78$), respectively. Finally, we standardized all continuous covariates to a mean of zero and a standard deviation of one.

We examined the range of our covariates and removed one due to limited variation among sites. Disturbance was relatively constant throughout all catchments ranging from 1.40 to 2.53. The LDI for tributaries ranged from 1.40 to 2.53 and was more limited in the mainstem Red River (1.91 – 2.00). Therefore, we removed this variable from consideration prior to model building.

We evaluated several multi-species, single-season occupancy models in a Bayesian framework using JAGS (Just Another Gibbs Sampler, Plummer 2003) and Program R (version 4.2.2). We hypothesized different combinations of covariates would be important for occupancy by both species but held detection covariates constant for each hypothesis. We tested different combinations of occupancy variables to support overarching hypotheses related to factors supporting either Carp growth or spawning (Tables 6-7). The most complex growth model contained sinuosity, width-to-depth ratio, chlorophyll-a, discharge, and reaches with the presence of backwater (Tables 6-7). The most complex spawning model contained discharge, salinity, distance to dam, and reaches with the presence of backwater (Tables 6-7). We included reaches with the presence of backwater and discharge in both model frameworks as previous research indicates that Carp were associated with the presence of backwater and discharge which may be associated with higher forage potential, warmer water temperatures for bioenergetics, decreased energy expenditure, staging locations for spawning and adequate flow for spawning (Williamson and Garvey 2005; Coulter et al. 2017, Song et al. 2018) (*see* Table 8). All models contained grouping factors for year and river (i.e., Red River, Kiamichi, etc.) where multiple sites were nested within river (i.e., to account for pseudo replication, Wagner 2006). Broad normal priors were used for the coefficients, with gamma priors for standard deviations and uniform priors for occupancy and detection probabilities. All models were run with 3 chains in parallel beginning with a 1,000 iteration adapt phase, a 30,000-iteration burn-in, and a total of 150,000 iterations thinning every 3 iterations using the jagsUI package (Kellner 2015).

We ranked our models using the Watanabe-Akaike information criterion (WAIC) with the NIMBLE package (de Velpine et al. 2022) and selected the models with a delta WAIC score less than 2 as models with equal support (i.e., top-ranked models) (Watanabe 2010; Vranckx et al. 2021). WAIC is considered a Bayesian model selection criterion because it samples from the entirety of the posterior distribution compared to other model selection methods such as the deviance information criterion (DIC) and has been demonstrated to perform better than other model selection methods for complex Bayesian hierarchical models (Luo 2021; Vranckx et al. 2021).

For our top ranked models, we calculated the mode estimates, 90% highest density intervals (HDI), and estimated detection and occupancy probabilities for the retained covariates. We then predicted the occupancy probability and detection probability for each covariate in our final models within their observed range in the catchment (while holding the other model covariates at mean levels).

We evaluated model convergence and model fit of our top ranked models. We used the Brooks-Gelman-Rubin statistic ($\check{R}$) to assess model convergence, where an $\check{R}$ value < 1.1 indicates adequate convergence (Gelman and Rubin 1992; Gelman et al. 2000). Finally, we assessed model fit with the Bayesian p-value where a value between 0.05 and 0.95 indicates adequate model fit (Kery and Royle 2016).

Objective 2. Determine habitat associations of large river fish assemblages

Native fish sampling

At each juvenile and adult site, we sampled native fishes using multiple gears as described for Objective 1. Briefly, sites targeting juvenile and smaller-bodied fishes were sampled using three gear types: mini-fyke nets, beach seines, and larval tows. Mini-fyke nets were set in 1-2 m of water for approximately 6 h during daylight. Beach seining was conducted within areas of the site that allowed for seining (i.e., depths <1m). Larval tows were conducted by towing an ichthyoplankton net upstream for approximately 10 min at each site. Identifiable species were enumerated and recorded for each gear used. All larval individuals and unknown species were preserved in a 70% ethanol solution for later identification in the lab. At sites targeting larger-bodied fishes, we conducted electrofishing and net surveys. Three gill nets and three hoop nets were placed throughout each site to soak for approximately 6 h. Following net placement, the site was sampled via boat electrofishing. All sampled fish were identified to species, and the sampling method associated with each catch was recorded.

Native fish habitat

At each site, we quantified the physicochemical factors that may also be related to native fish distributions as described for Objective 1. Briefly, we collected both detection and occupancy covariates. For juvenile and smaller-bodied fishes we quantified: water temperature (°C), dissolved oxygen (mg/L), turbidity (cm), discharge (m^3/s), salinity (ppt), average depth (m), width-to-depth ratio (m), zooplankton biomass (µg), large woody debris (%), forewater/backwater (%), and pools (%). We also quantified several geospatial covariates: distance from dam, distance from confluence, sinuosity, slope, drainage area, and lithology. For adult and larger-bodied fishes we quantified chlorophyll-a (mg/L), salinity (ppt), water temperature (°C), water visibility (cm), discharge (m^3/s), and width-to-depth ratio (m). We also calculated distance from dam, sinuosity, slope, drainage area, disturbance, and lithology using existing geospatial data and tools.

Native fish data analyses: juvenile and adult occupancy modeling

We built two multispecies single-season occupancy models (MSOM) to 1) quantify juvenile nursery habitat by native fishes, and 2) quantify habitat associations of large-bodied adult fishes (Mackenzie et al. 2002). An occupancy model allows for the estimation of a probability of occurrence while accounting for incomplete detection by the sampling gears. Variation in both detection and occupancy is explained by collected environmental covariates (Mackenzie 2006). We built occupancy models (OM) using temporally replicated surveys at sites to create a detection history (1 if the species is detected, and 0 if it is not). Repeated surveys allow for the model to create estimates of both a detection probability (p_i) and an occupancy probability (ψ_i) (Kéry and Royle 2016). We were able to meet all four of the assumptions for OM (see objective 1 for description). We met the assumption of species' closure by establishing a season (i.e., May – October for juveniles and April – September for adults) during the spawning period of many native fishes of the catchment (e.g., after the water has reached >18°C). Our season ended while juvenile fishes were still using nursery habitat but before water temperatures declined appreciably during late autumn, and before adult fishes moved to over-wintering habitats. The second and third OM assumptions were met with the inclusion of both detection and occupancy covariates to explain variation in detection or occupancy probabilities (Mackenzie et al. 2002). We met the final assumption by spacing our juvenile sites at least 250 m apart and our adult sites at least 1 km apart so surveying one site did not influence detection at an adjacent site. Lastly, we included grouping factors to account for the nested nature of river systems and to account for pseudoreplication in these data.

We transformed and standardized data prior to model development. For adult fish occupancy modeling, we used the same approach (i.e., same sites and covariates) that were used to model adult Carp occupancy, as such the transformation and standardization process was the same (see *data analysis* section in Objective 1). For juvenile sites, we first began with the detection covariates and any covariates that were not normally distributed were transformed. Dissolved oxygen, visibility, effort, and discharge were log-transformed in the juvenile data set due to their right-skewedness. Next, we checked detection covariates to ensure they were not multicollinear ($| r | > 0.50$; Roever et al. 2014) using Pearson's correlation coefficient. All detection variables had $| r | \leq 0.35$ and were therefore, retained for the model building process. We completed the same process for occupancy covariates. The percent of limestone lithology, slope, LWD, thalweg depth, W:D, and zooplankton counts were all log transformed due to skewed distributions. Additionally, drainage area, percent of deep pools in the reach, and percent of slackwater in the reach were transformed into categorical variables based on natural breaks in these data (i.e., bimodal). Categorical transformation of drainage area represented either high (>50,000 km^2) or low (<50,000 km^2) drainage areas, whereas deep pools and slackwater represented either presence or absence. Categorical covariates were tested for independence by evaluating frequency at which they occurred together at each site. The W:D was multicollinear with salinity ($| r | = 0.53$) and LDI ($| r | = 0.52$). Further, median discharge was multicollinear with zooplankton ($| r | = -0.63$). Slope was also highly negatively correlated with sinuosity ($| r | = -0.53$). We retained W:D, median discharge, and slope for model development. Lastly, all continuous covariates were standardized to a mean of zero and a standard deviation of one to improve model convergence and interpretation (Mackenzie and Royle 2005; Mackenzie et al. 2017).

We built occupancy models using covariates to inform the variation in both detection and occupancy. We built the detection component of the model by choosing two covariates that were hypothesized to share relationships among juvenile fishes and gear detection (i.e., not species specific) so more emphasis could be placed on the occupancy portion of the model. To determine which detection covariates should be retained, we fit a global detection model and assessed the effect sizes of the covariates. Discharge and water temperature had the greatest effects sizes and are commonly used to explain detection (Maire et al. 2019; Carpenter-Bundhoo et al. 2023); therefore, we fit the detection model with these two parameters to avoid overfitting the model.

Moreover, we tested for trap effects (i.e., increase or decrease in detection probability after first detection) within the model (Mollenhauer et al. 2018) by assigning a 1 after each detection to see changes in detection probability. The detection component of the model is expressed as:

$$logit(p_{ij}) = \Sigma_{k=1}^{38} a_{0k} + \Sigma_{m=1}^{2} \Sigma_{n=1}^{2} \beta_m X_{n[ij]},$$

$$for\ i = 1, 2 \ldots. N\ for\ j = 1, 2 \ldots. J,$$

$$a_{0k} \sim t(\mu, \sigma^2, \upsilon),$$

$$\beta_m \sim t(\mu, \sigma^2, \upsilon),$$

Where:

p_{ij} = detection probability during survey j at site i

a_{0k} = mean species deflection k from the assemblage mean intercept

β_m = mean assemblage slope

X_n = detection covariates

The occupancy portion of the model was built similarly to the detection portion, except we fit species-specific relationships using the covariates. The detection component was held constant as the occupancy component was fit. We fit the occupancy component with the presence of slackwater in the reach, the presence of deeper-water pools in the reach, high or low drainage area, and the continuous covariates of thalweg depth, W:D, LWD, distance to the nearest upstream dam, median discharge, slope, and percent limestone lithology. Each species was modeled around the group mean, hyperparameter

$$\mu$$

The interpretation is similar to a random-slopes model where individual species are treated as random intercepts rather than focusing on interspecies differences. The resulting occupancy probabilities are interpreted similar to individual models but with the power of a single model (Kéry and Royle 2016). We also included grouping factors for both segment and sample year to account for any unexplained variability within the model. The inclusion of grouping factors within the model also accounts for pseudoreplication and spatial correlation created by the nested site study design (Wagner et al. 2006).

The occupancy component of the model is expressed as:

$$logit\ (\psi_i) = \Sigma_{k=1}^{38} a_{0k} + \Sigma_{k=1}^{38} a_{POOLk\,[i]} + \Sigma_{k=1}^{38} a_{SLACKk\,[i]} + \Sigma_{k=1}^{38} a_{DRAINk\,[i]}$$

$$+\Sigma_{m=1}^{7}\Sigma_{k=1}^{38}\Sigma_{n=1}^{7}\beta_m X_{n[i]},$$

$$\Sigma_{k=1}^{38}\gamma_{Rk[i]} + \Sigma_{k=1}^{38}\gamma_{Yk[i]}, \text{ for i = 1, 2....N,}$$

$$a_{0k}, a_{POOLk}, a_{SLACKk}, a_{DRAINk} \sim t(\mu, \sigma^2, \upsilon),$$

$$\beta_{mk} \sim t(\mu, \sigma^2, \upsilon),$$

$$\gamma_{Rk} \sim t(\mu, \sigma^2, \upsilon), \text{ for R = 1, 2....3,}$$

$$\gamma_{Yk} \sim t(\mu, \sigma^2, \upsilon), \text{ for Y = 1....2}$$

Where:

ψ_i = species probability of occurrence at site *i*
a_{0k} = species *k* deflection from the assemblage mean intercept
a_{POOLk} = categorical variable deep pools where no deep pools was the reference
a_{Slackk} = categorical variable slackwater where no slackwater was the reference
a_{DRAINk} = categorical variable drainage area where high drainage area was the reference
β_{mk} = species *k* deflection from assemblage mean slope *m*
X_n = continuous occupancy covariates
γ_{Sk} = segment grouping factor for species *k*
γ_{Yk}= year grouping factor for species *k*

We used vague priors to calculate the posterior distributions. When informative prior information is not available, vague uninformative priors are used to give the model a starting point for estimating parameters with minimal effect on the model results (Kruschke 2014; Kéry and Royle 2016). Vague truncated normally distributed priors (i.e., t-distribution) were given to main effects, and vague gamma priors were applied to their standard deviations. The t-distribution adds a normality parameter υ (see equation above) which accounts for heavy tails and can improve model fit (Kruschke 2014). Lastly, uniform priors were used for the detection and occurrence intercepts to aid in model convergence.

We assessed the posterior distribution of the model and covariates using Markov Chain Monte Carlo (MCMC) simulations (Marjoram et al. 2003). Due to the large number of covariates included in the model, 150,000 iterations were run on 3 chains with a burn-in of 10,000 and thinning of 5. The model was fit using the package jagsUI (Kellner 2015) and the program JAGS (Plummer 2003) within the statistical computing software R (Version 4.2.2, R Core Team 2022). The back transformed logit parameter was used to calculate the detection and occurrence probabilities. Model convergence was evaluated using the Brooks-Gelman-Rubin statistic $\hat{R}$ (Gelman et al. 1992, 2000), where parameter estimations, $\hat{R} < 1.1$, indicate appropriate mixing of chains. Lastly, we used an omnibus goodness-of-fit test (i.e., evaluating chi-squared discrepancies; Mackenzie and Bailey 2004), where

$\hat{c}$

values within 1.00 to 1.02 are considered to have adequate dispersion (Kéry and Royle 2016). Additionally, the Bayesian p-value also provides a posterior predictive check, where values near 0.5 (i.e., values that are not close to 0 or 1) are considered to fit the observed data (Kruschke 2014; Kéry and Royle 2016; Conn et al. 2018).

Objective 3. Summarize the population demographics of Bighead and Silver Carp in the lower Red River basin

Adult Carp otolith extraction, processing, ageing, and growth

We removed lapilli otoliths for age and growth analyses following Seibert and Phelps (2013). Briefly, the lapilli otoliths, located at the posterior of the skull, were accessed using a hacksaw. A cut was made through the top of skull at the juncture of the preopercle and opercula. Otoliths were then removed using forceps and placed into coin envelopes marked with an individual fish number for later laboratory analyses.

In the laboratory, otoliths were sectioned and prepared for age estimation. First, we marked the nucleus on the exterior of the otolith with a ballpoint pen. We then placed the otolith in epoxy resin (West System 105-A) and allowed it to harden for 24-h. After hardening, the otolith was sectioned using an isomet saw (Buehler IsoMet Low Speed Precision Cutter, Lake Bluff, Illinois) and a single 0.5 to 0.6-mm cross-section was removed from the center of the otolith ensuring the inclusion of the nucleus. We then polished the sectioned otolith for 1.5 min on each side with 3-μm diamond lapping paper (Diamond Lapping Film, 203-mm diameter, plain backing, Electron Microscopy Sciences, Hatfield, PA). Subsequently, we mounted the sectioned otolith onto a slide using thermoplastic cement. The slide was then placed under a dissecting microscope equipped with a light source and imaged with a digital camera (Luminera Infinity 2, Tyledyne Luminera, Ontario). The images were saved for later growth analyses.

Age and growth of Carp

Two readers separately enumerated the annuli of the sectioned otolith to age each fish using transmitted light under a dissection microscope. An annulus was defined as a pair of translucent and opaque bands that continued uninterrupted around the nucleus (Dzul et al. 2012). The edge was counted as an annulus for fish captured prior to April 1st because an annulus was presumed to be created during the spawning season (Minard and Dye 1998; Ericksen 1999). There was no prior knowledge of the fish's length, weight, or age to avoid reader bias. If there was no consensus on the age of a fish, then the readers discussed how they derived the age, and a consensus was obtained.

We quantified the proportional growth of Carp to determine how growth related to discharge and temperature patterns and fish length (*see* Data Analyses). The annuli and edge were analyzed for proportional growth using Infinity Analyze 7 software (Tyledyne Luminera, Ontario) (Quist and Isermann 2017). Otoliths were measured for incremental growth along the midventral axis. The focus was identified, and then individual radii distances were recorded from the focus longitudinally to the outside edge of each opaque band to determine individual year growth (Weisberg et al. 2010). The distance from the focus to the edge was used to relate incremental growth to fish length.

Body condition and fecundity

Body condition and fecundity of Bighead and Silver Carp were analyzed for Carp captured in the mainstem Red River and its major tributaries from June 2021 through December 2022. For body condition, we calculated the relative weight (W_r) of individual fishes using standard weight (W_s) equations described by Lamer et al. (2015). For Bighead Carp, the W_s equation is:

$$\log_{10} W_{s(g)} = -4.65006 + 2.88934 \ (\log_{10}(tl_{(mm)})$$

For Silver Carp, the W_s equation is:

$$\log_{10} W_{s(g)} = -4.65006 + 2.88934 \ (\log_{10}(tl_{(mm)})$$

These equations were developed such that a W_r value of 100 indicates that a fish is in average condition (Lamer et al. 2015). Typically, Wr is correlated with growth, but growth measures (above) would be more direct. Moreover, population data should represent the entire geographic range of the species to avoid misinterpretation of the growth form (Murphy et al. 1990).

We calculated the gonadosomatic index (GSI) of female Carp and estimated fecundity. GSI, a ratio of gonad weight to body weight, is a commonly used indicator of reproductive periods. The reliability of GSI in determining reproductive status has varied among species with different reproductive strategies and is most useful when fish species spawn once annually. Although results are mixed in intermittent spawners GSI can sometimes be used to identify spawning peaks (see Brewer et al. 2006). Ovaries were removed from collected fish in the field, blotted to remove excess fluid, weighed, and placed in 70% ethanol for later enumeration. GSI of female fish was calculated as (gonad weight⁄ total body weight) * 100 (Strange 1996). Fecundity was estimated based on density-weight relationships where a sample was taken from each ovary, enumerated, and then multiplied by the weight of the ovaries (Crim and Glebe 1990). We began by taking the total weight (g, +/- 1 g) of the ovary. We then took subsamples (0.3 – 0.5 g) from the anterior, middle, and posterior of the ovary and enumerated the eggs for each subsample. From these enumerated subsamples, we then estimated the average eggs per gram and extrapolated that to the respective ovary weight.

Growth, mortality, and recruitment analyses

We calculated the mean back-calculated length-at-age for all ages to be used in a growth model. Back calculation for length-at-age was conducted using the Dahl-Lea method because of the lack of a known biological intercept (Francis 1990; Quist and Isermann 2017). We fit a von Bertalanffy growth model (vBGM) to Carp using the previously collected back-calculated length-at-age data. We used a vBGM for Carp because it is widely used for comparing growth between fish populations (Quist and Isermann 2017) and can elucidate important population growth parameters, such as the theoretical maximum length (L_∞) and the population growth coefficient (k). These parameters can then be compared post mitigation if management practices aim to reduce fish growth.

We used a mixed-effects model, described by Weisberg et al. (2010), to relate Silver Carp and Bighead Carp growth to environmental conditions of the lower Red River catchment. It can be difficult to relate growth to the environment because growth is correlated with fish age, fish length, and fish from the same cohort because cohorts can display higher growth rates than others (Watkins et al. 2017). Advances in mixed-effects growth models have permitted us to account for the age, length, and interactions between individual fish during a given year to assess the effects of environmental factors on growth (Weisberg et al. 2010). We modeled age, discharge, and water temperature as fixed effects while year and fish were random effects. This catchment experiences relatively high annual weather fluctuations including longer periods of flood and drought (see Mollenhauer et al. 2022).

We hypothesized that both Bighead Carp and Silver Carp growth were related to discharge and water temperature conditions. We created species-specific models relating the 75th percentile of discharge (m^3/s) (i.e., relatively high flows), the coefficient of variation (CV) of discharge (i.e., flow variability), the 75th percentile of air temperature (°C), and the CV of air temperature to fish growth from April through September across the catchment. We used air temperature as a surrogate for water temperature due to the lack of consistent water temperature data for all the years considered, and water temperature is highly related to air temperature throughout the catchment (Morrill et al. 2005; Adlam et al. 2022). The oldest fish in our sample (e.g., 17) would have been recruited in 2004, however because no fish younger than age 3 were observed in the lower Red River catchment we truncated our data to model growth from age 3 through the maximum age. Thus, we collected discharge and temperature data from 2007 through 2019 and calculated the 75th percentile and CV for the season (April 1st = September 30th).

We used Akaike's information criterion corrected for small sample size (AICc) to rank several models (Segiura 1978). We constructed the following models: random effects (i.e., year, fish) and fish length with no environmental factors, all combinations with random effects, and a global model. We conducted model averaging for models that had an Akaike's difference (ΔAIC) less than two (Burnham and Anderson 2002). We then calculated the marginal R^2 and the conditional R^2 for both fixed and random effects, respectively, for the averaged models (Nakagawa and Shielzeth 2013). We used the "lme4" (Bates et al. 2015), "AICcmodavg" (Mazerolle 2020), and "MuMIn" (Barton 2022) packages for our analyses.

We used two catch curves to analyze mortality and recruitment of Silver Carp. We used a Chapman-Robson peak-plus catch-curve corrected for overdispersion to estimate mortality and recruitment variability via the recruitment variability index (RVI) (Isermann et al. 2002) for Silver Carp only due to the small sample size for Bighead Carp (Smith et al. 2012). Peak plus denotes that the first age class used in the analysis is the age following the age with the largest quantity (Smith et al. 2012). Catch-curves for estimating mortality and recruitment are susceptible to bias when age classes are missing from these data (Catalano 2009), however all age classes were present for Silver Carp.

RESULTS

In Arkansas, we sampled 24 sites targeting juvenile Carp and small-bodied native fishes and 22 sites targeting adult Carps and native fishes (Table 1). We completed 95 surveys at the 24 juvenile sampling sites and 100 surveys at our 22 adult sapling sites. As expected, gillnets and electrofishing were the most effective at capturing larger-bodied fishes, whereas fyke nets and seining collected mainly smaller-bodied fishes. Hoop nets were not as effective at collecting fishes as other gear types.

The experimental electrofishing settings were not as effective at collecting Carp or getting Carp to jump as the standard settings used during the initial fish assemblage shocking events. When Carp were observed jumping, we were somewhat able to manipulate their swimming direction by using the electrofisher. On several instances, we were able to observe the wakes of Carp being driven towards set gillnets as they attempted to escape the electric field. However, most Carp that were actively driven towards the nets would either jump the net upon reaching it or turn around and swim away from it and around the electrofishing boat. We have attempted to set our gillnets parallel to the bank to electrofish between the net and bank as was suggested by the Arkansas Game and Fish Commission (Jimmy Barnett, Arkansas Game and Fish Commission, oral communication, 2021). Thus far, this has not resulted in any noticeable differences in our catch. We also baited hoop nets with cattle cubes as was suggested by commercial fishermen in Arkansas. However, neither modification improved Carp catch.

Objective 1. Determine the spatial and temporal extent of Bighead Carp and Silver Carp in the Red River basin

All Carp modeling and analysis was completed using sampling data collected from both tributary sites and mainstem Red River sites in all three states (AR, OK, and TX). Silver and Bighead Carp were detected in both the mainstem Red River and tributaries within the lower Red River basin (Figure 4). Silver Carp were detected at 23 of the mainstem Red River sites and 17 of the tributary sites with an overall naïve occupancy of 0.69. Bighead Carp were detected at 10 of the mainstem Red River sites and 13 of the tributary sites with an overall naïve occupancy of 0.40.

Carp were observed or captured across the catchment using a variety of gears. We collected 355 Carp, of which 122 were captured via electrofishing, 206 were captured using gillnets, and the remaining fish were either provided by bow fisherpersons (via the USFWS) or jumped in our boat during sampling (all Silver Carp). We captured 266 Silver Carp and 89 Bighead Carp throughout the lower Red River catchment during our 2021 and 2022 sampling seasons (Table 9, 201 Silver Carp and 27 Bighead Carp were captured in Arkansas, respectively). Most Carp captured in the mainstem Red River were sampled from reaches with backwater habitat. Carp were visually confirmed (i.e., observed jumping during sampling but not netted) during 34 surveys (Table 10). For Bighead Carp throughout the lower basin (AR, OK, TX), 83% (67 of 81) were captured in gillnets and 17% (14 of 81) were captured using electrofishing. For Silver Carp throughout the lower basin, 56% (139 of 247) were captured in gillnets, 44% (108 of 247) were captured from electrofishing, and the remainder were fish that jumped into the boat while sampling or were captured by bow fisherpersons.

The occupancy models that had the most support for both species (i.e., WAIC difference <2, Vranckx et al. 2021) included the covariates: presence of backwater in the reach, sinuosity, width-to-depth ratio, and chlorophyll-a (µg/L) (Tables 11 - 12). All top ranked models included the detection covariates of water temperature (°C), Secchi depth (cm), discharge, and electrofishing effort (s) (Table 13).

Detection varied with environment indicating catch-per-unit effort (CPUE) would not be adequate to represent carp abundance trends. Detection probability, with our occupancy covariates held at mean levels, ranged from 0.39 to 0.40 for Bighead Carp and 0.60 to 0.63 for Silver Carp (Table 14). Bighead and Silver Carp detection was positively associated with increasing water temperature (Figure 5), and electrofishing effort (Figure 6) and negatively associated with discharge (Figure 7) and Secchi depth (Figure 8). Given variation in detection, CPUE data are not appropriate for use as trend data, but are provided in Appendix A.

Occupancy probability, with our detection covariates held at mean levels, ranged from 0.53 to 0.78 for Bighead Carp and 0.78 to 0.85 for Silver Carp (Table 14). Carp occupancy was positively related to reaches with the presence of backwater habitat and negatively associated with sinuosity (Figure 9). Both species of Carp were also negatively associated with width-to-depth ratio (Figure 10) indicating Carp used reaches with narrower and deeper channels. Silver Carp occupancy was positively associated with chlorophyll-a (Figure 11), whereas Bighead Carp occupancy had no relationship with chlorophyll-a (Table 12).

Our top-ranked models converged and had adequate model fit. Our final models achieved convergence as evidenced by all parameters having R-hat values < 1.1 and visual assessment of the Markov chains (Tables 12-13) (Kéry and Royle 2016). The Bayesian p-values for models with equal support ranged from 0.275 to 0.292 and the c-hat values ranged from 1.094 to 1.114 indicating adequate model fit (Kéry and Royle 2016).

Objective 2. Determine habitat associations of large river fish assemblages

A total of 120,072 fishes, comprising 70 species and 41 genera, from the mainstem Red River in Arkansas (Table 15, Scientific names provided in Appendix B). All vouchered fish have been reviewed in the laboratory and identified to species or genus. The most abundant fish species collected during juvenile sampling was Red Shiner (55,654), followed by Bullhead Minnow (19,773), Mosquitofish (7,026), Chub Shiner (5,905), and Emerald Shiner (5,205). The most abundant large-bodied fish species sampled during adult sampling was Smallmouth Buffalo (455), followed by Bigmouth Buffalo (315), River Carpsucker (306), Blue Sucker (232), and Black Buffalo (193). Of the 70 fish species, 4 of those were non-native including Common Carp, Bighead Carp, Silver Carp, and Grass Carp. The genera that contained the most species collected was *Lepomis* (Table 16). Length-frequency histograms were created for the seven most prevalent large-bodied species: Smallmouth Buffalo (Figure 12), Black Buffalo (Figure 13), Bigmouth Buffalo (Figure 14), Longnose Gar (Figure 15), Flathead Catfish (Figure 16), River Carpsucker (Figure 17) and Blue Sucker (Figure 18). Additionally, a log-transformed length-weight relationship was also calculated for six of the seven most prevalent large-bodied species (Flathead Catfish was not included due to the lack of recorded weights on smaller individuals) (Figures 19-24).

Juvenile nursery habitats

Prior to model building, we omitted data from a few sites and species. We retained data from 99 of the 104 sites for analyses. We omitted 5 sites because some had single surveys and others were missing physicochemical covariate information. We omitted 4 species from model development because they were either ubiquitous, extremely rare, or non-native (retaining 38 species). Species with extremely high (e.g., Red Shiner and Mosquitofish), or low naïve occupancy (e.g., Striped Bass) were removed from the dataset to aid in model convergence.

The final model converged and had adequate fit (Table 17). All model parameters displayed appropriate chain mixing with $\hat{R}$ <1.1 (Kéry and Royle 2016). The OM displayed adequate dispersion of posterior values ($\hat{c}$ of 1.003), and adequate goodness-of-fit with a Bayesian p-value of 0.505.

The probability of detection and occupancy varied by species; however, some relationships with covariates were shared though there were differences in effect sizes. The group mean detection probability was 0.19, with the individual species ranging from 0.04 to 0.70 (Figure 25). Species detection increased with increasing water temperatures, and discharge conditions (Table 18; Figure 26). Further, the group mean occupancy probability was 0.57 with the individual species ranging from 0.15 to 0.96 (Figure 25). All 38 juvenile species had positive occupancy relationships with reaches having deep pools and slackwater habitats present, and the distance from the nearest upstream dam (Figures 27-30). Lastly, all species had a negative occupancy relationship with deeper thalwegs and the percentage of limestone within the catchment (Figures 27-30). Although species had the same relationship with thalweg depth, the effect size of these relationships differed. Some species (e.g., Longear Sunfish and Bantam Sunfish) had relatively weak negative relationships, whereas Warmouth and Redear Sunfish had stronger relationships.

Several nursery habitat relationships were species specific (Table 19; Figures 27 -30). The occupancy relationships with drainage area, segment slope, amount of LWD, W:D ratio, and seasonal median discharge were variable among species and taxonomic groups. Five species (Chub Shiner, Gizzard Shad, Mississippi Silverside, Threadfin Shad, and White Bass) were positively associated with larger drainage areas, whereas all other species were negatively related. Most juvenile species were negatively associated with LWD except for Channel Catfish, Longnose Gar, and Slough Darter. Seasonal median discharge had a generally positive relationship with most juvenile fishes; however, Longear Sunfish, Orangespotted Sunfish, Logperch, and Silver Chub had negative relationships with median discharge. The segment slope and W:D ratio were split between positive and negative relationships among all species. For example, Dusky Darter exhibited a strong negative relationship with slope, whereas Freshwater Drum had a strong positive relationship. Moreover, Blacktail Shiner had a strong negative relationship with W:D ratio, whereas Shoal Chub exhibited a strong negative relationship. Lastly, the grouping factors of segment and year accounted for variance of 1.425 and 1.194 respectively.

Adult fish habitat

For modeling adult river fishes, we included 25 species in the model. These species included the families Acipenseridae, Catostomidae, Centrarchidae, Cyprinidae, Ictaluridae, Lepisostedae, Moronidae, Polyodontidae, and Sciaenidae. The model successfully converged and displayed adequate fit (Table 20). All model parameters displayed appropriate chain mixing with $\hat{R}$ <1.1. The OM displayed adequate dispersion of posterior values ($\hat{c}$ of 0.992), and adequate goodness-of-fit with a Bayesian p-value of 0.629.

Large-bodied fishes displayed variability in both the probability of detection and occupancy. Species detection probability ranged from 0.25 to 0.84 with a group mean of 0.41 (Table 21). As expected, species' detection increased with both increasing water temperatures and electrofishing effort. The group mean occupancy probability was higher for large-bodied fishes at 0.70, with individual species' occupancy ranging from 0.19 to 0.98 (Table 22).

We found that, similar to juvenile fishes, some occupancy relationships were shared between large-bodied fishes; however, others varied by species (Table 22; Figures 32- 35). All species were negatively related to increasing drainage area, elevation, and chlorophyll-a concentrations. Alternatively, all species were positively associated with increasing discharge and salinity conditions. Large-bodied species displayed variable relationships with width-to-depth ratio, meander of the stream channel, amount of blackwater in the reach, and distance from the nearest upstream dam. All species were negatively associated with distance from the nearest upstream dam except for Blue Catfish. Most species were positively related to increasing backwater within a reach; however, species including Alligator Gar, Blue Catfish, Channel Catfish, Flathead Catfish, Freshwater Drum, Spotted Bass, Spotted Gar, White Bass, Longear Sunfish, and Green Sunfish were negatively associated with reaches that contained >1% backwater habitat. Many of the fishes were negatively associated with more sinuous channels. However, Blue Catfish, Bigmouth Buffalo, Freshwater Drum, Shortnose Gar, Spotted Gar, White Bass, Orangespotted Sunfish, and Green Sunfish were positively associated with more sinuous stream segments. Species tended to be relatively evenly split with their relationships with channel shape. However, some species within the same genus exhibited variable relationships. For example, Shortnose Gar, Spotted Gar, Bigmouth Buffalo, and Smallmouth Buffalo were associated with narrower deeper channels, whereas Longnose Gar and Black Buffalo tended to be more associated with shallower, wider channels. Blue Sucker, Flathead Catfish, and Shovelnose Sturgeon were also strongly associated with shallower, and wider channels. Lastly, the grouping factors of segment and year accounted for additional variance (0.579 and 1.400, respectively).

Objective 3. Summarize the population demographics of Bighead and Silver Carp in the lower Red River basin

A total of 266 Silver Carp (157 males, 100 females, 9 unsexed, 1.6:1.0 sex ratio) and 89 Bighead Carp (57 males, 28 females, 4 unsexed, 2.0:1.0 sex ratio) were sampled in 2021 and 2022 throughout the lower basin (Table 9). Silver Carp tended to be smaller and younger, on average, compared to Bighead Carp though Silver Carp tended to grow faster early in life (Table 23). On average, the Silver Carp we collected were 887-mm TL (range: 616-1091-mm TL), whereas Bighead Carp were 1,102-mm TL (range: 868-1,360-mm TL). The mean age of Bighead Carp estimated using otoliths was 9 years, whereas Silver Carp mean age was lower (6 years). The oldest sampled Silver Carp and Bighead Carp were age 14 and 17, respectively (Figure 36). Silver Carp were larger (i.e., TL) than Bighead Carp, on average, until age 5. Silver Carp and Bighead Carp mean back-calculated lengths at age 5 were 740 and 746-mm TL, respectively.

Silver Carp mortality was relatively low and recruitment into the population appeared steady. Our catch-curves for Silver Carp were fit using ages 6 through 14 because age 5 fish had the highest count in our sample. The instantaneous mortality estimate (*Z*) was 0.32, conferring an annual total mortality rate (i.e., fishing and natural mortality, *M*) of 0.27. Recruitment variability was relatively stable for Silver Carp (SVC, 0.86) (Figure 37). L_∞ for both species was relatively high (SVC = 920-mm, Bighead Carp, BHC = 1349-mm), whereas growth rate (*k*) was higher for Silver Carp (*k* = 0.31) compared to Bighead Carp (*k* =0.12) (Figure 38).

Air temperature, discharge variability, and high discharge conditions were related to growth of Silver Carp and Bighead Carp. We model-averaged 13 Weisberg models associated with Silver Carp growth and two models associated with Bighead Carp growth that had a delta AIC score less than 2 to reduce model bias and address uncertainty (Tables 24-25) (Kruse et al. 2022). Bighead Carp growth was positively associated with warmer air temperatures (75th percentile of air temperature) and negatively associated with discharge variability (CV of discharge). Similarly, Silver Carp growth was positively associated with the warm air temperature (75th percentile of air temperature) and negatively associated with discharge variability (i.e., CV of discharge). However, Silver Carp growth was also positively related to high discharge conditions (75th percentile of discharge) and the variability of air temperature as a surrogate for water temperature (i.e., CV of air temperature; Table 26).

Our fixed and random effects explained a large portion of the variability in our growth models. The marginal R^2s for our Silver Carp models having equal support ranged from 0.51 to 0.56. Including random effects explained 22% to 27% more variability in our data (R^2- 0.73 to 0.78). The fixed effects in our top-ranked Bighead Carp models with equal support explained 57% of the variation in our data (marginal R^2- 0.57). Including the random effects of year and individual fish explained an additional 10% of the variation in growth (conditional R^2- 0.67).

For Bighead Carp captured in the lower Red River catchment, W_r ranged from 94.48 to 106.97, with an average of 100.80 (*n = 83, sd: 2.14*). For Silver Carp, W_r ranged from 90.05 to 106.03, with an average of 100.86 (*n = 259, sd = 1.50*).

We examined fecundity of both species by macroscopic observations of ovaries, gonadosomatic index (GSI) calculations, and egg counts estimates of female carp. For both Bighead and Silver Carp, we observed ovaries occupying much of the body cavity and containing developed eggs (i.e., oocytes occupy most of the coelomic cavity) throughout the year. GSI was highest in June for both Bighead Carp and Silver Carp (Figures 39 and 40), with average June GSI values of 16.74 and 21.62, respectively. GSI values for Bighead Carp ranged from 4.07 to 20.65, with an average of 10.76. GSI values for Silver Carp ranged from 3.87 to 26.50, with an average of 15.61. Egg count estimates for Bighead Carp ranged between 254,816 and 1,406,849 with an average of 780,314. Egg count estimates for Silver Carp ranged between 233,739 and 2,510,504 with an average of 1,484,695.

DISCUSSION

Objective 1. Determine the spatial and temporal extent of Bighead and Silver Carp in the Red River basin

Many age-0 fishes are difficult to detect in large river systems (Brewer and Ellersieck 2011), including Bighead and Silver Carp (Roth et al. 2020). Carp are extremely difficult to sample (Wanner and Klumb 2009; Bouska et al. 2017; Roth et al. 2020) and detection was reported at approximately 38% in the presumably highly populated Illinois River basin (Coulter et al. 2018). We selected sampling gears following Collins et al. (2017), who found both mini-fyke nets and beach seines to be the most efficient for capturing age-0 Carp. However, we did not capture any age-0 Carp either due to extremely low sampling detection (i.e., possibly due to very wet conditions in 2021), lack of spawning in Oklahoma, or other influences. Camacho (2016), Collins et al. (2017), and Chick et al. (2020a) have reported stark differences in the successful collection of larval and juvenile Carp in successive years. For example, Collins et al. (2017) collected 39,398 Silver Carp in 2014; however, they collected only 116 in 2015. During the same years, Camacho (2016) captured a higher density of eggs and larval fish in 2014 than in 2015. Our 2021 (i.e., extremely wet) and 2022 (i.e., extremely dry) sampling seasons may be emblematic of extremely low capture years where adults chose not to reproduce (or reproduced further downriver). Because Carp in the lower Red River basin have not been documented at densities as high as the Upper Mississippi River, sampling inefficiencies may be exacerbated.

Sand-bed streams of the Central Great Plains, including the Red River are extremely dynamic and continuously shift over time (e.g., a backwater may be present during the wet months and absent during the dry months). Due to the constant shifts and extreme conditions associated with sand-bed streams, detection of fishes is quite variable and often imperfect (Mollenhauer et al. 2018). The extensive high-flow events observed in 2021 may have influenced our ability to successfully detect juveniles of both species of Carp. Alternatively, the extensive drought conditions of 2022 may have not been favorable conditions for Carp spawning. In June 2021, Red River discharge reached near 2,549 m^3/s (90,000 ft^3/s), roughly

1,982 m^3/s (70,000 ft^3/s) higher than the 78-year median (USGS gage 07337000) (U.S. Geological Survey 2023). However, in June 2022, Red River discharge reached near 80 m^3/s (2,825 ft^3/s), which is roughly 260 m^3/s (9,180 ft^3/s) lower than the 78-year median (USGS gage 07337000). Discharge is assumed to be a spawning cue for Carp and both our seining efficiency and mini-fyke net effort may have been affected by high flows (though it is unlikely we would not have detected a single juvenile). Moreover, because Carp are pelagophils, their eggs may have washed much further downriver during these extremely high flows. Another possibility is the abnormally high and low flows created unfavorable spawning conditions. Lastly, some investigators have suggested water hardness may relate to eggs bursting under some conditions, but this idea has been discounted by others (Chapman and Deters 2009; Rach et al. 2010). Interactions with water hardness and other environmental factors on successful reproduction may be possible.

Occupancy by both Bighead Carp and Silver Carp reflects a catchment that has been invaded for quite some time. Typically, Bighead Carp is the first to invade followed by Silver Carp which then outcompete the former. Silver Carp occupancy was relatively higher (0.78 – 0.85) across the catchment when compared to Bighead Carp (0.53 – 0.78). These occupancy rates indicate that Carp likely inhabit reaches across the majority of the lower Red River catchment (i.e., though first reported in 2012, Patton and Tackett 2015). Estimating species distributions is an important aspect of fisheries management as it can be used to identify important locations for conservation or rehabilitation of imperiled species, or locations for targeted mitigation for invasive species (Anderson et al. 2012). Unfortunately, some of the same features leading to homogenization of the fish assemblage in the lower Red River (Mollenhauer et al. 2022) are also features that appear to benefit invasive Carp.

Although catchment-level, land-use disturbance was relatively constant across our study area, both species of Carp were associated with several instream habitat features that may reflect local disturbances. Across a broader geographic area, more cosmopolitan fish species in the basin were associated with land-use disturbances and altered flow regimes (Mollenhauer et al. 2022). We did not examine longer-term flow patterns due to the temporal scale of our study, and we did not relate Carp occupancy to land-use disturbances because the variability was minimal across our study area. However, several of the attributes we found related to Carp occupancy are related to local disturbances. Lower sinuosity reaches, for example, can reflect channelization or other degradations that result in a less complex channel (Lennox and Rasmussen 2016) and channel incision (i.e., deeper and narrow channels) (Rowe et al. 2009). Habitat complexity typically declines in areas where sinuosity is low and width-to-depth ratios reflect narrower and deeper stream channels. Degradation of natural riparian vegetation, bridge construction, and scouring associated with dams can cause erosion or armoring of stream banks, thereby increasing channel depth and these conditions tend to be associated with invasive species (Bechta and Platts 1986; Chen et al. 2010; Stein et al. 2013; Bueno et al. 2023). Altered flow regimes, common in the catchment (Mollenhauer et al. 2022), also lead to degradation of instream habitat over time where complex, braided channels tend to become greatly miniaturized over time and disconnected from the floodplain (Brewer et al. 2016). The lower Red River has also been regulated to some degree using wing dikes and other structures to direct flow and increase channel depth (Matthews et al. 2005). Calkins et al. (2012) found that Silver Carp used river reaches with wing dikes and avoided those lacking wing dikes likely due to the creation of deeper water, but also the velocity refuges formed behind the dikes (Braun et al. 2016). Ironically, these human alterations are found lower in the catchment, but we did show some correlation between width-to-depth ratio and drainage area. Higher in the stream network, most of the major tributaries are dammed or have deep incised channels associated with erodible lands (Powers 2011). These areas are not managed using environmental flows and thus, except for periods when flood flows are released, several of the tributaries provide slow-moving, warm water that may provide important Carp refuge and feeding areas.

The disconnection between the floodplain and main channel in many reaches of the Red River catchment likely exacerbates the importance of tributary habitat and reaches containing backwaters to both invasive Bighead Carp and Silver Carp. We found Silver Carp to be positively correlated with chlorophyll-a concentrations, which may relate to their feeding strategy. Silver Carp are considered obligate phytoplanktivores, incidentally consuming zooplankton (Li et al. 2013; Ochs et al. 2019). Although variability in our measured chlorophyll-a concentrations was high, some of highest densities of chlorophyll-a concentrations in the lower Red River catchment were observed in tributaries (e.g., Choctaw Creek, Bois d'arc Creek) (though not highly correlated with backwater reaches). Williamson and Garvey (2005) found that Silver Carp predominately consumed phytoplankton in the Mississippi River and proposed that Silver Carp used low-velocity habitats to maximize foraging opportunities. Both the lower tributaries in our study area and backwater habitat provide low-velocity habitats that would facilitate foraging opportunities during the warm-water period. Carp association with low-velocity and off-channel habitats during the warm-water periods is common in many documented areas of the United States (e.g., Illinois River, DeGrandchamp et al. 2008; Wabash River, Coulter et al. 2016a). However, DeGrandchamp (2006) found Bighead Carp and Silver Carp avoided backwater habitats of the Illinois River and instead used main-channel margins during summer and autumn. Effectively monitoring these habitats over time will be beneficial to understanding future population changes.

Objective 2. Determine habitat associations of large river fish assemblages

Throughout the sampling period, we documented 70 fish species throughout the lower Red River basin of Arkansas. Relatively few sampling efforts covering this spatial extent have been devoted to collecting data on the native fish assemblage within the lower Red River basin. From 1995 to 2001, Buchanan et al. (2003) sampled the Arkansas portion of the Red River and reported the collection of 72 fish species. Of the 72 species collected from 1995 to 2001, we collected 62 from all Arkansas sample sites. In addition to the 62 species caught from Buchanan et al. (2003), we collected eight unique species including: American Eel, Bigeye Shiner, Bighead Carp, Flier, Quillback, Sand Shiner, Silver Carp, and Slenderhead Darter. We did not detect 10 species that were reported in Buchanan et al. (2003), however, 9 of those 10 species were described by the authors as “Uncommon” or “Rare” relative to other species (Banded Pygmy Sunfish, Blackside Darter, Blackspotted Topminnow, Creole Darter, Freckled Madtom, Goldeye, Mud Darter, Redspotted Sunfish, and Suckermouth Minnow). One of the sampling techniques used by Buchanan et al. (2003) included rotenone application. Differences in the sampling efficiency between our study and that of Buchanan et al. may be due either to the latter’s use of rotenone, a method we did not use, or to the simple fact that these species are relatively rare. It is worth noting however, that we have sampled four new species in Arkansas in spring 2023 including Bowfin, Grass Pickerel, Redspotted Sunfish, and Yellow Bass.

The high degree of habitat heterogeneity in portions of the lower Red River offers a unique opportunity to study a complex of niches and the species that occupy them. The river is typified by both pools within the thalweg throughout the year as well as sections of shallow braided channels during low flow. In some areas, there are more homogenous habitats where abundant wing dikes and rip-rap lined banks direct flow to maintain deeper pools, while also creating slackwater areas behind them. Other stretches of the river contain little to no artificial channelization, allowing for more dynamic habitat that is typically shallower with a wider channel (i.e., closer to a more natural channel in the Southern Great Plains). Additionally, large oxbow lakes are also present that become laterally connected to the mainstem river during high flow periods, allowing for faunal exchange between the two habitats. By quantifying these reach scale habitat parameters, along with coarse scale metrics, we were able to identify numerous associations between habitat and large-bodied fishes in the lower Red River basin that may be important for species conservation when considering the overlap between invasive Carp habitat use.

Our results from juvenile modeling indicate that nursery habitats in large rivers are largely context dependent, even for closely related species. Nursery habitats in the lower Red River can generally be described as reaches containing off-channel slackwater habitat, having deep pools, with shallow average thalweg depths, further away from dams with lower percentages of limestone geology. Although taxonomically similar species are often thought to use similar habitats that is not always the case (Lowe-McConnell 1987). For example, we found that Green Sunfish *Lepomis cyanellus* and Redear Sunfish *Lepomis microlophus* were positively associated with wider, shallower channels, whereas Bantam Sunfish, Bluegill *Lepomis macrochirus*, Longear Sunfish, and Orangespotted Sunfish tended to occur in reaches with narrower and deeper channels. Although these species are not of conservation concern, it demonstrates the perils of assuming closely related species share habitat choices because they have other shared traits (e.g., body morphology, feeding strategies). Changes in channel slope also appeared to provide context dependency to nursery habitats where fishes in the genera *Ictalurus*, *Ictiobus*, *Pomoxis*, *Lepomis*, and *Dorosoma* all had species with opposing relationships with segment slope. Increased slope can lead to stronger water velocities (Gordon et al. 1992), create more heterogenous water depths (Troutman et al. 2007), and diversify the channel units within the river segment (Harvey and Bencala 1993). It appears that more common species may be more tolerant of homogenous water depths with low water velocities (e.g., Spotted Bass and Bluegill); however, rarer species (e.g., Skipjack Herring and Bigmouth Buffalo) may benefit from the higher water velocity that creates more diverse habitats (Marchetti and Moyle 2001; Walters et al. 2003). Although the mechanisms for these associations are unknown, these varying relationships within closely related species indicate that river slope and width-to-depth ratio relate to different nursery habitat for assemblage members.

Although our results from modeling large-bodied fish habitat indicate there is variation in habitat associations among species, we observed some relationships that were shared between sympatric species. Fish species are often aggregated into guilds when conducting assemblage studies to simplify analyses assuming that species within the same guild will have similar responses (Benoit et al. 2021). Although we did not run our analyses by aggregating fish species into guilds, we observed that some species within similar functional groups tended to have similar habitat associations (though certainly not all of them). For example, filter feeders and semi-benthic species were associated with reaches with backwater present, whereas more benthic species tended to be associated with wider, shallower habitat within the main river channel. All three buffalo species, Longnose and Shortnose Gar, River Carpsucker, Paddlefish, Orangespotted Sunfish, and Bluegill were positively associated with sites containing more backwater. Backwaters provide access to new food resources and can allow fishes to escape swift currents and limit energy expenditure (Junk et al. 1989; Power et al. 1995; Williamson and Garvey 2005). Paddlefish and Bigmouth Buffalo filter feed in the water column and frequently use backwater habitats in other systems where it is hypothesized that they can feed more efficiently (Minckley et al. 1970; Sampson et al. 2009). The substrate in these backwater areas consists of fine silt and clay deposits that may offer foraging resources that are less available in the main channel for benthic omnivores such as Smallmouth Buffalo, Black Buffalo, and River Carpsucker (Quist and Spiegel 2012). Backwater habitats are also probably used by some of these fishes for spawning and subsequent nursery habitat (Quist and Spiegel 2012; Dutterer et al. 2013) as we found both adult and juvenile Orangespotted Sunfish and Bluegill to be associated with them. Although we sampled Alligator Gar *Atractosteus spatula* at sites with more backwater, they had only a weak negative association with them. Instead, they were commonly sampled in tributary sites which may relate to the lower prevalence of backwater habitat as the landscape has continued to become modified for human uses. Shovelnose Sturgeon, alternatively, was weakly associated with reaches containing backwater habitat but more strongly related to wide, shallow, less sinuous reaches. Numerous other species also had a positive association with these areas, including several sunfishes and many benthic species such as Blue Suckers, Black Buffalo, and all three catfish species. Shovelnose Sturgeon use shallow (1.0 - 2.0 m) water depths, over sand substrate, and relatively low velocities in the Kansas River at certain times of the year (Quist et al. 1999). We observed similar behavior with Shovelnose Sturgeon in the lower Red River basin, as cross-sectional depths at sites where we detected Shovelnose Sturgeon averaged between 0.8 and 2.6 m. Blue Suckers are also associated with shallow water depths and areas of swift water velocities in other systems (Acre et al. 2021; Neely et al. 2009). Channel Catfish and Flathead Catfish were observed more frequently in shallower habitats of other rivers, despite their reputation of seeking out the deep pools (Daugherty and Sutton 2005; Braun and Phelps 2016). Although the mechanisms behind these relationships are unclear, our results suggest that wider, and shallow habitats within the basin are important to many of the fish species.

Accounting for incomplete detection is particularly important to assess changes in distributions or occupancy over time, both of which are important when invasive species that may compete for food sources have been introduced. Accounting for detection is also important when surveying for smaller-bodied, rarer, and cryptic species within aquatic ecosystems (Albanese et al. 2011; Schloesser et al. 2012; Wedderburn 2018), but may also help understand fish-habitat relationships of more common species (Sliwinski et al. 2016; Guillera-Arroita 2017). In fact, some species are quite difficult to detect, but are quite common across a catchment (Mollenhauer et al. 2022). Sampling fish assemblages is increasingly difficult as river size, flow, and turbidity increase (Flotemersch et al. 2006). Thus, the importance of accounting for detection when sampling juvenile and adult native fishes in the lower Red River basin is evident from the low detection rates of some species with relatively high occupancy. (e.g., Alligator Gar, Blue Catfish, Blue Sucker, Silver Chub, Logperch, and Redear Sunfish). Without accounting for detection probability, occupancy estimates would have been much lower than the modeled outcome (Mackenzie et al. 2009) and relationships with the habitat parameters would be altered (see also Gerber et al. 2020). By accounting for detection, we were able to produce a less biased estimate of true occupancy within the lower Red River catchment. With the introduction of invasive Bighead Carp and Silver Carp in the catchment, concerns over changes in occupancy or condition of native fishes may be warranted (Schrank et al. 2003). In other catchments, there is evidence that changes to the fish assemblage occur as densities of Carp increase (Carey and Wahl 2010; DeBoer et al. 2018). Having baseline data on the assemblage of juvenile and large-bodied native fishes will be important for monitoring changes in these populations over time and evaluating future management actions.

Objective 3. Summarize the population demographics of Bighead and Silver Carp in the lower Red River basin

Both Silver Carp and Bighead Carp in the Red River catchment have body sizes (i.e., length-at-age) that are commonly associated with relatively recent or continued population invasions. No individuals of either species younger than 3 years of age were collected; however, the younger fish were relatively large with a mean back-calculated TL of 603 mm for Silver Carp and 569 mm for Bighead Carp at age 3. Coulter et. al (2018) found that individuals with greater body condition are more likely to be located on the fringe of the species distribution and are primarily responsible for expanding the species range. River fishes with higher body condition are generally more mobile (Kanno et al. 2023). Furthermore, rivers with robust populations of Silver Carp have relatively smaller fish. For example, Sullivan et al. (2021) found that the mean TL for Silver Carp ranged from 532 – 737 mm in the Missouri, Mississippi, Wabash, and Illinois rivers, whereas the mean TL was 887 mm in our samples from the lower Red River catchment. Additionally, TL for newly established populations of Silver Carp in the Mississippi River and Bighead Carp in the Missouri River ranged from 600 to 800 mm and 450 to 1,099 mm, respectively (Schrank and Guy 2002; Williamson and Garvey 2005).

It is unknown where Carp recruit in the Red River catchment. Silver Carp recruitment variability was relatively stable (RVI of 0.86), which is comparable to what is observed in other catchments such as the Missouri, Mississippi, De Moines, and Wabash rivers (RVI 0.66 – 0.95, Sullivan et al. 2021). This may be due to fish consistently recruiting to the catchment from other river systems (i.e., Atchafalaya River) or steady recruitment in the Red River. However, reproduction was not documented in our study area in 2021-2022 (Ramsey 2023) suggesting these fish were originally from a different basin (i.e., Mississippi River) expanding the invasion front or recruiting from Louisiana. Lack of recruitment in this study area could be due to improper environmental conditions, skewed sex ratios, or disrupted behavioral cues (e.g., dam operations where cues are decoupled). Fertilization rates by Carp can be quite low (e.g., 37%, Gonzal et al. 1987; Lenaerts et al. 2023). If sex ratios are skewed, fertilization rates may be even lower. Moreover, Carp exhibit schooling behaviors (Murchy et al. 2017), and chemical cues associated with schools may be necessary for attracting females. If the populations are relatively low density compared to other populations, then they may currently lack emergent properties that facilitate successful reproduction.

Bighead Carp and Silver Carp in the Red River catchment appear to live longer and grow larger than other populations. Silver Carp L_∞ in the Missouri and Mississippi rivers ranged from 691 to 802-mm TL and Bighead Carp L_∞ was 983-mm in the Mississippi River (Tsehaye et al. 2013; Ridgeway and Bettoli 2017), whereas Silver Carp and Bighead Carp in the lower Red River had a L_∞ of 920 and 1348-mm TL, respectively. This may be because older age classes were present in the lower Red River population, as Silver Carp maximum age was much higher in the lower Red River (i.e., 14 years old) than that typically seen in the Mississippi River basin (i.e., 7 years old) (Schrank and Guy 2002; Williamson and Garvey 2005). This is further highlighted by Silver Carp growth coefficient (*k).* The growth coefficient represents the speed at which fish length approaches the L_∞, with a higher *k* indicating faster growth (Quist and Isermann 2017). Although Silver Carp L_∞ was higher than other populations, the rate of growth (*k* = 0.31) was similar to that of populations in the Mississippi and Illinois rivers (0.23 – 0.445, Tsehaye et al. 2013, Sullivan et. al 2021), whereas Bighead Carp growth rate (*k* = 0.12) was slower relative to Mississippi River populations (0.433, Tsehaye et al. 2013). However, several of the previous studies conducted on Carp in the Mississippi and Illinois rivers used different ageing structures (i.e., fin rays) which may underage Carp compared to lapilli otoliths. This may bias growth estimates, because growth models estimate parameters such as L_∞ and *k* from length-at-age estimates.

Our results indicate lapilli otoliths for ageing and monitoring populations of both Bighead Carp and Silver Carp would be the best choice among hard structures even though between-reader-agreement (BRA) was lower than found in other fishes. Proper age estimates are critical for assessing any of these rates (Koenigs et al. 2013; Anderson et al. 2023). Determining the accuracy of an ageing structure can be difficult for invasive species using known-age fish or marginal increment analysis (Rugg et al. 2014; Anderson et al. 2023). Precision estimates can be used as a surrogate to determine the best structure to age fish when no structure has been validated (Campana 2001). Common precision metrics include BRA and the mean coefficient of variation (CV), where the highest BRA and lowest mean CV indicate the highest precision (Seibert and Phelps 2013). Between-reader-agreement was relatively low for lapilli otoliths (SVC = 0.79, BHC = 0.69) compared other species such as Walleye *Stizostedion vitreum* (BRA

= 0.98), Largemouth Bass *Micropterus salmoides* (BRA = 0.91), Smallmouth Bass *Micropterus dolomieu* (BRA = 0.94), Yellow Perch *Perca flavescens* (BRA = 0.98), and Brown Bullhead *Ameiurus nebulosus* (BRA = 0.92) (Isermann et al. 2003; Maceina and Sammons 2006). Longer lived fishes are inherently more difficult to age compared to fishes with shorter life spans due to crowding of annuli, especially in warm-water systems when growth is more consistent (Quist and Isermann 2017). For example, Dunton et al. (2016) found that BRA for Atlantic Sturgeon *Acipenser oxyrinchus oxyrinchus* was 63% for fin spines and Labay et al. (2011) found that BRA for Blue Sucker *Cycleptus elongatus* was 50% for fin-rays.

Like Seibert and Phelps (2013), we found that using lapilli otoliths for ageing Silver Carp resulted in the highest precision. We are the first to find the same pattern when ageing Bighead Carp. It is dangerous to speculate that patterns observed in one species would be the same for another. For example, both the asteriscus and lapilli otoliths have been validated for ageing Bigmouth Buffalo (Lackmann et al. 2021), yet only lapilli otoliths have been used to age Smallmouth Buffalo and Black Buffalo (Paukert and Long 1999; Love et al. 2019). Although it may be easier to use other structures (Schrank and Guy 2002) to age Bighead Carp, the resulting age would likely be underestimated compared to using otoliths. Age-bias plots comparing age-estimates between lapilli otoliths and all other structures indicated that all other structures in the analysis underestimated fish-age compared to lapilli otoliths (Figures B1 – B2). Similar results have been found with other species including Saugeye *Sander canadensis x vitreus*, Catastomid *Catostomidae spp.*, and Cyprinids *Cyprinidae spp.* species. (Quist et al. 2007; Koch et al. 2018). In addition, the lapilli otolith was useful for determining patterns in growth.

Factors that increase water temperatures and stabilize flows may positively affect growth and recruitment for both species of Carp; however, pressures on water resources and declines in precipitation reducing flows may negatively affect Silver Carp growth. Climate models predict that air temperatures will increase over the next several decades (Dixon et al. 2020; Portner and Roberts 2022). These increasing water temperatures throughout the catchment may lead to an environment that fosters increased growth and an extended spawning period for both Carp species (once successful). Based on a series of predicted models and reviewed data, feeding was observed by Silver Carp at 15-30 °C (Kolar et al. 2007; Cooke and Hill 2010), Bighead Carp at 20-30 °C, and observed or predicted spawning temperatures ranged 14-30 °C (see Table 2 of Cooke 2016). Pease and Paukert (2014) found that Smallmouth Bass *Micropterus dolomieu* growth would increase with warming water temperature due to climate change. Furthermore, McCann et al. (2018) found that Sea Lamprey *Petromyzon marinus* spawning occurred earlier in the year due to increased stream water temperature resulting in possible increased growth and survival of juveniles in the Great Lakes basin. The combination of warming water temperatures increasing Carp growth (assuming available food) and their observed tendency to supplant native species may exacerbate the invasive capabilities of these species. Additionally, growth for both species of Carp was negatively associated with discharge variability. Major impoundments exist on the mainstem Red River (i.e., Dennison Dam) and many of the tributaries (i.e., Kiamichi, Muddy Boggy, Sulpher River) which lead to stabilized flows (Gison et al. 2005; Wang et al. 2016; Zhang et al. 2017). Additional impoundments have recently been constructed or are planned in the catchment (e.g., Bois'd Arc Creek) (Payne et al. 2021), which may further decrease flow variability and lead to increased growth for both Carp species. Flow variability is also positively associated with occupancy of several native species (Mollenhauer et al. 2022). However, the taxing of water resources in the Southern Great Plains and a slight reduction in precipitation is projected to decrease the overall duration and magnitude of flows (Brikowski 2008: Dixon et al. 2020; Portner and Roberts 2022). For example, Dallas, TX requires additional water resources from the Red River catchment, and Oklahoma City will also be diverting additional water from a tributary of the Red River (i.e., Kiamichi River) (Burch et al. 2020; Payne et al. 2021). This may result in a decrease in the consistency of year-to-year growth for Silver Carp punctuated by increased growth during flood years in the lower Red River catchment.

Carp growth and low mortality may be related to low fish density, high food availability, and decreased fishing mortality in the lower Red River. For example, Lorenzen and Endberg (2002) found that asymptotic length for 9 teleost populations had an inverse relationship with species specific biomass density. Additionally, the lower Red River catchment may offer abundant forage which facilitates increased growth. Our chlorophyll-*a* concentrations were on average 32.97 µg/L in the Red River, whereas chlorophyll-a levels in the Mississippi River from 1998 to 2018 were over 20 µg/L only 12% of the time (Turner et al. 2022). Silver Carp exhibited lower mortality (0.32) than populations in the Mississippi River basin (0.65, Tsehaye et al. 2013). The demographic data described by Tsehaye et al. (2013) was derived using pectoral fin spines, which may have led to underestimating fish age and possibly overestimating mortality

(Koenigs et al. 2013). The higher mortality observed in the Mississippi River basin may be related to density dependent mortality or lower fishing mortality compared to other river catchments. For example, Matte et al. (2020) found that mortality of Brook Trout *Salvelinus fontinalis* was positively associated with density. Carp densities are currently perceived to be lower than many other rivers (though sampling indicates otherwise at some locations) and lower densities may improve overall survival. A commercial fishery for Buffalofishes persists in the Arkansas portion of the lower Red River, with incidental Carp bycatch. However, commercial harvest is not permitted in the Oklahoma or Texas portions of the catchment which may alleviate harvest pressure for these Carp populations (but also on native fishes as bycatch). High fishing mortality from commercial harvest and mitigation efforts persists in the Missouri, Mississippi, and Illinois rivers. However, in many cases, there is very limited evidence that removal efforts have resulted in any change in overall population abundance or if they alter the reproductive potential in those populations (i.e., compensatory response).

RECOMMENDATIONS

Future monitoring strategies would benefit from consideration of gear detection and the use of multiple sampling gears. Not accounting for incomplete gear detection can lead to the underestimation of a species' distribution and management strategies that do not have the desired outcomes due to consideration of incorrect underlying ecological relationships (Mackenzie et al. 2002; Anderson et al. 2012). For example, ecological relationships could be inferred with discharge that are a function of detection probability where fish are simply more likely to be captured at lower discharge locations. We found detection probability for Bighead Carp was relatively low (average was 0.39 – 0.40), whereas detection for Silver Carp was higher (average was 0.60 – 0.63). However, we incorporated visual confirmations of Silver Carp into our estimates; otherwise, detection of Silver Carp would have been similar to that of Bighead Carp (0.36). Our results indicate that sampling both Bighead Carp and Silver Carp during warmer water temperatures during relatively low discharge would maximize detection, particularly if the river is turbid. Detection was also lower in the mainstem river. Detection probability of fishes in large rivers is commonly affected by water temperature, discharge, and clarity (Gwinn et al. 2016; Mollenhauer et al. 2018; Zentner et al. 2021). Carp display schooling behavior during warm-water periods which may increase sampling detection (Sullivan et al. 2017). Silver Carp are commonly observed avoiding sampling gears (Williamson and Garvey 2005; Irons et al. 2007). With low detection probabilities, agencies would benefit from either accounting for detection or completing multiple surveys during the season if monitoring for species presence or abundance. In our study area, Bighead Carp could be present at 10 sites but only detected at less than half if we relied on a single survey. This underestimation would be exacerbated if sampling were conducted with a single gear. Moreover, use of multiple gears is necessary if agencies are concerned about monitoring both species at different life stages (Wanner and Klumb 2009). If Carp become more abundant in the Red River catchment, then sampling efficiencies may increase over time (Sullivan et al. 2017), but perhaps at the expense of ecological consequences.

As Bighead Carp and Silver Carp occupy the Red River catchment for longer periods of time, management strategies aimed at preventing their spread and exploiting their vulnerabilities will be key to population control. It would be beneficial for agencies to consider restrictions on locations for anglers to obtain bait if concerned about Carp spreading to new systems. Collecting live bait from one waterway and transferring it to another can aid the spread of Carp to nearby reservoirs or river locations above large dams. Although there is currently no documentation of reproduction in the Red River upstream of the LA-AR border (Ramsey 2023), regular recruitment is occurring in the catchment either from other basins, reaches further downriver, and/or intermittently in the study area (i.e., several large river fishes have been observed to not spawn each year (e.g., White Sucker *Catostomus commersonii*, Quinn and Ross 1985; see also review by Rideout et al. 2005). Future efforts aimed at determining the mobility and timing associated with mobility would be beneficial to assessing the proportion of the population that can be targeted for removal at certain locations. Moreover, if fish recruit from downriver areas, determining actions that prevent movements upstream from locks and dams may be beneficial (e.g., water movement strategies or barriers at the locks, Moy et al. 2011; Hasler et al. 2019; Cupp et al. 2021). Zielenski et al. (2018) found that alterations to lock-and-dam flows via gate operation could reduce Carp passage while maintaining native fish passage. Interestingly, Bighead Carp have low salinity tolerances during their early life stages (Garcia et al. 1999) which may be useful information for determining possible spawning and rearing locations. For example, average survival time of 11-day post-hatch fry was only 3 days at 4% salinity but increased to 96 days at 35 days post hatch (Garcia et al. 1999). However, it is unlikely that salinity will limit reproduction by Silver Carp (larvae tolerance of 6,000–12,000 mg/L CaCO3, Abdusamadov 1986) which appear to be more common in the catchment than Bighead Carp (i.e., based on counts and similar detection probabilities). Targeted removal efforts at locations associated with both species (e.g., reaches with backwaters, near wing dikes, at tributary confluences) may be beneficial in reducing Carp numbers, though changes in resulting population abundances have not been demonstrated to our knowledge. Moreover, caution should be taken with removal efforts as we commonly sampled native big river fishes of concern in the same habitats associated with Carp (e.g., Paddlefish, Alligator Gar *Atractosteus spatula*). To minimize the persistence of Bighead Carp and Silver Carp, while promoting conservation of native fishes, managers would benefit from consideration of a structured approach that considers the responses of multiple species. This approach may be limited by lack of basic information related to the life-history of native fishes. However, unintended consequences can be associated with active management efforts. For example, flow management could be used to increase habitat complexity within some portions of the catchment, but it is unclear how changes in flow may affect non-native fishes (Marks et al. 2010). Agencies would benefit from considering a variety of alternatives that can be tested on a limited basis (or with theoretical models) as both positive and negative feedbacks have been associated with efforts to limit invasive populations.

As Silver Carp and Bighead Carp continue to expand their invasion front, proper assessment and management of these populations will be beneficial if the goal is to reduce their numbers or overall body size. Experimental flows are a mitigation tool that may be used to reduce Carp growth and overall body size via increased discharge variation. For example, Oliveira et al. (2020) found that experimental flows increased body condition of a barbell *Luciobarbus bocagei* in the Vouga River basin. Additionally, Kelly et al. (2017) found that Longnose Dace *Rhinichthys cataractae* and Slimy Sculpin *Cottus cognatus* mortality increased with flow alterations. Altering hydrographs to increase flow variability could negatively affect Carp growth and survival while benefiting some native fishes (see Mollenhauer et al. 2021). However, Silver Carp recruitment has been positively related to flow variability in their native ranges (Coulter et al. 2016b). Therefore, caution is warranted when devising experimental flows with goals related to invasive species as they are sometimes met with unintended consequences. If Carp are not currently successfully recruiting in the lower Red River catchment, then focusing control efforts on immigration points may be a useful strategy. Moreover, examination of possible reproduction over multiple years will be useful to determine when and if reproduction can occur, particularly if the population continues to grow.

Invasive Carp in this catchment are likely to increase without mitigation efforts. Implementing commercial harvest or other removal efforts could increase annual mortality of these populations (though we are unaware of this inducing population collapse or documented declines over large rivers); however, this could harm species of concern (i.e., Alligator Gar *Atractosteus spatula* and Paddlefish) which shared habitat with these invasive fishes and may have limited population level effects on Carp. Novel strategies for attracting Carp, even to artificial habitat, during specific times of the year when native fish mortality would be lower (i.e., cooler water) or timing mitigation efforts when native species densities are lower in these habitats (i.e., backwaters) would seem prudent to reduce the associated risk to native species.

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Table 1. Sample reach locations (latitude [Lat], longitude [Long]), sample dates, and target life stage (i.e., juvenile or adult) for sampling of Silver Carp and Bighead Carp that occurred in the mainstem Red River of the lower Red River basin of Arkansas in 2021-2022.

River	Date	State	Lat	Long	Life stage
Red River	6/29/21	AR	33.58209	-94.06972	Juvenile
Red River	6/29/21	AR	33.57293	-94.06393	Juvenile
Red River	7/5/21	AR	33.60696	-93.84081	Juvenile
Red River	7/5/21	AR	33.61398	-93.81815	Juvenile
Red River	7/9/21	AR	33.56543	-94.38145	Juvenile
Red River	7/12/21	AR	33.58073	-94.36604	Juvenile
Red River	7/13/21	AR	33.43079	-93.7422	Juvenile
Red River	7/14/21	AR	33.09698	-93.85526	Juvenile
Red River	7/18/21	AR	33.549957	-94.31302	Juvenile
Red River	7/21/21	AR	33.58427	-94.4208	Juvenile
Red River	7/21/21	AR	33.58951	-94.44394	Juvenile
Red River	7/21/21	AR	33.59219	-94.4448	Juvenile
Red River	8/4/21	AR	33.56526	-94.3829	Juvenile
Red River	8/9/21	AR	33.07613	-93.83746	Juvenile
Red River	8/9/21	AR	33.06145	-93.82997	Juvenile
Red River	8/10/21	AR	33.10633	-93.86211	Juvenile
Red River	8/10/21	AR	33.14479	-93.84147	Juvenile
Red River	8/12/21	AR	33.394423	-93.71021	Juvenile
Red River	8/12/21	AR	33.39787	-93.7123	Juvenile
Red River	8/13/21	AR	33.61343	-93.82169	Juvenile
Red River	8/13/21	AR	33.55794	-93.79581	Juvenile
Red River	8/18/21	AR	33.60696	-93.84081	Juvenile
Red River	8/24/21	AR	33.58073	-94.36604	Juvenile
Red River	8/30/21	AR	33.06145	-93.82997	Juvenile
Red River	8/31/21	AR	33.39787	-93.7123	Juvenile
Red River	9/1/21	AR	33.15117	-93.82481	Juvenile
Red River	9/2/21	AR	33.61343	-93.82169	Juvenile
Red River	9/21/21	AR	33.56526	-94.3829	Juvenile
Red River	9/22/21	AR	33.549957	-94.31302	Juvenile
Red River	10/4/21	AR	33.58209	-94.06972	Juvenile

Red River	10/5/21	AR	33.57043	-94.06522	Juvenile
Red River	10/6/21	AR	33.60468	-93.83881	Juvenile
Red River	10/8/21	AR	33.39787	-93.7123	Juvenile
Red River	10/11/21	AR	33.58951	-94.44394	Juvenile
Red River	10/21/21	AR	33.42818	-93.74236	Juvenile
Red River	11/1/21	AR	33.5464	-94.38893	Juvenile
Red River	11/2/21	AR	33.07613	-93.83746	Juvenile
Red River	11/8/21	AR	33.57043	-94.06522	Juvenile
Red River	11/11/21	AR	33.61374	-93.8195	Juvenile
Red River	11/15/21	AR	33.5464	-94.38893	Juvenile
Red River	12/1/21	AR	33.394423	-93.71021	Juvenile
Red River	5/23/22	AR	33.09698	-93.85526	Juvenile
Red River	5/23/22	AR	33.1014	-93.85952	Juvenile
Red River	5/26/22	AR	33.394423	-93.71021	Juvenile
Red River	5/26/22	AR	33.39787	-93.7123	Juvenile
Red River	5/27/22	AR	33.60468	-93.83881	Juvenile
Red River	5/27/22	AR	33.61374	-93.8195	Juvenile
Red River	5/29/22	AR	33.56572	-94.38213	Juvenile
Red River	5/29/22	AR	33.57875	-94.36662	Juvenile
Red River	6/7/22	AR	33.05964	-93.82763	Juvenile
Red River	6/7/22	AR	33.07613	-93.83746	Juvenile
Red River	6/8/22	AR	33.394423	-93.71021	Juvenile
Red River	6/8/22	AR	33.39787	-93.7123	Juvenile
Red River	6/9/22	AR	33.61374	-93.8195	Juvenile
Red River	6/9/22	AR	33.60468	-93.83881	Juvenile
Red River	6/14/22	AR	33.59486	-94.44614	Juvenile
Red River	6/14/22	AR	33.58951	-94.44394	Juvenile
Red River	6/15/22	AR	33.58209	-94.06972	Juvenile
Red River	6/15/22	AR	33.57043	-94.06522	Juvenile
Red River	6/17/22	AR	33.39787	-93.7123	Juvenile
Red River	6/17/22	AR	33.394423	-93.71021	Juvenile
Red River	6/23/22	AR	33.05964	-93.82763	Juvenile
Red River	6/23/22	AR	33.07613	-93.83746	Juvenile
Red River	6/24/22	AR	33.55794	-93.79581	Juvenile

Red River	6/24/22	AR	33.56409	-93.81904	Juvenile
Red River	7/2/22	AR	33.57875	-94.36662	Juvenile
Red River	7/2/22	AR	33.56572	-94.38213	Juvenile
Red River	7/8/22	AR	33.56572	-94.38213	Juvenile
Red River	7/8/22	AR	33.57875	-94.36662	Juvenile
Red River	7/13/22	AR	33.09698	-93.85526	Juvenile
Red River	7/13/22	AR	33.1014	-93.85952	Juvenile
Red River	7/15/22	AR	33.60468	-93.83881	Juvenile
Red River	7/15/22	AR	33.61374	-93.8195	Juvenile
Red River	7/18/22	AR	33.55376	-94.03548	Juvenile
Red River	7/18/22	AR	33.55618	-94.02374	Juvenile
Red River	7/27/22	AR	33.58951	-94.44394	Juvenile
Red River	7/27/22	AR	33.59486	-94.44614	Juvenile
Red River	7/28/22	AR	33.56409	-93.81904	Juvenile
Red River	7/28/22	AR	33.55794	-93.79581	Juvenile
Red River	7/29/22	AR	33.05964	-93.82763	Juvenile
Red River	7/29/22	AR	33.07613	-93.83746	Juvenile
Red River	8/9/22	AR	33.09698	-93.85526	Juvenile
Red River	8/9/22	AR	33.1014	-93.85952	Juvenile
Red River	8/11/22	AR	33.56409	-93.81904	Juvenile
Red River	8/11/22	AR	33.55794	-93.79581	Juvenile
Red River	8/12/22	AR	33.58209	-94.06972	Juvenile
Red River	8/12/22	AR	33.57043	-94.06522	Juvenile
Red River	9/7/22	AR	33.55618	-94.02374	Juvenile
Red River	9/7/22	AR	33.55376	-94.03548	Juvenile
Red River	9/14/22	AR	33.59486	-94.44614	Juvenile
Red River	9/14/22	AR	33.58951	-94.44394	Juvenile
Red River	9/15/22	AR	33.58209	-94.06972	Juvenile
Red River	9/15/22	AR	33.57043	-94.06522	Juvenile
Red River	9/30/22	AR	33.55376	-94.03548	Juvenile
Red River	9/30/22	AR	33.55618	-94.02374	Juvenile
Red River	6/29/21	AR	33.55708	-94.04868	Adult
Red River	7/5/21	AR	33.60915	-93.8242	Adult
Red River	7/9/21	AR	33.56842	-94.38122	Adult

Red River	7/12/21	AR	33.58881	-94.37804	Adult
Red River	7/13/21	AR	33.43524	-93.73965	Adult
Red River	7/13/21	AR	33.09082	-93.85964	Adult
Red River	7/18/21	AR	33.5515	-94.39453	Adult
Red River	8/4/21	AR	33.58881	-94.37804	Adult
Red River	8/18/21	AR	33.60932	-93.85986	Adult
Red River	8/24/21	AR	33.56842	-94.38122	Adult
Red River	8/30/21	AR	33.06602	-93.83293	Adult
Red River	8/31/21	AR	33.39703	-93.71171	Adult
Red River	9/1/21	AR	33.1568	-93.81832	Adult
Red River	9/2/21	AR	33.60915	-93.8242	Adult
Red River	9/21/21	AR	33.58881	-94.37804	Adult
Red River	9/22/21	AR	33.5515	-94.39453	Adult
Red River	10/11/21	AR	33.5998	-94.44686	Adult
Red River	10/08/21	AR	33.39703	-93.71171	Adult
Red River	10/06/21	AR	33.60932	-93.85986	Adult
Red River	10/05/21	AR	33.55708	-94.04868	Adult
Red River	10/04/21	AR	33.57537	-94.08128	Adult
Red River	10/21/21	AR	33.43524	-93.73965	Adult
Red River	11/01/21	AR	33.5515	-94.39453	Adult
Red River	11/02/21	AR	33.07597	-93.8387	Adult
Red River	11/08	AR	33.55708	-94.04868	Adult
Red River	11/11/21	AR	33.60915	-93.8242	Adult
Red River	11/15/21	AR	33.5515	-94.39453	Adult
Red River	12/01/21	AR	33.39703	-93.71171	Adult
Red River	12/06/21	AR	33.60932	-93.85986	Adult
Red River	12-7-21	AR	33.59526	-94.42342	Adult
Red River	12/8/21	AR	33.09082	-93.85964	Adult
Red River	12/14/21	AR	33.55226	-94.04026	Adult
Red River	12/16/21	AR	33.55718	-94.0195	Adult
Red River	01/06/22	AR	33.07597	-93.8387	Adult
Red River	1/10/22	AR	33.39703	-93.71171	Adult
Red River	1/11/22	AR	33.5515	-94.39453	Adult
Red River	1/12/22	AR	33.58881	-94.37804	Adult

Red River	1/18/22	AR	33.34793	-93.71021	Adult
Red River	1/31/22	AR	33.60915	-93.8242	Adult
Red River	2/01/22	AR	33.59526	-94.42342	Adult
Red River	3/31/2022	AR	33.07597	-93.8387	Adult
Red River	3/29/22	AR	33.55718	-94.0195	Adult
Red River	3/22/22	AR	33.59526	-94.42342	Adult
Red River	3/15/22	AR	33.56842	-94.38122	Adult
Red River	3/23/22	AR	33.58881	-94.37804	Adult
Red River	3/24/22	AR	33.56842	-94.38122	Adult
Red River	4/01/22	AR	33.39703	-93.71171	Adult
Red River	4/04/22	AR	33.60915	-93.8242	Adult
Red River	4/05/22	AR	33.5515	-94.39453	Adult
Red River	4/06/22	AR	33.34793	-93.71021	Adult
Red River	4/11/22	AR	33.5998	-94.44686	Adult
Red River	4/12/22	AR	33.09082	-93.85964	Adult
Red River	4/25/22	AR	33.55708	-94.04868	Adult
Red River	4/26/22	AR	33.57537	-94.08128	Adult
Red River	4/29/22	AR	33.58881	-94.37804	Adult
Red River	5/02/22	AR	33.06602	-93.83293	Adult
Red River	5/6/22	AR	33.5515	-94.39453	Adult
Red River	5/11/22	AR	33.14741	-93.83134	Adult
Red River	5/12/22	AR	33.13784	-93.82909	Adult
Red River	5/23/22	AR	33.14741	-93.83134	Adult
Red River	5/27/22	AR	33.09082	-93.85964	Adult
Red River	5/28/22	AR	33.58881	-94.37804	Adult
Red River	6/5/22	AR	33.55708	-94.04868	Adult
Red River	6/7/22	AR	33.57537	-94.08128	Adult
Red River	6/8/22	AR	33.60915	-93.8242	Adult
Red River	6/9/22	AR	33.39703	-93.71171	Adult
Red River	6/13/22	AR	33.13784	-93.82909	Adult
Red River	6/15/22	AR	33.5998	-94.44686	Adult
Red River	6/17/22	AR	33.34793	-93.71021	Adult
Red River	6/21/22	AR	33.58881	-94.37804	Adult
Red River	7/6/22	AR	33.5998	-94.44686	Adult

Red River	7/8/22	AR	33.5515	-94.39453	Adult
Red River	7/15/22	AR	33.57537	-94.08128	Adult
Red River	7/15/22	AR	33.55708	-94.04868	Adult
Red River	7/20/22	AR	33.34793	-93.71021	Adult
Red River	7/20/22	AR	33.39703	-93.71171	Adult
Red River	7/25/22	AR	33.60915	-93.8242	Adult
Red River	7/27/22	AR	33.14741	-93.83134	Adult
Red River	7/27/22	AR	33.14741	-93.83134	Adult
Red River	8/8/22	AR	33.59898	-93.81232	Adult
Red River	8/10/22	AR	33.55718	-94.0195	Adult
Red River	8/23/22	AR	33.59898	-93.81232	Adult
Red River	8/29/22	AR	33.55718	-94.0195	Adult
Red River	9/12/22	AR	33.59898	-93.81232	Adult
Red River	9/21/22	AR	33.55718	-94.0195	Adult
Red River	10/10/22	AR	33.106	-93.86143	Adult
Red River	10/12/22	AR	33.33958	-93.69724	Adult
Red River	10/18/22	AR	33.54689	-94.38066	Adult
Red River	10/26/22	AR	33.60848	-93.81358	Adult
Red River	11/8/22	AR	33.56936	-94.06402	Adult
Red River	11/15/22	AR	33.56399	-94.00924	Adult
Red River	11/16/22	AR	33.54689	-94.38066	Adult
Red River	12/5/22	AR	33.58588	-94.41962	Adult
Red River	12/6/22	AR	33.33958	-93.69724	Adult
Red River	1/10/23	AR	33.03102	-93.82587	Adult
Red River	1/11/23	AR	33.54689	-94.38066	Adult
Red River	1/19/23	AR	33.03102	-93.82587	Adult
Red River	1/26/23	AR	33.56936	-94.06402	Adult
Red River	1/30/23	AR	33.14349	-93.84161	Adult
Red River	2/6/23	AR	33.33958	-93.69724	Adult

Table 2. The dimensions of each sampling net used for Silver and Bighead Carp studies in the Red River basin, Arkansas.   The target life-history stage is indicated.

Gear	Length	Height	Mesh size	Target stage
Gillnet	100’	12’	3.5”, 4”, 4.25”	Adult
Gillnet	180’	12’	3.5”, 4”, 4.25”	Adult
Hoop net	16’	4’	3”	Adult
Seine	15’	6’	1/8”	Juvenile
Seine	11’	6’	1/32”	Juvenile
Mini-fyke net	4’	2’	1/8”	Juvenile
Larval tow	1.65m	0.5m	500µm	Juvenile

Table 3. Detection covariates with their associated spatial scale, resolution, and a description of the ecological importance (Justification) for juvenile fishes. Bold covariates were retained for model building after consideration of correlations and effect sizes.

Scale	Covariate	Justification
Reach	Calendar day (24 h)	As fish grow larger and increase in abundance during the season, they are easier to detect[1]
	Temperature (1.0 °C)	Fish move more and grow larger in warmer conditions making them easier to detect.[1,2]
	Clarity (1.0 cm)	Higher clarity water may allow fish to more easily evade gears.[3]
	Dissolved oxygen (1.00 mg/L)	Decreased dissolved oxygen levels can make fish harder to detect .[4]
	Seine effort (1.0 m^2)	Higher sampling effort can increase species detection.[5]
Segment	**Discharge** (m^3/s)	High flows can reduce gear efficiency, making fish more difficult to detect.[6,7]

1. (Brewer and Ellersieck 2011) 2. (Coutant 1976) 3. (Zamor and Grossman 2007) 4. (Tyler and Targett 2007) 5. (Pritt et al. 2014) 6. (Nunn et al. 2012) 7. (Love et al. 2017)

Table 4. Occupancy covariates with their associated spatial scale, resolution, and a description of the ecological importance (Justification) for juvenile fishes. Bold covariates were retained for model building after consideration of correlations | r |<0.50. Parameters with * indicate they were transformed to categorical covariates due to the distribution of these data. LDI indicates landscape disturbance index, LWD indicates large woody debris, and Dam indicates the distance from the nearest upstream dam.

Scale	Covariate	Justification
Reach	Salinity (1.0 ppt)	Salinity levels in the Red River basin are highly variable and may influence occupancy.[1]
	Zooplankton (1.0 #)	Increased zooplankton densities may increase juvenile fish occupancy because they are the primary food source.[2]
	Thalweg depth (1.0 m)	Juvenile fishes may be negatively associated with deeper channel depths.[3]
	Width-to-depth (1.0 m)	Wider, shallower channels may be more positively associated with nursery habitat.[4]
	LWD (1.00 %)	Juvenile fish may be positively associated with LWD because they use it as shelter.[4,5]
	***Slackwater** (1.00 %)	Juvenile fish likely occupy reaches containing slackwaters because they are important nursery habitats for large river fishes.[6]
	***Deep pools** (1.00 %)	Pools offer low-velocity areas within the main channel and can positively influence occupancy.[7]
	Dam (1.0 km)	Dams are potential spawning locations of migratory species and affect flow regimes.[7,8]
Segment	**Discharge** (m^3/s)	Reaches experiencing lower discharges may be beneficial for juvenile species.[9,10]
	Sinuosity (1.0 index)	More sinuous stretches of river may contain more habitat complexity that can be used by juvenile fishes.[11]
	Slope (1.00%)	Higher stream gradients have higher water velocities which may negatively influence juvenile species occupancy.[12]

Catchment	***Drainage area** (1.0 km^2)	Juvenile fish may occupy nursery habitats within tributaries more strongly than the mainstem river.[13]
	LDI (1.0 index)	Human disturbance can degrade nursery habitat negatively influencing occupancy.[14]
	Limestone (1.00%)	Limestone composition controls local pH levels which can affect egg survival.[15,16]

1. (Hargrave and Taylor 2010b) 2. (Fernando 1994) 3. (Lamouroux et al. 1998) 4. (Thomson et al. 2001) 5. (Everett and Ruiz 1993) 6. (Galat et al. 2004) 7. (Schwartz and Herricks 2005) 7. (Poff et al. 1997) 8. (Soares et al. 2022) 9. (Nunn et al. 2012) 10. (Love et al. 2017) 11. (Warfe and Barmuta 2006) 12. (Camana et al. 2016) 13. (Pracheil et al. 2009) 14. (Schlosser 1995) 15. (Frissell et al. 1986) 16. (Swain et al. 2020)

Table 5. Covariates used to estimate occupancy probability (Ψ) and detection (p) hypothesized to be related to Carp and native fish distributions in the lower Red River catchment with the corresponding state (occupancy [Ψ], and detection [p]), scale, data source, unit, URL, and citation.

Habitat factor	State	Scale	Data source	Unit	URL
Drainage area[1]	Ψ	Catchment	NHD+/Stream Stats	km^2	https://apps.nationalmap.gov/downloader/#/
Disturbance[2]	Ψ	Catchment	NLCD	LDI	https://apps.nationalmap.gov/downloader/#/
Lithology[3]	Ψ	Catchment	U.S. Geological Survey	% limestone	https://mrdata.usgs.gov/geology/state/
Sinuosity[1]	Ψ	Segment	ArcPro GIS		https://apps.nationalmap.gov/downloader/#/
Slope[1]	Ψ	Segment	ArcPro GIS	%	https://apps.nationalmap.gov/downloader/#/
Discharge[4]	Ψ	Segment	U.S. Geological Survey	m^3/s	https://waterdata.usgs.gov/nwis/rt
Distance to Dam[1]	Ψ	Reach	ArcPro GIS	rkm	https://apps.nationalmap.gov/downloader/#/
Percent backwater	Ψ	Reach	Field collection	%	
Width to depth	Ψ	Reach	Field collection		
Salinity	Ψ	Reach	YSI pro dds	ppt	
Chlorophyll-a	Ψ	Reach	Water sample	mg/L	
Temperature	P	Reach	Field collection	°C	
Discharge[4]	P	Segment	U.S. Geological Survey	m^3/s	https://waterdata.usgs.gov/nwis/rt
Secchi depth	P	Reach	Field collection	cm	
Electrofishing effort	p	Reach	Field collection	S	

Table 6. Covariate combinations (backwater [Bck], discharge [Q], chlorophyll-*a* [Chla], width-to-depth ratio [W:D], sinuosity [Sin], distance to dam [Dtd], and salinity [Sal]) for the two overarching hypothesized models (growth and spawn) related to Carp occupancy in the Red River basin.

Model framework	Model combinations
Growth	Bck
	Q
	Bck + Q
	Chla
	W:D
	Bck + Chla
	Bck + Sin
	Bck + W:D
	Q + Chla
	Q + Sin
	Q + W:D
	Sin + Chla
	Sin + Chla
	W:D + Chla
	W:D + Sin
	Bck + Q + Chla
	Bck + Q + Sin
	Bck + Q + W:D
	Bck + Sin + Chla
	Bck + W:D + Chla
	Bck + W:D + Sin
	Bck + Q + W:D + Chla
	Bck + Q + W:D + Sin
	Bck + W:D + Sin + Chla
	Q + W:D + Sin + Chla
	Bck + Q + W:D + Sin + Chla
Spawn	Bck
	Q
	Bck + Q
	Dtd
	Sal
	Bck + Dtd
	Bck + Sal
	Q + Dtd
	Q + Sal

	Sal + Dtd
	Bck + Q + Dtd
	Bck + Q + Sal
	Bck + Sal + Dtd
	Sal + Dtd + Q
	Bck + Q + Sal + Dtd

Table 7. Model combinations for evaluating the relationship between Silver Carp and Bighead Carp growth and environmental factors. Model combinations for Weisberg models: model intercept [B0], fish age [A], coefficient of variation (CV) of discharge [CV.Q], CV of air temperature [CV.T], discharge [Q], and air temperature [T]. Random effects (i.e., fish and year) were included in all models.

Models
~ B0 + A
~ B0 + A + CV.Q
~ B0 + A + CV.T
~ B0 + A + Q
~ B0 + A + Q + CV.Q
~ B0 + A + Q + CV.T
~ B0 + A + Q + CV.T + CV.Q
~ B0 + A + Q + T
~ B0 + A + T
~ B0 + A + T + CV.Q
~ B0 + A + T + CV.T
~ B0 + A + T + CV.T + CV.Q
~ B0 + A + T + Q
~ B0 + A + T + Q + CV.Q
~ B0 + A + T + Q + CV.T
~ B0 + A + T + Q + CV.T + CV.Q

Table 8. Overarching hypothesized model (growth and spawn) with associated covariates (backwater [Bck], discharge [Q], width-to-depth ratio [W:D], sinuosity [Sin], chlorophyll-*a* [Chla], salinity [Sal], and distance to dam [Dtd]) and the corresponding hypothesis of their relationship to occupancy by Silver Carp and Bighead Carp.

Model	Covariate	Hypothesis
Growth	Bck	Backwaters can offer higher forage potential, growth potential because of warmer water temperature for bioenergetics, and decreased energy expenditure. [1,2,3]
	Q	Negatively associated because of increased energy expenditure and lower forage availability. [4, 5, 6, 7]
	W:D	Carp growth positively associated due to low-velocity habitats, increased forage, and decreased competitor species due to lower habitat complexity [8, 9, 10, 11]
	Sin	Increased growth because of decreased competitor species and decreased habitat complexity. [10, 11]
	Chla	Increased forage available for growth. [12, 13, 14]
Spawn	Bck	Possibly used as staging locations for spawning. [15, 16, 17]
	Q	Positively associated with discharge because of increased flow requirements for pelagic spawners and successful spawning associated with high discharge. [18, 19, 20]
	Sal	Improper salinity can hinder spawning. [21, 22]
	Dtd	Positively associated with presence because of minimum flow distance requirements for successful spawning and flow alteration can affect recruitment. [23, 24, 25]

[1]Williamson and Garvey 2005, [2]Humphries et al. 2006, [3]Coulter et al. 2017, [4]rNewbold et al. 2016, [5]Hoover et al. 2017, [6]MacNamara et al. 2018, [7]Pretchel et al. (2018), [8]Williamson and Garvey 2005, [9]Scheler et al. 2012, [10]Hasegawa and Maekawa (2008), [11]Alexander et al. (2015), [12]Calkins et al. 2012, [13]Li et al. 2013, [14]Ochs et al. 2019, [15]Junk et al. 1989, [16]Coulter et al. 2017, [17]Whitten et al. 2021, [18]Kolar et al. 2007, [19]Gibson-Reinemer et al. 2017, [20]Lenaerts et al. 2021, [21]Akimova et al. 2016, [22]Neves et al. 2019, [23]Duan et al. 2009, [24]Song et al. (2018), [25]Parkos III et al. 2021

Table 9. Demographic information of most Bighead Carp (BHC) and Silver Carp (SVC) collected from May 2021 through December 2022 during sampling events. The sample date, location, and gears used are provided. Total length (TL, mm), weight (W, g), and sex (male [M] or female [F]) of each fish are provided. The age estimates using otoliths are provided. These carp were sampled using gillnets (GN), electrofishing (EF), bow-fishermen (BF) which were received from the U.S. Fish and Wildlife Service or jumped in the boat during a survey (JM). The latitude and longitude were measured at the most downstream portion of each reach. These locations (and those lacking demographic data) have all been provided to the U.S. Geological Survey, NAS reporting page via communication with Dr. Matt Neilson (U.S. Geological Survey, written communication, 2023). Livers from a subsample of these fish were frozen and are currently being housed in a laboratory freezer at Auburn University. Fin clips from a subset of these fish were mailed to the U.S. Geological Survey on August 9, 2022 (Stephen F. Spear, U.S. Geological Survey, 2022). We have two additional containers of livers and fin clips that have been collected since August 2022 that are currently housed in a laboratory at Auburn University. We stopped collecting livers and fin clips in May 2023.

State	River	Date	Latitude	Longitude	Species	TL	W	Gear	Sex	Age
TX	Bois d'Arc	7/7/2021	33.82851	-95.85503	BHC	1048	12840	GN	F	11
OK	Red River	7/16/2021	33.63824	-94.58038	BHC	1240	-	GN	F	4
TX	Bois d'Arc	7/23/2021	33.82851	-95.85503	BHC	1245	-	GN	M	11
TX	Bois d'Arc	7/23/2021	33.82851	-95.85503	BHC	1090	-	GN	F	13
AR	Red River	8/4/2021	33.57763	-94.36778	BHC	1108	13670	GN	M	9
TX	Choctaw	8/10/2021	33.71952	-96.3907	BHC	1097	14220	GN	F	12
TX	Choctaw	8/10/2021	33.71952	-96.3907	BHC	1100	13480	GN	M	11
TX	Choctaw	8/10/2021	33.71952	-96.3907	BHC	1140	15180	GN	M	6
TX	Choctaw	8/10/2021	33.71952	-96.3907	BHC	990	9260	GN	M	5
TX	Choctaw	8/11/2021	33.72068	-96.39828	BHC	1069	12000	GN	M	11
OK	Red River	8/23/2021	33.8032	-94.91955	BHC	1230	21500	GN	-	6
AR	Red River	8/24/2021	33.57763	-94.36778	BHC	960	17500	GN	-	9
TX	Choctaw	11/16/2021	33.71952	-96.3907	BHC	1205	18000	GN	M	13
TX	Choctaw	11/16/2021	33.71952	-96.3907	BHC	1033	10025	EF	F	13

TX	Choctaw	12/15/2021	33.71952	-96.3907	BHC	1225	23000	EF	F	16
TX	Choctaw	1/4/2022	33.71952	-96.3907	BHC	974	11000	EF	M	8
TX	Choctaw	1/5/2022	33.71952	-96.3907	BHC	1252	-	EF	F	15
OK	Kiamichi	1/19/2022	34.00923	-95.38224	BHC	1092	12400	EF	F	9
OK	Red River	2/8/2022	33.77009	-96.42174	BHC	1020	11600	EF	M	8
OK	Red River	2/8/2022	33.77009	-96.42174	BHC	1232	20450	GN	M	10
OK	Red River	2/8/2022	33.77009	-96.42174	BHC	1152	17200	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	BHC	1052	17100	GN	M	15
AR	Red River	3/23/2022	33.58165	-94.36528	BHC	968	8870	GN	F	9
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1204	17600	GN	M	11
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1200	18000	GN	M	8
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1114	15500	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1180	16500	GN	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1164	18500	GN	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1142	15300	GN	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1206	18300	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1148	16400	GN	M	11
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1092	15400	GN	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1050	13000	GN	M	4
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1062	9784	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1090	14500	GN	M	13
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1299	20000	GN	M	17
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1123	14600	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1151	14600	GN	M	11
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1210	16100	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	BHC	1120	18400	GN	M	12
TX	Choctaw	4/13/2022	33.72068	-96.39828	BHC	1258	17000	GN	F	15
TX	Choctaw	4/13/2022	33.72068	-96.39828	BHC	1152	12500	GN	F	10
OK	Red River	5/13/2022	33.91901	-95.07648	BHC	1063	10600	GN	M	9

OK	Kiamichi	5/26/2022	33.9605	-95.25517	BHC	1050	9300	GN	M	11
OK	Kiamichi	5/26/2022	33.9605	-95.25517	BHC	1068	11400	GN	M	8
AR	Red River	5/28/2022	33.58165	-94.36528	BHC	1004	11892	GN	M	9
AR	Red River	5/28/2022	33.58165	-94.36528	BHC	1198	16750	EF	F	12
AR	Red River	5/28/2022	33.58165	-94.36528	BHC	1350	27750	EF	F	12
OK	Red River	6/6/2022	33.8032	-94.91955	BHC	1298	-	EF	F	11
OK	Red River	6/6/2022	33.8032	-94.91955	BHC	1016	-	GN	M	10
OK	Red River	6/16/2022	33.63824	-94.58038	BHC	1050	16600	GN	-	-
AR	Red River	6/21/2022	33.58165	-94.36528	BHC	1172	15250	EF	M	15
OK	Kiamichi	6/23/2022	33.9605	-95.25517	BHC	1015	10300	GN	F	9
OK	Kiamichi	6/23/2022	33.9605	-95.25517	BHC	1250	25250	GN	M	16
OK	Kiamichi	6/23/2022	33.9605	-95.25517	BHC	1048	11600	GN	M	11
OK	Garland Creek	6/24/2022	33.92015	-95.07693	BHC	1122	14900	GN	F	5
OK	Garland Creek	6/24/2022	33.92015	-95.07693	BHC	1333	13700	GN	M	-
OK	Garland Creek	6/24/2022	33.92015	-95.07693	BHC	949	11100	GN	M	4
TX	Pine Creek	6/28/2022	33.87272	-95.30441	BHC	952	10200	GN	M	9
OK	Muddy Boggy	7/5/2022	33.94254	-95.59405	BHC	1033	12000	GN	M	9
OK	Muddy Boggy	7/5/2022	33.94254	-95.59405	BHC	979	11900	GN	M	12
OK	Muddy Boggy	7/5/2022	33.94254	-95.59405	BHC	1022	21000	GN	M	11
OK	Muddy Boggy	7/5/2022	33.94254	-95.59405	BHC	1046	11400	GN	M	12
OK	Muddy Boggy	7/5/2022	33.94254	-95.59405	BHC	1033	18000	GN	-	11
TX	Choctaw	7/19/2022	33.72068	-96.39828	BHC	1073	20500	GN	F	13
OK	Kiamichi	7/28/2022	33.9605	-95.25517	BHC	1051	11600	GN	M	11
OK	Kiamichi	7/28/2022	33.9605	-95.25517	BHC	1050	11100	GN	M	13
OK	Kiamichi	8/1/2022	33.96159	-95.28264	BHC	1021	9500	EF	F	10
OK	Kiamichi	8/1/2022	33.96159	-95.28264	BHC	1201	21100	GN	M	12
TX	Bois d'Arc	8/2/2022	33.82851	-95.85503	BHC	1000	12900	GN	M	10
TX	Choctaw	8/3/2022	33.71952	-96.3907	BHC	1054	19500	GN	F	15
TX	Bois d'Arc	8/5/2022	33.82851	-95.85503	BHC	1004	10000	GN	M	7

TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	BHC	1105	15500	GN	M	8
TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	BHC	1018	14500	EF	M	9
TX	Bois d'Arc	8/11/2022	33.82252	-95.86404	BHC	868	9000	GN	M	11
TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	BHC	1061	15500	GN	M	12
OK	Kiamichi	11/3/2022	33.00632	-95.37972	BHC	1020	11200	EF	F	
OK	Kiamichi	11/3/2022	33.00632	-95.37972	BHC	1012	10500	EF	F	
OK	Cutoff Oxbow	11/7/2022	33.75273	-94.75616	BHC	1360	35500	GN	F	
AR	Red River	11/16/2022	33.54689	-94.38066	BHC	1134	18600	GN	M	
AR	Red River	11/16/2022	33.54689	-94.38066	BHC	1133	14450	GN	M	
AR	Red River	7/5/2021	33.60848	-93.81358	SVC	710	3880	EF	F	4
AR	Red River	7/9/2021	33.57763	-94.36778	SVC	897	7260	GN	M	-
AR	Red River	7/12/2021	33.58165	-94.36528	SVC	912	7460	GN	M	6
OK	Kiamichi	7/15/2021	33.96051	-95.29222	SVC	708	3850	GN	M	3
AR	Red River	8/4/2021	33.57763	-94.36778	SVC	808	6460	EF	M	5
TX	Choctaw	8/10/2021	33.71952	-96.3907	SVC	850	7600	GN	M	7
TX	Choctaw	8/11/2021	33.72068	-96.39828	SVC	851	8100	EF	M	8
TX	Choctaw	8/11/2021	33.72068	-96.39828	SVC	882	8350	EF	F	3
AR	Red River	8/24/2021	33.57763	-94.36778	SVC	850	9000	EF	-	8
AR	Red River	8/24/2021	33.57763	-94.36778	SVC	752	5020	EF	F	5
AR	Red River	8/24/2021	33.57763	-94.36778	SVC	783	6300	GN	-	4
AR	Red River	9/21/2021	33.58165	-94.36528	SVC	876	8500	JM	F	4
AR	Red River	9/21/2021	33.58165	-94.36528	SVC	752	4800	GN	F	3
AR	Red River	10/24/2021	33.58165	-94.36528	SVC	952	9500	GN	-	8
AR	Red River	10/24/2021	33.58165	-94.36528	SVC	830	6000	JM	-	5
TX	Choctaw	11/16/2021	33.71952	-96.3907	SVC	932	10750	GN	F	3
TX	Choctaw	11/16/2021	33.71952	-96.3907	SVC	765	6000	EF	F	5
TX	Choctaw	11/16/2021	33.71952	-96.3907	SVC	1020	12050	EF	F	10
TX	Choctaw	12/15/2021	33.71952	-96.3907	SVC	902	8000	GN	M	7
TX	Choctaw	1/4/2022	33.71952	-96.3907	SVC	911	8500	EF	F	4

AR	Red River	1/6/2022	33.05954	-93.82767	SVC	750	4750	GN	M	5
AR	Red River	1/6/2022	33.05954	-93.82767	SVC	820	5500	GN	M	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	915	11000	EF	F	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	865	8600	EF	M	9
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	902	8600	EF	M	9
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	904	7000	EF	M	8
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	894	7000	EF	M	8
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	848	7000	EF	M	6
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	850	7700	EF	M	10
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	899	10000	EF	F	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	868	7000	EF	M	7
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	945	12600	EF	F	6
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	815	7500	EF	M	4
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	852	8000	EF	F	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	1090	15200	EF	F	12
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	842	7500	EF	F	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	926	11500	EF	M	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	915	11400	EF	F	13
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	1036	12900	EF	F	11
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	872	9500	EF	F	6
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	945	11800	EF	F	11
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	821	6250	EF	M	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	828	6750	GN	M	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	828	8000	GN	M	11
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	822	8200	GN	F	5
AR	Red River	1/12/2022	33.58165	-94.36528	SVC	820	8750	GN	M	6
AR	Red River	1/18/2022	33.33958	-93.69724	SVC	872	6750	EF	M	4
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	928	10000	GN	M	8
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	834	7400	GN	F	5

OK	Red River	2/8/2022	33.77009	-96.42174	SVC	878	7100	GN	M	4
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	892	8000	GN	M	9
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	920	8900	GN	M	9
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	798	6000	GN	M	4
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	828	6400	GN	M	5
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	780	6250	GN	F	5
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	818	6000	GN	M	4
OK	Red River	2/8/2022	33.77009	-96.42174	SVC	854	7600	GN	M	9
TX	Choctaw	3/2/2022	33.72068	-96.39828	SVC	797	5750	GN	M	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	938	9478	EF	M	10
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	870	6732	EF	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	898	8860	EF	F	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	829	4768	EF	M	7
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	811	6406	EF	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	910	8076	EF	M	7
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	888	8718	EF	F	6
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	920	8616	EF	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	919	9728	EF	F	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	813	6668	EF	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	939	9402	EF	F	7
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	1021	12646	EF	F	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	900	9776	EF	F	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	922	7674	EF	M	11
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	902	8484	EF	M	6
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	818	6486	EF	M	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	933	8404	EF	M	14
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	920	9034	EF	M	13
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	874	8328	EF	F	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	875	7622	EF	M	5

AR	Red River	3/15/2022	33.57763	-94.36778	SVC	999	11980	EF	F	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	954	9654	EF	M	11
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	988	11412	EF	F	7
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	882	8256	EF	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	832	7998	GN	M	10
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	902	8340	GN	M	10
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	847	7836	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	900	7878	GN	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	920	8904	GN	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	790	5890	GN	M	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	792	6700	GN	M	6
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	901	7256	GN	M	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	870	7832	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	798	6592	GN	M	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	901	7518	GN	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	905	8166	GN	M	7
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	834	7080	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	844	5888	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	833	6996	GN	M	8
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	911	9292	GN	M	10
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	772	5470	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	802	9546	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	910	9098	GN	M	9
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	946	11584	GN	F	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	800	6306	GN	M	5
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	894	8016	GN	M	12
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	858	6208	GN	M	4
AR	Red River	3/15/2022	33.57763	-94.36778	SVC	856	7390	GN	M	5
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	858	5982	GN	M	7

AR	Red River	3/23/2022	33.58165	-94.36528	SVC	862	7488	GN	M	9
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	874	9482	GN	M	12
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	912	9138	GN	M	7
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	854	7824	GN	F	4
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	740	-	EF	F	7
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	820	6300	GN	F	7
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	838	7134	EF	M	5
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	850	6974	EF	M	6
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	890	8000	GN	M	11
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	784	5300	EF	M	5
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	930	-	EF	F	10
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	808	5964	GN	M	6
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	1040	12200	EF	F	8
AR	Red River	3/23/2022	33.58165	-94.36528	SVC	928	-	EF	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	788	5850	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	876	6502	GN	M	14
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	918	9408	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	908	8700	GN	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	850	6914	GN	M	-
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	852	6302	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	824	5912	GN	M	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	1070	15600	GN	F	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	1056	13250	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	992	11288	GN	F	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	968	10756	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	873	7524	GN	M	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	918	8322	EF	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	988	10432	EF	F	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	1050	13500	EF	F	10

AR	Red River	3/24/2022	33.57763	-94.36778	SVC	886	9752	EF	F	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	966	10716	EF	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	924	9352	EF	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	830	6824	EF	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	838	7328	EF	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	976	12020	EF	F	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	874	9176	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	878	6896	GN	M	8
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	960	10902	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	936	11272	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	794	5698	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	998	10056	GN	F	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	1010	13400	GN	F	8
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	946	10834	GN	F	8
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	904	11096	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	888	9218	GN	F	-
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	916	8822	GN	M	7
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	912	9860	GN	F	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	920	11484	GN	F	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	856	8964	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	938	12100	GN	F	7
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	948	11300	GN	F	9
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	885	9200	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	875	9260	GN	F	12
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	820	6000	GN	M	8
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	818	5858	GN	M	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	806	6158	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	888	9212	GN	M	11
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	878	7626	GN	M	9

AR	Red River	3/24/2022	33.57763	-94.36778	SVC	980	10894	GN	F	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	904	10266	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	898	9604	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	910	8956	GN	M	12
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	852	6174	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	864	7476	GN	M	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	866	9756	GN	F	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	928	9302	GN	M	-
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	816	6510	GN	M	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	890	8332	GN	M	9
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	934	9078	GN	M	13
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	941	9136	GN	M	8
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	902	8780	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	874	10392	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	830	6382	GN	M	4
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	920	10268	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	976	10612	GN	F	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	870	8194	GN	M	6
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	928	9964	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	942	9370	GN	M	10
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	891	8850	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	822	8978	GN	F	5
AR	Red River	3/24/2022	33.57763	-94.36778	SVC	1042	13700	GN	F	11
AR	Red River	4/4/2022	33.60848	-93.81358	SVC	891	9000	EF	M	7
TX	Choctaw	4/13/2022	33.72068	-96.39828	SVC	842	7100	EF	M	5
AR	Red River	4/29/2022	33.58165	-94.36528	SVC	915	9000	EF	F	4
OK	Red River	5/4/2022	33.8032	-94.91955	SVC	888	8000	GN	F	3
OK	Garland Creek	5/13/2022	33.92015	-95.07693	SVC	937	9400	EF	F	9
OK	Kiamichi	5/26/2022	33.9605	-95.25517	SVC	752	4750	EF	M	4

OK	Kiamichi	5/26/2022	33.9605	-95.25517	SVC	887	7100	GN	M	6
OK	Kiamichi	5/26/2022	33.9605	-95.25517	SVC	859	6500	GN	M	9
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	789	4338	GN	M	8
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	912	8876	GN	M	6
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	813	6324	GN	M	5
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	886	8662	GN	F	4
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	919	11388	GN	F	4
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	850	8168	GN	M	5
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	869	8812	EF	F	4
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	616	3122	EF	M	5
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	850	10284	EF	F	10
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	921	12020	GN	F	4
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	907	9692	EF	F	4
AR	Red River	5/28/2022	33.58165	-94.36528	SVC	891	9318	EF	F	7
OK	Muddy Boggy	6/1/2022	33.94254	-95.59405	SVC	892	7600	GN	-	6
TX	Choctaw	6/3/2022	33.72068	-96.39828	SVC	831	7100	JM	-	4
TX	Choctaw	6/4/2022	33.71952	-96.3907	SVC	-	-	GN	-	8
TX	Choctaw	6/4/2022	33.71952	-96.3907	SVC	-	-	GN	-	4
AR	Red River	6/5/2022	33.56936	-94.06402	SVC	964	9500	JM	M	9
AR	Red River	6/5/2022	33.56936	-94.06402	SVC	891	8000	GN	M	4
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	940	12000	EF	F	5
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	992	12250	EF	F	7
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	999	12250	EF	F	4
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	1014	13500	EF	F	7
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	985	8750	EF	F	4
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	952	8250	EF	M	6
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	949	11000	JM	F	4
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	942	7500	EF	M	9
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	901	7400	JM	M	4

AR	Red River	6/21/2022	33.58165	-94.36528	SVC	1062	13800	EF	F	8
AR	Red River	6/21/2022	33.58165	-94.36528	SVC	849	7100	GN	M	3
OK	Red River	6/24/2022	33.91901	-95.07648	SVC	1091	12000	EF	F	12
OK	Garland Creek	6/24/2022	33.92015	-95.07693	SVC	928	0	EF	M	8
OK	Red River	6/30/2022	33.88492	-95.46896	SVC	900	0	GN	M	6
OK	Muddy Boggy	7/5/2022	33.94254	-95.59405	SVC	792	6000	GN	M	3
OK	Red River	7/14/2022	33.91901	-95.07648	SVC	875	7250	EF	M	6
TX	Choctaw	7/19/2022	33.72068	-96.39828	SVC	808	7000	EF	-	5
OK	Red River	7/22/2022	33.6583	-94.54367	SVC	881	8500	EF	M	4
OK	Kiamichi	8/1/2022	33.96159	-95.28264	SVC	748	5100	EF	M	6
TX	Bois d'Arc	8/2/2022	33.82851	-95.85503	SVC	805	7000	JM	M	3
TX	Bois d'Arc	8/2/2022	33.82851	-95.85503	SVC	853	7900	GN	M	8
TX	Bois d'Arc	8/5/2022	33.82851	-95.85503	SVC	814	2500	EF	F	5
TX	Bois d'Arc	8/5/2022	33.82851	-95.85503	SVC	855	8000	GN	M	10
OK	Kiamichi	8/9/2022	33.96159	-95.28264	SVC	861	6800	EF	F	7
AR	Red River	8/10/2022	33.56399	-94.00924	SVC	945	9000	EF	M	9
TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	SVC	964	13500	EF	F	5
TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	SVC	906	10000	EF	F	9
TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	SVC	902	10000	EF	F	9
TX	Bois d'Arc	8/11/2022	33.82851	-95.85503	SVC	902	10000	EF	F	6
OK	Red River	8/26/2022	33.96024	-95.20688	SVC	894	8500	EF	M	7
AR	Red River	8/29/2022	33.56399	-94.00924	SVC	855	7900	EF	M	5
AR	Red River	10/18/2022	33.54988	-94.36266	SVC	740	4100	EF	M	3
AR	Red River	10/18/2022	33.54988	-94.36266	SVC	841	7000	EF	M	5
AR	Red River	10/18/2022	33.54988	-94.36266	SVC	825	7500	EF	M	9
AR	Red River	11/8/2022	33.56936	-94.06402	SVC	796	5600	EF	M	
AR	Red River	11/8/2022	33.56936	-94.06402	SVC	835	6750	GN	M	
AR	Red River	11/15/2022	33.56399	-94.00924	SVC	861	7500	GN	M	
AR	Red River	11/16/2022	33.54689	-94.38066	SVC	844	7100	EF	M	

AR	Red River	11/16/2022	33.54689	-94.38066	SVC	801	5200	GN	M	
AR	Red River	11/16/2022	33.54689	-94.38066	SVC	753	5200	GN	M	
TX	Choctaw	6/23/2021	33.77368	-96.41828	SVC	745	4900	BF	M	3
TX	Choctaw	7/19/2021	33.72074	-96.3769	SVC	910	9500	BF	M	9
TX	Choctaw	7/21/2021	33.72004	-96.39876	SVC	850	8160	JM	M	7
OK	Webb Creek	7/25/2021	33.77368	-96.41828	SVC	720	4620	BF	M	3
OK	Red River	8/10/2021	33.77693	-96.47263	BHC	925	6350	BF	M	7
OK	Red River	9/5/2021	33.79629	-96.51525	BHC	1130	15600	BF	F	10
OK	Red River	9/6/2021	33.79629	-96.51525	BHC	1130	19700	BF	F	-
OK	Red River	9/6/2021	33.79629	-96.51525	BHC	1090	14600	BF	F	12
OK	Webb Creek	12/1/2021	33.7729	-96.41801	SVC	883	7940	BF	M	-
OK	Webb Creek	12/1/2021	33.7729	-96.41801	SVC	864	8300	BF	F	8
OK	Red River	2/27/2022	33.82107	-96.56023	BHC	990	13050	BF	F	8
OK	Webb Creek	6/21/2022	33.77355	-96.41837	SVC	820	6500	BF	F	6
OK	Red River	5/18/2022	33.82131	-96.55203	BHC	1095	19100	BF	F	8
OK	Red River	4/21/2022	33.82131	-96.55203	BHC	1010	17000	BF	F	10
OK	Red River	9/3/2022	33.82042	-96.56031	SVC	920	9150	BF	F	8
OK	Red River	9/7/2022	33.82042	-96.56031	SVC	850	7160	BF	M	10
OK	Red River	10/8/2022	33.82147	-96.54313	SVC	916	8390	BF	M	3
OK	Kiamichi	4/1/2022	34.00912	-95.38141	SVC	1040	13640	BF	F	13
OK	Red River	8/15/2022	33.82042	-96.56031	SVC	860	9300	BF	F	8
OK	Red River	6/30/2022	33.82042	-96.56031	BHC	1040	14850	BF	M	7

Table 10. Carp visually confirmed (i.e., observed jumping or jumped in boat) from May 2021 through December 2022 within a site but not collected during fish sampling on the Red River and its tributaries. The observations indicate the state, date, location, habitat, and species observed (SVC =Silver Carp, BHC=Bighead Carp).

River	State	Date	Latitude	Longitude	Species
Muddy Boggy	OK	7/2/2021	33.94339	-95.60174	SVC
Muddy Boggy	OK	7/27/2021	33.93557	-95.63493	SVC
Muddy Boggy	OK	7/28/2021	33.92844	-95.65096	SVC
Red River	OK	7/29/2021	33.65393	-94.56868	SVC / BHC
Pine Creek	TX	8/3/2021	33.86477	-95.30788	BHC
Red River	AR	8/31/2021	33.39703	-93.71171	SVC
Red River	AR	10/8/2021	33.39703	-93.71171	SVC
Red River	AR	4/1/2022	33.39703	-93.71171	SVC
Red River	AR	4/5/2022	33.5515	-94.39453	SVC
Red River	OK	4/19/2022	33.88111	-95.50545	SVC
Red River	OK	4/21/2022	33.95053	-95.24028	SVC
Red River	AR	4/26/2022	33.57537	-94.08128	SVC
Red River	AR	5/6/2022	33.5515	-94.39453	SVC
Buzzard Creek	OK	5/9/2022	33.90033	-95.05406	SVC
Red River	AR	5/12/2022	33.13784	-93.82909	SVC
Garland Creek	OK	5/16/2022	33.92473	-95.08337	SVC
Muddy Boggy	OK	5/31/2022	33.92844	-95.65096	SVC
Red River	AR	6/7/2022	33.57537	-94.08128	SVC
Red River	AR	6/8/2022	33.60915	-93.8242	SVC
Red River	AR	6/13/2022	33.13784	-93.82909	BHC
Pine Creek	TX	6/14/2022	33.86477	-95.30788	SVC
Red River	AR	6/15/2022	33.5998	-94.44686	SVC
Red River	AR	6/17/2022	33.34793	-93.71021	SVC / BHC
Choctaw	TX	6/22/2022	33.72223	-96.41024	SVC
Red River	AR	7/15/2022	33.55708	-94.04868	SVC
Red River	AR	7/20/2022	33.34793	-93.71021	SVC
Muddy Boggy	OK	7/21/2022	33.93833	-95.60911	SVC
Red River	AR	7/25/2022	33.60915	-93.8242	SVC
Choctaw	TX	8/3/2022	33.71952	-96.3907	SVC
Red River	OK	8/4/2022	33.96302	-95.22118	BHC
Red River	AR	8/23/2022	33.59898	-93.81232	SVC
Red River	OK	8/26/2022	33.96302	-95.22118	BHC
Kiamichi	OK	9/9/2022	33.95095	-95.29142	SVC
Red River	AR	9/21/2022	33.55718	-94.0195	SVC

Table 11. Occupancy model covariate combinations (width-to-depth ratio [W:D], sinuosity [Sin], backwater [Bck], chlorophyll-*a* [Chla], salinity [Sal], discharge [Q], and distance to dam [Dtd]) hypothesized to be related to carp presence with the corresponding Watanabe-Akaike information criterion (WAIC) and ΔWAIC scores.

Model	WAIC	ΔWAIC
W:D + Sin	249.53	0
Bck	249.73	0.2
Bck + W:D + Sin	250.02	0.49
Bck + W:D	251.04	1.51
Bck + W:D + Chla	251.29	1.76
Bck + Sin	252.91	3.38
Bck + W:D + Sin + Chla	253.68	4.15
W:D	253.81	4.28
Sal	253.92	4.39
Q	254.26	4.73
W:D + Chla	255.03	5.5
Bck + Sin + Chla	255.16	5.63
Chla	255.27	5.74
Sin + Chla	255.71	6.18
Bck + Q	257.14	7.61
Bck + Sal	257.22	7.69
Bck + Chla	257.38	7.85
Q + Sin	258.2	8.67
Sin + Chla	258.39	8.86
Bck + Dtd	258.61	9.08
Bck + Q + W:D	260.02	10.49
Dtd	260.57	11.04
Bck + Q + Sin	260.99	11.46
Q + W:D	261.94	12.41
Bck + Q + Dtd	263.24	13.71
Q + Dtd	263.53	14
Sal + Dtd	265.59	16.06
Bck + Q + W:D + Chla	266.03	16.5
Bck + Sal + Dtd	266.71	17.18
Sal + Dtd + Q	267.02	17.49
Q + Sal	267.27	17.74
Q + Chla	269.1	19.57
Bck + Q + W:D + Sin	270.06	20.53
Bck + Q + Sal + Dtd	272.67	23.14
Bck + Q + Chla	273.31	23.78
Bck + Q + Sal	276.74	27.21
Q + W:D + Sin + Chla	277.31	27.78
Bck + Q + W:D + Sin + Chla	295.63	46.1

Table 12. The mode, 90% highest density interval (HDI), standard error (SE), and Rhat values for occupancy covariates (backwater [Bck], width-to-depth [W:D], chlorophyll-*a* [Chla], and sinuosity [Sin]) for the top ranked occupancy models for Bighead Carp and Silver Carp in the lower Red River catchment.

Species	Model	Covariate	Mode	SE	90% HDI	Rhat
Bighead Carp	Bck	Bck	2.348	0.08	(0.04, 7.43)	1.004
	Bck + W:D	Bck	1.193	0.07	(-0.73, 3.21)	1
	Bck + W:D + Chla	Bck	1.203	0.07	(-0.90, 3.42)	1.001
	Bck + W:D + Sin	Bck	2.619	0.08	(-0.15, 6.72)	0.999
	Bck + W:D + Chla	Chla	0.004	0.09	(-1.37, 1.16)	1
	Bck + W:D + Sin	Sin	-1.748	0.06	(-3.28, -0.50)	0.999
	W.D + Sin	Sin	-1.218	0.06	(-2.15, -0.32)	1
	Bck + W:D	W:D	-1.638	0.08	(-3.06, -0.42)	1.001
	Bck + W:D + Chla	W:D	-1.784	0.08	(-3.39, -0.46)	1.001
	Bck + W:D + Sin	W:D	-2.217	0.10	(-4.12, -0.69)	0.999
	W.D + Sin	W:D	-2.051	0.10	(-3.77, -0.68)	1
Silver Carp	Bck	Bck	2.311	0.08	(-0.33, 7.67)	1.003
	Bck + W:D	Bck	1.159	0.07	(-1.01, 3.70)	1
	Bck + W:D + Chla	Bck	1.177	0.07	(-1.24, 3.90)	1.001
	Bck + W:D + Sin	Bck	2.42	0.08	(-0.37, 6.95)	0.999
	Bck + W:D + Chla	Chla	0.621	0.09	(-0.66, 2.00)	1
	Bck + W:D + Sin	Sin	-1.575	0.06	(-3.16, -0.30)	0.999
	W.D + Sin	Sin	-1.176	0.06	(-2.24, -0.25)	1
	Bck + W:D	W:D	-1.177	0.08	(-2.46, -0.02)	1
	Bck + W:D + Chla	W:D	-1.284	0.08	(-2.67, -0.02)	1
	Bck + W:D + Sin	W:D	-1.436	0.10	(-3.05, 0.12)	0.999
	W:D + Sin	W:D	-1.323	0.10	(-2.64, -0.02)	1

Table 13. The mode, 90% highest density interval (HDI), standard error (SE), and Rhat values for detection covariates (discharge [Q], electrofishing effort [Sec], Secchi depth [Secchi], and water temperature [Temp]) for the top ranked models (backwater [Bck], width-to-depth ratio [W:D], Chlorophyll-*a* [Chla], and sinuosity [Sin]) for Bighead Carp (BHC) and Silver Carp (SVC) in the lower Red River catchment.

Species	Model	Covariate	Mode	SE	90% HDI	Rhat
BHC	Bck	Q	-0.418	0.03	(-0.83, -0.04)	1
	Bck + W:D	Q	-0.462	0.03	(-0.88, -0.06)	1
	Bck + W:D + Chla	Q	-0.465	0.03	(-0.89, -0.07)	1
	Bck + W:D + Sin	Q	-0.437	0.03	(-0.84, -0.05)	1
	W:D + Sin	Q	-0.48	0.03	(-0.90, -0.07)	1
	Bck	Sec	0.69	0.03	(0.24, 1.14)	1
	Bck + W:D	Sec	0.599	0.03	(0.13, 1.05)	1
	Bck + W:D + Chla	Sec	0.597	0.03	(0.14, 1.06)	1
	Bck + W:D + Sin	Sec	0.667	0.03	(0.22, 1.13)	1
	W:D + Sin	Sec	0.584	0.03	(0.10, 1.03)	1
	Bck	Secchi	-0.393	0.04	(-0.90, 0.13)	1.001
	Bck + W:D	Secchi	-0.403	0.04	(-0.90, 0.11)	1
	Bck + W:D + Chla	Secchi	-0.399	0.04	(-0.87, 0.12)	1
	Bck + W:D + Sin	Secchi	-0.457	0.04	(-0.94, 0.04)	1
	W:D + Sin	Secchi	-0.482	0.04	(-0.98, 0.01)	1
	Bck	Temp	0.818	0.04	(0.28, 1.41)	1
	Bck + W:D	Temp	0.736	0.03	(0.22, 1.31)	1
	Bck + W:D + Chla	Temp	0.725	0.03	(0.21, 1.29)	1.001
	Bck + W:D + Sin	Temp	0.836	0.04	(0.31, 1.43)	1
	W:D + Sin	Temp	0.749	0.03	(0.23, 1.33)	1
SVC	Bck	Q	-0.39	0.03	(-0.74, -0.03)	1
	Bck + W:D	Q	-0.418	0.03	(-0.79, -0.04)	1
	Bck + W:D + Chla	Q	-0.41	0.03	(-0.78, -0.04)	1
	Bck + W:D + Sin	Q	-0.408	0.03	(-0.78, -0.05)	1
	W:D + Sin	Q	-0.421	0.03	(-0.81, -0.04)	1

Bck	Sec	0.795	0.03	(0.41, 1.21)	1
Bck + W:D	Sec	0.736	0.03	(0.33, 1.16)	1
Bck + W:D + Chla	Sec	0.744	0.03	(0.33, 1.16)	1
Bck + W:D + Sin	Sec	0.764	0.03	(0.38, 1.18)	1
W:D + Sin	Sec	0.743	0.03	(0.34, 1.16)	1
Bck	Secchi	-0.731	0.04	(-1.17, -0.31)	1
Bck + W:D	Secchi	-0.722	0.04	(-1.17, -0.31)	1
Bck + W:D + Chla	Secchi	-0.704	0.04	(-1.14, -0.28)	0.999
Bck + W:D + Sin	Secchi	-0.752	0.04	(-1.19, -0.33)	1
W:D + Sin	Secchi	-0.777	0.04	(-1.22, -0.36)	1
Bck	Temp	0.525	0.04	(0.13, 0.93)	1
Bck + W:D	Temp	0.534	0.03	(0.14, 0.94)	1
Bck + W:D + Chla	Temp	0.522	0.03	(0.12, 0.92)	1
Bck + W:D + Sin	Temp	0.535	0.04	(0.13, 0.95)	1.001
W:D + Sin	Temp	0.527	0.03	(0.12, 0.93)	1

Table 14. Occupancy and detection estimates and corresponding 90% highest density intervals (HDI) for the top ranked models (backwater [Bck], width-to-depth ratio [W:D], chlorophyll-a [Chla], and sinuosity [Sin]) for Silver Carp (SVC) and Bighead Carp (BHC) in the Red River catchment.

Species	Model	Occupancy	90% HDI	Detection	90% HDI
Silver Carp	Bck	0.83	(0.51, 0.97)	0.6	(0.50, 0.70)
	Bck + W:D	0.78	(0.33, 0.96)	0.61	(0.51, 0.71)
	Bck + W:D + Chla	0.79	(0.32, 0.97)	0.61	(0.50, 0.71)
	Bck + W:D + Sin	0.8	(0.27, 0.98)	0.61	(0.51, 0.71)
	W:D + Sin	0.85	(0.43, 0.97)	0.63	(0.53, 0.72)
Bighead Carp	Bck	0.78	(0.39, 0.96)	0.39	(0.25, 0.54)
	Bck + W:D	0.61	(0.23, 0.91)	0.4	(0.27, 0.55)
	Bck + W:D + Chla	0.65	(0.23, 0.94)	0.4	(0.27, 0.54)
	Bck + W:D + Sin	0.53	(0.15, 0.91)	0.39	(0.27, 0.53)
	W.D + Sin	0.68	(0.29, 0.92)	0.4	(0.28, 0.55)

Table 15. The number of individuals, by species and by sampling gear, sampled from the lower Red River, Arkansas. (EF is electrofishing; FN is mini-fyke net; GN is gillnet; HN is hoopnet; LT is larval tow; SE is seine).

Species	EF	FN	GN	HN	LT	SE	Total
Alligator Gar	2	-	36	-	-	-	38
American Eel	1	-	-	-	-	-	1
American Paddlefish	9	-	55	-	-	-	64
Bantam Sunfish	-	4	-	-	-	12	16
Bigeye Shiner	-	1	-	-	-	1	2
Bighead Carp	3	-	24	-	-	-	27
Bigmouth Buffalo	62	-	252	1	-	2	317
Black Buffalo	32	-	159	2	-	-	193
Black Crappie	4	211	-	-	-	35	250
Blackstripe Topminnow	-	9	-	-	-	29	38
Blacktail Shiner	2	3	-	-	-	48	53
Blue Catfish	142	-	27	-	-	3	172
Blue Sucker	208	-	17	7	-	-	232
Bluegill	61	652	-	-	-	607	1320
Bluntnose Darter	-	3	-	-	-	4	7
Brook Silverside	6	7	-	-	-	98	111
Bullhead Minnow	58	3269	-	-	-	16504	19831
Channel Catfish	13	10	3	-	-	17	43
Chub Shiner	10	550	-	-	-	5355	5915
Common Carp	3	-	11	-	-	-	14
Dusky Darter	1	51	-	-	-	18	70
Emerald Shiner	133	3415	-	-	19	1771	5338
Flathead Catfish	172	1	1	-	-	2	176
Flier	-	1	-	-	-	-	1
Freshwater Drum	161	50	5	1	5	56	278

Ghost Shiner	-	14	-	-	-	6	20
Gizzard Shad	456	562	11	-	1	1621	2651
Golden Shiner	-	51	-	-	-	26	77
Golden Topminnow	-	17	-	-	-	11	28
Grass Carp	5	-	45	-	-	-	50
Green Sunfish	33	11	-	-	-	36	80
Largemouth Bass	4	-	-	-	-	-	4
Logperch	-	27	-	-	-	12	39
Longear Sunfish	72	288	-	-	-	585	945
Longnose Gar	72	13	73	4	1	11	174
Mississippi Silverside	47	1861	-	-	-	2241	4149
Mississippi Silvery Minnow	-	-	-	-	-	2	2
Mosquitofish	-	648	-	-	-	6378	7026
Orangespotted Sunfish	16	1701	-	-	-	1455	3172
Pallid Shiner	-	-	-	-	-	2	2
Pirate Perch	-	-	-	-	-	21	21
Pugnose Minnow	-	-	-	-	-	1	1
Quillback	1	-	-	-	-	-	1
Red Shiner	887	15550	-	-	92	40012	56541
Redear Sunfish	1	5	-	-	-	12	18
River Carpsucker	300	41	3	3	-	408	755
River Darter	-	3	-	-	-	4	7
Sand Shiner	-	23	-	-	-	2	25
Shoal Chub	-	24	-	-	-	261	285
Shortnose Gar	43	79	5	1	-	1	129
Shovelnose Sturgeon	17	-	1	-	-	-	18
Silver Carp	88	-	115	-	-	-	203
Silver Chub	23	234	-	-	-	371	628

Silverband Shiner	6	3	-	-	-	19	28
Skipjack Herring	-	2	-	-	-	3	5
Slenderhead Darter	-	-	-	-	-	1	1
Slough Darter	-	2	-	-	-	9	11
Smallmouth Buffalo	197	1	248	10	-	6	462
Spotted Bass	94	63	-	-	-	621	778
Spotted Gar	33	4	-	-	-	4	41
Spotted Sucker	-	1	-	-	-	2	3
Striped Bass	2	5	-	-	-	1	8
Tadpole Madtom	1	2	-	-	-	-	3
Threadfin Shad	335	1988	-	-	15	2782	5120
Warmouth	5	51	-	-	-	111	167
Western Sand Darter	-	3	-	-	-	17	20
Western Starhead Topminnow	-	2	-	-	-	-	2
White Bass	19	337	-	-	-	200	556
White Crappie	21	1068	-	2	-	217	1308
Yellow Bullhead	-	1	-	-	-	-	1

Table 16. List of genera, the number of species within each genus, the total sampled, and the percent of total of all fishes sampled. Due to the disproportionately high observations of Red Shiner and Bullhead Minnow, the percent of total was calculated without including those counts.

Genus	N. of Species	Total Collected	Percent of Total
Alosa	1	5	0.01%
Ameiurus	1	1	<0.01%
Ammocrypta	2	22	0.05%
Anguilla	1	1	<0.01%
Aphredoderus	1	21	0.05%
Aplodinotus	1	278	0.64%
Atractosteus	1	38	0.09%
Carpiodes	1	755	1.73%
Carpoides	1	1	<0.01%
Centrarchus	1	1	<0.01%
Ctenopharyngodon	1	50	0.11%
Cycleptus	1	232	0.53%
Cyprinella	1	53	0.12%
Cyprinus	1	14	0.03%
Dorosoma	2	7771	17.78%
Etheostoma	2	18	0.04%
Fundulus	2	66	0.15%
Gambusia	1	7026	16.08%
Hybognathus	1	2	<0.01%
Hybopsis	1	2	<0.01%
Hypophthalmichthys	2	230	0.53%
Ictalurus	2	215	0.49%
Ictiobus	3	972	2.22%
Labidesthes	1	111	0.25%
Lepisosteus	3	344	0.79%
Lepomis	7	5718	13.08%

Macrhybopsis	2	913	2.09%
Menidia	1	4149	9.49%
Micropterus	2	782	1.79%
Minytrema	1	3	0.01%
Morone	2	564	1.29%
Notemigonus	1	77	0.18%
Notropis	6	11328	25.92%
Noturus	1	3	0.01%
Opsopoeodus	1	1	<0.01%
Percina	4	117	0.27%
Polyodon	1	64	0.15%
Pomoxis	2	1558	3.57%
Pylodictis	1	176	0.40%
Scaphirhynchus	1	18	0.04%

Table 17. Model estimates from the final nursery habitat occupancy model. ψ (Psi) and p are the group mean occupancy and detection estimates within the study area respectively. $\hat{R}$ (R-hat) is the measure of model convergence. $\hat{c}$ (c-hat) is a measure of posterior dispersion. The Bayesian p-value represents the goodness-of-fit test for the model. Segment and year sigma are a measure of the variance captured by the grouping factors. Lower (LHDI) and upper (UHDI) 95% high density intervals.

Coefficient	**Mean**	**LHDI**	**UHDI**
ψ (group)	0.571	0.184	0.929
p (group)	0.187	0.118	0.258
$\hat{R}$	1.00	0.995	1.003
$\hat{c}$	1.003	0.892	1.116
Bayesian p-value	0.505	0.00	1.00
Segment - Sigma	1.429	0.699	2.289
Year - Sigma	1.176	0.00	2.627

Table 18. Detection model coefficients for juvenile native species (probability scale) and covariates (logit scale) included in the in the final model, and their lower (LHDI) and upper (UHDI) 95% high density intervals. Daily average water temperature was collected during each survey and discharge measurements were obtained from the nearest U.S. Geological Survey streamgage.

Coefficient	**Median**	**LHDI**	**UHDI**
Discharge	0.265	0.180	0.349
Temperature	0.263	0.179	0.342
Bantam Sunfish	0.064	0.023	0.165
Bigmouth Buffalo	0.058	0.020	0.155
Black Crappie	0.336	0.249	0.436
Blackstriped Topminnow	0.044	0.011	0.151
Blacktail Shiner	0.075	0.022	0.225
Blue Catfish	0.043	0.013	0.134
Bluegill	0.587	0.501	0.668
Brook Silverside	0.084	0.029	0.215
Bullhead Minnow	0.390	0.315	0.476
Channel Catfish	0.237	0.144	0.359
Chub Shiner	0.439	0.348	0.534
Dusky Darter	0.041	0.010	0.145
Emerald Shiner	0.122	0.067	0.214
Freshwater Drum	0.285	0.211	0.374
Gizzard Shad	0.351	0.282	0.436
Green Sunfish	0.276	0.190	0.394
Logperch	0.142	0.071	0.263
Longear Sunfish	0.703	0.620	0.777
Longnose Gar	0.154	0.090	0.268
Mississippi Silverside	0.254	0.189	0.337
Orangespotted Sunfish	0.553	0.462	0.638
Redear Sunfish	0.091	0.040	0.193

River Carpsucker	0.511	0.426	0.601
Sand Shiner	0.052	0.018	0.136
Shoal Chub	0.153	0.088	0.259
Shortnose Gar	0.075	0.031	0.172
Silver Chub	0.085	0.041	0.164
Skipjack Herring	0.061	0.022	0.165
Slough Darter	0.149	0.064	0.306
Smallmouth Buffalo	0.089	0.040	0.196
Spotted Bass	0.697	0.629	0.758
Spotted Gar	0.055	0.014	0.159
Spotted Sucker	0.092	0.030	0.261
Suckermouth Minnow	0.068	0.024	0.167
Threadfin Shad	0.418	0.349	0.490
Warmouth	0.251	0.157	0.372
White Bass	0.331	0.253	0.424
White Crappie	0.580	0.498	0.663

Table 19. Occupancy model coefficients for juvenile native species (probability scale) and their covariates (logit scale) for the final model, and their lower (LHDI) and upper (UHDI) 95% high density intervals. The occupancy coefficient represents the probability of species occupancy within the study area. Continuous variables included were distance from the nearest upstream dam (Dam Distance), median discharge for the season (Discharge), percentage of limestone lithology within the catchment (Limestone), percentage of large woody debris within the reach (LWD), the percentage slope of the segment (Slope), average thalweg depth of the reach (Thalweg), and the width-to-depth ratio of the reach (W:D). Categorical variables were 1) pools: where the absence of deep pools was the reference, 2) slackwater: where the absence of slackwater was the reference, and 3) drainage area: where high drainage area was the reference.

Coefficient	**Median**	**LHDI**	**UHDI**
Bantam Sunfish - Dam Distance	0.159	-0.518	0.878
Bantam Sunfish - Discharge	0.366	-1.612	2.328
Bantam Sunfish - Drainage Area	-2.018	-5.781	1.508
Bantam Sunfish - Limestone	-0.747	-2.736	0.719
Bantam Sunfish - LWD	-1.240	-3.042	0.153
Bantam Sunfish - Occupancy	0.197	0.013	0.799
Bantam Sunfish - Pools	0.189	-0.902	1.320
Bantam Sunfish - Slackwater	1.056	-1.369	3.066
Bantam Sunfish - Slope	0.684	-1.478	3.303
Bantam Sunfish - Thalweg	-0.228	-1.305	1.262
Bantam Sunfish - W:D	-0.049	-1.369	1.233
Bigmouth Buffalo - Dam Distance	0.187	-0.500	0.891
Bigmouth Buffalo - Discharge	0.609	-0.941	2.255
Bigmouth Buffalo - Drainage Area	-1.569	-5.265	2.083
Bigmouth Buffalo - Limestone	-0.879	-2.828	0.349
Bigmouth Buffalo - LWD	-0.892	-2.608	0.576

Bigmouth Buffalo - Occupancy	0.224	0.018	0.823
Bigmouth Buffalo - Pools	0.188	-0.935	1.308
Bigmouth Buffalo - Slackwater	1.303	-0.761	3.509
Bigmouth Buffalo - Slope	0.328	-2.127	3.288
Bigmouth Buffalo - Thalweg	-0.361	-1.437	0.962
Bigmouth Buffalo - W:D	0.088	-0.996	1.435
Black Crappie - Dam Distance	0.197	-0.435	0.865
Black Crappie - Discharge	1.299	0.129	2.623
Black Crappie - Drainage Area	-1.486	-4.145	1.242
Black Crappie - Limestone	-0.824	-2.841	0.615
Black Crappie - LWD	-1.242	-2.510	-0.185
Black Crappie - Occupancy	0.776	0.250	0.974
Black Crappie - Pools	0.381	-0.544	1.563
Black Crappie - Slackwater	1.205	-0.350	2.768
Black Crappie - Slope	1.315	-0.292	3.252
Black Crappie - Thalweg	-0.534	-1.542	0.286
Black Crappie - W:D	0.004	-0.892	0.893
Blackstriped Topminnow - Dam Distance	0.181	-0.490	0.904
Blackstriped Topminnow - Discharge	0.585	-1.212	2.412
Blackstriped Topminnow - Drainage Area	-2.026	-6.235	2.005
Blackstriped Topminnow - Limestone	-0.738	-2.767	0.655
Blackstriped Topminnow - LWD	-0.939	-2.799	0.560
Blackstriped Topminnow - Occupancy	0.149	0.008	0.770
Blackstriped Topminnow - Pools	0.190	-0.908	1.322
Blackstriped Topminnow - Slackwater	1.091	-1.346	3.288
Blackstriped Topminnow - Slope	-0.524	-3.265	2.289

Blackstriped Topminnow - Thalweg	-0.592	-1.984	0.497
Blackstriped Topminnow - W:D	0.160	-1.036	1.763
Blacktail Shiner - Dam Distance	0.161	-0.513	0.866
Blacktail Shiner - Discharge	1.227	-0.524	3.165
Blacktail Shiner - Drainage Area	-3.266	-7.902	0.537
Blacktail Shiner - Limestone	-0.626	-2.503	0.885
Blacktail Shiner - LWD	-0.070	-1.402	1.350
Blacktail Shiner - Occupancy	0.301	0.025	0.848
Blacktail Shiner - Pools	0.283	-0.750	1.474
Blacktail Shiner - Slackwater	1.018	-1.280	3.062
Blacktail Shiner - Slope	0.399	-2.292	3.784
Blacktail Shiner - Thalweg	-0.756	-2.234	0.223
Blacktail Shiner - W:D	-0.150	-1.513	0.971
Blue Catfish - Dam Distance	0.221	-0.443	0.960
Blue Catfish - Discharge	0.298	-1.668	2.103
Blue Catfish - Drainage Area	-1.400	-5.420	2.961
Blue Catfish - Limestone	-0.689	-2.601	0.778
Blue Catfish - LWD	-0.190	-1.983	1.737
Blue Catfish - Occupancy	0.210	0.015	0.815
Blue Catfish - Pools	0.252	-0.806	1.374
Blue Catfish - Slackwater	1.506	-0.373	4.121
Blue Catfish - Slope	-0.727	-3.214	1.782
Blue Catfish - Thalweg	-0.349	-1.630	1.062
Blue Catfish - W:D	0.202	-0.999	1.926
Bluegill - Dam Distance	0.120	-0.550	0.810
Bluegill - Discharge	0.731	-0.486	2.056

Bluegill - Drainage Area	-2.011	-5.000	0.992
Bluegill - Limestone	-0.693	-2.294	0.554
Bluegill - LWD	-0.487	-1.579	0.537
Bluegill - Occupancy	0.950	0.606	0.996
Bluegill - Pools	0.264	-0.761	1.361
Bluegill - Slackwater	1.612	0.189	3.530
Bluegill - Slope	0.639	-0.933	2.568
Bluegill - Thalweg	-0.510	-1.509	0.357
Bluegill - W:D	-0.181	-1.315	0.796
Brook Silverside - Dam Distance	0.186	-0.498	0.880
Brook Silverside - Discharge	0.929	-0.664	2.494
Brook Silverside - Drainage Area	-2.216	-5.858	1.328
Brook Silverside - Limestone	-0.900	-2.840	0.312
Brook Silverside - LWD	-0.439	-1.946	1.051
Brook Silverside - Occupancy	0.256	0.021	0.832
Brook Silverside - Pools	0.266	-0.741	1.404
Brook Silverside - Slackwater	1.023	-1.346	3.075
Brook Silverside - Slope	0.542	-1.415	2.834
Brook Silverside - Thalweg	-0.706	-2.173	0.264
Brook Silverside - W:D	0.141	-0.928	1.541
Bullhead Minnow - Dam Distance	0.181	-0.465	0.869
Bullhead Minnow - Discharge	0.558	-0.906	2.009
Bullhead Minnow - Drainage Area	-1.010	-4.060	2.455
Bullhead Minnow - Limestone	-0.782	-2.320	0.331
Bullhead Minnow - LWD	-1.200	-2.683	0.025
Bullhead Minnow - Occupancy	0.863	0.349	0.987

Bullhead Minnow - Pools	0.310	-0.616	1.478
Bullhead Minnow - Slackwater	1.897	0.291	4.294
Bullhead Minnow - Slope	0.005	-1.514	1.839
Bullhead Minnow - Thalweg	-0.663	-2.013	0.283
Bullhead Minnow - W:D	0.022	-1.075	1.287
Channel Catfish - Dam Distance	0.215	-0.413	0.903
Channel Catfish - Discharge	0.947	-0.249	2.211
Channel Catfish - Drainage Area	-1.904	-4.956	1.257
Channel Catfish - Limestone	-0.750	-2.501	0.544
Channel Catfish - LWD	0.877	-0.663	2.373
Channel Catfish - Occupancy	0.725	0.186	0.970
Channel Catfish - Pools	0.275	-0.624	1.365
Channel Catfish - Slackwater	0.989	-0.849	2.671
Channel Catfish - Slope	0.527	-1.331	3.011
Channel Catfish - Thalweg	-0.367	-1.348	0.671
Channel Catfish - W:D	0.120	-0.848	1.278
Chub Shiner - Dam Distance	0.242	-0.408	0.954
Chub Shiner - Discharge	0.725	-0.542	2.066
Chub Shiner - Drainage Area	0.065	-3.102	3.367
Chub Shiner - Limestone	-0.854	-2.546	0.256
Chub Shiner - LWD	-1.264	-2.825	0.031
Chub Shiner - Occupancy	0.746	0.147	0.973
Chub Shiner - Pools	0.113	-1.061	1.082
Chub Shiner - Slackwater	1.012	-0.778	2.701
Chub Shiner - Slope	-2.035	-3.858	-0.446
Chub Shiner - Thalweg	-0.048	-1.047	1.450

Chub Shiner - W:D	0.506	-0.654	2.411
Dusky Darter - Dam Distance	0.187	-0.480	0.904
Dusky Darter - Discharge	0.251	-1.821	2.190
Dusky Darter - Drainage Area	-2.775	-7.360	1.220
Dusky Darter - Limestone	-0.708	-2.688	0.763
Dusky Darter - LWD	-0.560	-2.400	1.178
Dusky Darter - Occupancy	0.156	0.009	0.766
Dusky Darter - Pools	0.185	-0.951	1.313
Dusky Darter - Slackwater	0.893	-2.071	2.928
Dusky Darter - Slope	0.719	-1.873	3.994
Dusky Darter - Thalweg	-0.292	-1.370	1.186
Dusky Darter - W:D	-0.138	-1.532	1.054
Emerald Shiner - Dam Distance	0.171	-0.498	0.859
Emerald Shiner - Discharge	1.628	-0.415	3.783
Emerald Shiner - Drainage Area	-0.393	-3.885	3.772
Emerald Shiner - Limestone	-0.534	-2.205	1.106
Emerald Shiner - LWD	-0.709	-2.477	0.760
Emerald Shiner - Occupancy	0.528	0.077	0.938
Emerald Shiner - Pools	0.281	-0.708	1.453
Emerald Shiner - Slackwater	1.195	-0.812	3.416
Emerald Shiner - Slope	-1.147	-3.887	1.433
Emerald Shiner - Thalweg	-0.167	-1.203	1.266
Emerald Shiner - W:D	-0.071	-1.357	1.165
Freshwater Drum - Dam Distance	0.149	-0.524	0.839
Freshwater Drum - Discharge	1.381	-0.143	3.163
Freshwater Drum - Drainage Area	-0.848	-3.900	2.488

Freshwater Drum - Limestone	-0.522	-2.575	1.020
Freshwater Drum - LWD	-1.186	-2.689	0.114
Freshwater Drum - Occupancy	0.727	0.174	0.967
Freshwater Drum - Pools	0.213	-0.794	1.243
Freshwater Drum - Slackwater	1.964	0.322	4.422
Freshwater Drum - Slope	-0.482	-1.918	1.194
Freshwater Drum - Thalweg	-0.468	-1.514	0.508
Freshwater Drum - W:D	0.274	-0.822	1.957
Gizzard Shad - Dam Distance	0.183	-0.469	0.874
Gizzard Shad - Discharge	0.958	-0.667	2.867
Gizzard Shad - Drainage Area	0.348	-3.114	4.132
Gizzard Shad - Limestone	-0.859	-2.700	0.410
Gizzard Shad - LWD	-0.247	-1.423	0.964
Gizzard Shad - Occupancy	0.837	0.289	0.985
Gizzard Shad - Pools	0.184	-0.938	1.206
Gizzard Shad - Slackwater	1.715	0.095	4.184
Gizzard Shad - Slope	0.276	-1.312	2.180
Gizzard Shad - Thalweg	-0.094	-1.096	1.311
Gizzard Shad - W:D	0.035	-1.025	1.343
Green Sunfish - Dam Distance	0.169	-0.494	0.844
Green Sunfish - Discharge	0.514	-0.795	1.893
Green Sunfish - Drainage Area	-1.212	-4.262	2.106
Green Sunfish - Limestone	-0.747	-2.402	0.419
Green Sunfish - LWD	-0.731	-2.261	0.533
Green Sunfish - Occupancy	0.714	0.172	0.966
Green Sunfish - Pools	0.138	-0.999	1.139

Green Sunfish - Slackwater	1.437	-0.280	3.607
Green Sunfish - Slope	1.438	-0.557	3.911
Green Sunfish - Thalweg	-0.056	-1.087	1.330
Green Sunfish - W:D	0.033	-1.042	1.176
Logperch - Dam Distance	0.145	-0.537	0.833
Logperch - Discharge	-0.549	-2.375	1.007
Logperch - Drainage Area	-2.415	-5.824	0.894
Logperch - Limestone	-0.894	-2.820	0.289
Logperch - LWD	-0.454	-1.784	0.758
Logperch - Occupancy	0.512	0.083	0.929
Logperch - Pools	0.250	-0.711	1.319
Logperch - Slackwater	0.896	-1.298	2.728
Logperch - Slope	-0.463	-2.338	1.594
Logperch - Thalweg	-0.386	-1.294	0.616
Logperch - W:D	-0.134	-1.254	0.888
Longear Sunfish - Dam Distance	0.201	-0.415	0.869
Longear Sunfish - Discharge	-1.076	-2.995	0.293
Longear Sunfish - Drainage Area	-2.014	-4.817	1.075
Longear Sunfish - Limestone	-0.688	-2.298	0.608
Longear Sunfish - LWD	-0.270	-1.107	0.534
Longear Sunfish - Occupancy	0.964	0.668	0.997
Longear Sunfish - Pools	0.125	-0.895	1.019
Longear Sunfish - Slackwater	0.428	-1.404	1.907
Longear Sunfish - Slope	0.064	-1.400	1.486
Longear Sunfish - Thalweg	-0.682	-1.702	0.106
Longear Sunfish - W:D	-0.047	-0.907	0.806

Longnose Gar - Dam Distance	0.207	-0.458	0.909
Longnose Gar - Discharge	0.010	-1.777	1.486
Longnose Gar - Drainage Area	-1.223	-4.672	2.934
Longnose Gar - Limestone	-0.713	-2.312	0.546
Longnose Gar - LWD	0.016	-1.492	1.591
Longnose Gar - Occupancy	0.661	0.123	0.966
Longnose Gar - Pools	0.149	-1.107	1.181
Longnose Gar - Slackwater	1.596	-0.122	4.162
Longnose Gar - Slope	-0.300	-2.197	1.944
Longnose Gar - Thalweg	-0.189	-1.148	1.024
Longnose Gar - W:D	-0.042	-1.225	1.181
Mississippi Silverside - Dam Distance	0.138	-0.544	0.828
Mississippi Silverside - Discharge	1.563	-0.165	3.403
Mississippi Silverside - Drainage Area	0.781	-2.555	4.408
Mississippi Silverside - Limestone	-0.867	-2.833	0.387
Mississippi Silverside - LWD	-0.860	-2.571	0.615
Mississippi Silverside - Occupancy	0.671	0.140	0.963
Mississippi Silverside - Pools	0.281	-0.669	1.400
Mississippi Silverside - Slackwater	1.580	-0.137	3.820
Mississippi Silverside - Slope	1.410	-0.570	3.702
Mississippi Silverside - Thalweg	-0.235	-1.263	1.042
Mississippi Silverside - W:D	0.330	-0.783	2.047
Orangespotted Sunfish - Dam Distance	0.218	-0.415	0.897
Orangespotted Sunfish - Discharge	-0.398	-1.588	0.738
Orangespotted Sunfish - Drainage Area	-1.338	-4.062	1.372
Orangespotted Sunfish - Limestone	-0.885	-2.795	0.281

Orangespotted Sunfish - LWD	-0.275	-1.378	0.758
Orangespotted Sunfish - Occupancy	0.883	0.378	0.988
Orangespotted Sunfish - Pools	0.176	-0.812	1.121
Orangespotted Sunfish - Slackwater	0.965	-0.614	2.368
Orangespotted Sunfish - Slope	-0.353	-1.461	0.873
Orangespotted Sunfish - Thalweg	-0.388	-1.232	0.408
Orangespotted Sunfish - W:D	-0.136	-1.081	0.736
Redear Sunfish - Dam Distance	0.145	-0.543	0.845
Redear Sunfish - Discharge	0.114	-1.472	1.745
Redear Sunfish - Drainage Area	-1.831	-5.358	1.635
Redear Sunfish - Limestone	-0.686	-2.612	0.953
Redear Sunfish - LWD	-0.972	-2.989	0.588
Redear Sunfish - Occupancy	0.346	0.038	0.880
Redear Sunfish - Pools	0.204	-0.850	1.320
Redear Sunfish - Slackwater	1.244	-0.824	3.326
Redear Sunfish - Slope	1.068	-0.893	4.094
Redear Sunfish - Thalweg	-0.317	-1.369	0.922
Redear Sunfish - W:D	0.132	-0.947	1.544
River Carpsucker - Dam Distance	0.188	-0.481	0.869
River Carpsucker - Discharge	0.585	-0.914	2.037
River Carpsucker - Drainage Area	-0.515	-3.653	3.308
River Carpsucker - Limestone	-0.804	-2.539	0.299
River Carpsucker - LWD	-0.881	-2.248	0.286
River Carpsucker - Occupancy	0.903	0.418	0.991
River Carpsucker - Pools	0.201	-0.844	1.266
River Carpsucker - Slackwater	1.446	-0.338	3.811

River Carpsucker - Slope	-1.071	-3.014	0.855
River Carpsucker - Thalweg	-0.192	-1.140	1.062
River Carpsucker - W:D	0.395	-0.754	2.194
Sand Shiner - Dam Distance	0.164	-0.501	0.866
Sand Shiner - Discharge	1.112	-0.646	3.089
Sand Shiner - Drainage Area	-1.095	-4.626	2.771
Sand Shiner - Limestone	-0.776	-2.787	0.663
Sand Shiner - LWD	-0.067	-1.623	1.585
Sand Shiner - Occupancy	0.254	0.020	0.849
Sand Shiner - Pools	0.245	-0.834	1.363
Sand Shiner - Slackwater	1.590	-0.198	4.259
Sand Shiner - Slope	1.439	-1.386	5.076
Sand Shiner - Thalweg	-0.586	-2.051	0.511
Sand Shiner - W:D	0.138	-1.011	1.746
Shoal Chub - Dam Distance	0.183	-0.465	0.879
Shoal Chub - Discharge	0.978	-0.649	2.761
Shoal Chub - Drainage Area	-0.970	-4.363	2.794
Shoal Chub - Limestone	-0.688	-2.543	0.723
Shoal Chub - LWD	-0.471	-1.941	0.871
Shoal Chub - Occupancy	0.526	0.084	0.925
Shoal Chub - Pools	0.326	-0.619	1.585
Shoal Chub - Slackwater	1.105	-0.968	3.121
Shoal Chub - Slope	-2.021	-4.795	0.231
Shoal Chub - Thalweg	-0.524	-1.805	0.579
Shoal Chub - W:D	0.345	-0.831	2.036
Shortnose Gar - Dam Distance	0.167	-0.518	0.863

Shortnose Gar - Discharge	0.952	-0.543	2.528
Shortnose Gar - Drainage Area	-1.002	-4.429	2.758
Shortnose Gar - Limestone	-0.806	-2.691	0.541
Shortnose Gar - LWD	-0.533	-2.357	1.182
Shortnose Gar - Occupancy	0.278	0.025	0.852
Shortnose Gar - Pools	0.230	-0.823	1.327
Shortnose Gar - Slackwater	1.370	-0.551	3.757
Shortnose Gar - Slope	1.480	-0.913	4.535
Shortnose Gar - Thalweg	-0.453	-1.781	0.753
Shortnose Gar - W:D	0.287	-0.858	1.981
Silver Chub - Dam Distance	0.194	-0.478	0.894
Silver Chub - Discharge	-0.717	-2.909	1.238
Silver Chub - Drainage Area	-0.893	-4.208	2.886
Silver Chub - Limestone	-0.705	-2.666	0.807
Silver Chub - LWD	-1.115	-3.027	0.402
Silver Chub - Occupancy	0.335	0.032	0.867
Silver Chub - Pools	0.206	-0.856	1.314
Silver Chub - Slackwater	1.150	-0.929	3.153
Silver Chub - Slope	-0.601	-2.643	1.442
Silver Chub - Thalweg	-0.250	-1.254	1.013
Silver Chub - W:D	0.017	-1.208	1.469
Skipjack Herring - Dam Distance	0.190	-0.481	0.900
Skipjack Herring - Discharge	0.903	-0.693	2.585
Skipjack Herring - Drainage Area	-1.382	-5.073	2.479
Skipjack Herring - Limestone	-0.910	-2.839	0.291
Skipjack Herring - LWD	-0.355	-2.053	1.316

Skipjack Herring - Occupancy	0.251	0.021	0.842
Skipjack Herring - Pools	0.266	-0.772	1.377
Skipjack Herring - Slackwater	1.398	-0.529	3.742
Skipjack Herring - Slope	-0.495	-2.790	1.908
Skipjack Herring - Thalweg	-0.369	-1.509	0.806
Skipjack Herring - W:D	0.001	-1.211	1.363
Slough Darter - Dam Distance	0.175	-0.503	0.867
Slough Darter - Discharge	0.182	-1.610	1.912
Slough Darter - Drainage Area	-4.270	-8.988	-0.206
Slough Darter - Limestone	-0.742	-2.523	0.583
Slough Darter - LWD	0.172	-1.169	1.782
Slough Darter - Occupancy	0.424	0.051	0.908
Slough Darter - Pools	0.210	-0.830	1.322
Slough Darter - Slackwater	0.677	-2.108	2.458
Slough Darter - Slope	0.702	-1.648	3.581
Slough Darter - Thalweg	-0.422	-1.558	0.698
Slough Darter - W:D	-0.276	-1.710	0.752
Smallmouth Buffalo - Dam Distance	0.190	-0.489	0.882
Smallmouth Buffalo - Discharge	0.603	-1.023	2.307
Smallmouth Buffalo - Drainage Area	-2.000	-5.910	1.712
Smallmouth Buffalo - Limestone	-0.652	-2.554	0.844
Smallmouth Buffalo - LWD	-0.686	-2.325	0.757
Smallmouth Buffalo - Occupancy	0.350	0.035	0.875
Smallmouth Buffalo - Pools	0.271	-0.739	1.391
Smallmouth Buffalo - Slackwater	1.536	-0.257	3.924
Smallmouth Buffalo - Slope	-1.310	-3.533	0.880

Smallmouth Buffalo - Thalweg	-0.457	-1.451	0.530
Smallmouth Buffalo - W:D	0.082	-1.062	1.464
Spotted Bass - Dam Distance	0.125	-0.537	0.800
Spotted Bass - Discharge	0.660	-0.582	1.960
Spotted Bass - Drainage Area	-1.227	-4.217	1.827
Spotted Bass - Limestone	-0.701	-2.359	0.664
Spotted Bass - LWD	-1.305	-2.659	-0.112
Spotted Bass - Occupancy	0.962	0.645	0.997
Spotted Bass - Pools	0.320	-0.573	1.451
Spotted Bass - Slackwater	1.863	0.409	3.940
Spotted Bass - Slope	1.365	-0.650	3.642
Spotted Bass - Thalweg	-0.683	-1.936	0.224
Spotted Bass - W:D	-0.081	-1.156	0.913
Spotted Gar - Dam Distance	0.193	-0.474	0.928
Spotted Gar - Discharge	0.156	-1.868	2.010
Spotted Gar - Drainage Area	-3.108	-7.890	0.871
Spotted Gar - Limestone	-0.696	-2.614	0.869
Spotted Gar - LWD	-0.500	-2.236	1.218
Spotted Gar - Occupancy	0.201	0.013	0.801
Spotted Gar - Pools	0.197	-0.865	1.353
Spotted Gar - Slackwater	0.974	-1.499	2.994
Spotted Gar - Slope	0.925	-1.684	4.054
Spotted Gar - Thalweg	-0.284	-1.391	1.148
Spotted Gar - W:D	-0.113	-1.461	1.084
Spotted Sucker - Dam Distance	0.151	-0.541	0.847
Spotted Sucker - Discharge	0.088	-1.742	1.759

Spotted Sucker - Drainage Area	-2.532	-6.297	1.010
Spotted Sucker - LWD	-0.237	-1.719	1.349
Spotted Sucker - Occupancy	0.254	0.020	0.830
Spotted Sucker - Pools	0.198	-0.894	1.258
Spotted Sucker - Slackwater	0.948	-1.529	2.805
Spotted Sucker - Slope	-0.449	-2.818	1.861
Spotted Sucker - Thalweg	-0.525	-1.617	0.435
Spotted Sucker - W:D	0.066	-1.091	1.382
Spotted Sucker -Limestone	-0.900	-2.889	0.305
Suckermouth Minnow - Dam Distance	0.159	-0.550	0.853
Suckermouth Minnow - Discharge	-0.174	-2.345	1.675
Suckermouth Minnow - Drainage Area	-2.357	-6.323	1.302
Suckermouth Minnow - Limestone	-0.688	-2.490	0.719
Suckermouth Minnow - LWD	-0.275	-1.806	1.329
Suckermouth Minnow - Occupancy	0.282	0.024	0.849
Suckermouth Minnow - Pools	0.267	-0.769	1.422
Suckermouth Minnow - Slackwater	0.973	-1.665	2.972
Suckermouth Minnow - Slope	1.954	-0.720	5.533
Suckermouth Minnow - Thalweg	-0.536	-1.863	0.560
Suckermouth Minnow - W:D	-0.125	-1.432	0.971
Threadfin Shad - Dam Distance	0.187	-0.478	0.882
Threadfin Shad - Discharge	0.325	-1.421	2.126
Threadfin Shad - Drainage Area	0.764	-2.697	5.005
Threadfin Shad - Limestone	-0.936	-2.679	0.186
Threadfin Shad - LWD	-0.651	-2.174	0.791
Threadfin Shad - Occupancy	0.886	0.389	0.992

Threadfin Shad - Pools	0.256	-0.728	1.346
Threadfin Shad - Slackwater	1.687	0.084	3.928
Threadfin Shad - Slope	-0.793	-2.788	1.607
Threadfin Shad - Thalweg	-0.409	-1.499	0.702
Threadfin Shad - W:D	0.183	-0.839	1.604
Warmouth - Dam Distance	0.232	-0.413	0.927
Warmouth - Discharge	0.064	-1.186	1.246
Warmouth - Drainage Area	-1.966	-4.805	0.905
Warmouth - Limestone	-0.703	-2.623	0.865
Warmouth - LWD	-0.408	-1.540	0.649
Warmouth - Occupancy	0.658	0.143	0.951
Warmouth - Pools	0.255	-0.660	1.340
Warmouth - Slackwater	0.986	-0.932	2.601
Warmouth - Slope	0.873	-0.514	2.391
Warmouth - Thalweg	-0.767	-1.813	0.020
Warmouth - W:D	-0.383	-1.662	0.537
White Bass - Dam Distance	0.125	-0.580	0.815
White Bass - Discharge	0.854	-0.637	2.499
White Bass - Drainage Area	0.223	-3.091	3.812
White Bass - Limestone	-0.856	-2.925	0.414
White Bass - LWD	-0.858	-2.189	0.223
White Bass - Occupancy	0.779	0.235	0.977
White Bass - Pools	0.167	-0.970	1.172
White Bass - Slackwater	1.322	-0.478	3.484
White Bass - Slope	-0.073	-1.613	1.764
White Bass - Thalweg	-0.362	-1.479	0.869

White Bass - W:D	0.061	-1.109	1.507
White Crappie - Dam Distance	0.204	-0.445	0.894
White Crappie - Discharge	1.549	0.076	3.247
White Crappie - Drainage Area	-0.447	-3.418	2.812
White Crappie - Limestone	-0.498	-1.970	0.882
White Crappie - LWD	-0.990	-2.249	0.100
White Crappie - Occupancy	0.938	0.545	0.995
White Crappie - Pools	0.296	-0.627	1.397
White Crappie - Slackwater	0.906	-0.899	2.540
White Crappie - Slope	-0.066	-1.415	1.598
White Crappie - Thalweg	-0.302	-1.192	0.662
White Crappie - W:D	-0.183	-1.310	0.763

Table 20. Model estimates from the final adult habitat occupancy model. ψ (Psi) and p are the group mean occupancy and detection estimates within the study area respectively. $\hat{R}$ (R-hat) is the measure of model convergence. $\hat{c}$ (c-hat) is a measure of posterior dispersion. The Bayesian p-value represents the goodness-of-fit test for the model. Segment and year sigma are a measure of the variance captured by the grouping factors. Lower (LHDI) and upper (UHDI) 95% high density intervals for Silver Carp and Bighead Carp.

Coefficient	**Mean**	**LHDI**	**UHDI**
ψ (group)	0.704	0.344	0.976
p (group)	0.414	0.589	0.258
$\hat{R}$	1.000	1.000	1.007
$\hat{c}$	0.992	0.937	1.048
Bayesian p-value	0.629	0.00	1.00
Segment - Sigma	0.579	0.001	1.194
Year - Sigma	1.400	0.338	2.965

Table 21. Detection model coefficients for adult species (probability scale) and covariates (logit scale) included in the final model, and their lower (LHDI) and upper (UHDI) 95% high density intervals. Daily average water temperature was collected during each survey and effort is electrofishing time (seconds).

Coefficient	**Median**	**LHDI**	**UHDI**
Effort	0.392	0.282	0.503
Temperature	0.124	0.004	0.238
Alligator Gar	0.446	0.322	0.572
Bighead Carp	0.445	0.327	0.562
Bigmouth Buffalo	0.726	0.617	0.816
Black Buffalo	0.711	0.622	0.789
Blue Catfish	0.576	0.467	0.678
Blue Sucker	0.508	0.379	0.642
Bluegill	0.561	0.412	0.707
Channel Catfish	0.365	0.219	0.525
Common Carp	0.270	0.142	0.441
Flathead Catfish	0.505	0.371	0.642
Freshwater Drum	0.572	0.455	0.682
Grass Carp	0.460	0.325	0.604
Green Sunfish	0.277	0.135	0.485
Longear Sunfish	0.394	0.247	0.572
Longnose Gar	0.739	0.649	0.812
Orangespotted Sunfish	0.356	0.201	0.554
Paddlefish	0.588	0.456	0.715
River Carpsucker	0.629	0.534	0.715
Shortnose Gar	0.522	0.387	0.653
Shovelnose Sturgeon	0.255	0.108	0.492
Silver Carp	0.593	0.494	0.685
Smallmouth Buffalo	0.845	0.771	0.900
Spotted Bass	0.511	0.361	0.664
Spotted Gar	0.409	0.285	0.544
White Bass	0.314	0.168	0.511

Table 22. Occupancy model coefficients for adult species (probability scale) and their covariates (logit scale) for the final model, and their lower (LHDI) and upper (UHDI) 95% high density intervals. The occupancy coefficient represents the probability of species occupancy within the study area. Continuous variables included were distance from the nearest upstream dam (Dam Distance), median discharge for the season (Discharge), average chlorophyll (mg/L), the elevation of the segment, the sinuosity of the segment, average measured salinity (ppt), and the width-to-depth ratio of the reach (W:D). Categorical variables were 1) backwater: present was the reference and was considered when >1% the site area was backwater and 2) drainage area: where high drainage area was the reference (>80,000 km^2).

Coefficient	**Median**	**LHDI**	**UHDI**
Alligator Gar - Occupancy	0.785	0.294	0.967
Bighead Carp - Occupancy	0.772	0.259	0.967
Bigmouth Buffalo - Occupancy	0.861	0.416	0.981
Black Buffalo - Occupancy	0.952	0.674	0.994
Blue Catfish - Occupancy	0.921	0.544	0.990
Blue Sucker - Occupancy	0.655	0.169	0.935
Bluegill - Occupancy	0.670	0.187	0.939
Channel Catfish - Occupancy	0.532	0.112	0.898
Common Carp - Occupancy	0.401	0.065	0.868
Flathead Catfish - Occupancy	0.656	0.175	0.936
Freshwater Drum - Occupancy	0.876	0.452	0.983
Grass Carp - Occupancy	0.682	0.198	0.945
Green Sunfish - Occupancy	0.311	0.043	0.797
Longear Sunfish - Occupancy	0.538	0.114	0.903
Longnose Gar - Occupancy	0.958	0.708	0.995
Orangespotted Sunfish - Occupancy	0.337	0.049	0.812
Paddlefish - Occupancy	0.725	0.225	0.956

River Carpsucker - Occupancy	0.934	0.601	0.992
Shortnose Gar - Occupancy	0.761	0.275	0.959
Shovelnose Sturgeon - Occupancy	0.187	0.020	0.689
Silver Carp - Occupancy	0.953	0.658	0.995
Smallmouth Buffalo - Occupancy	0.976	0.802	0.997
Spotted Bass - Occupancy	0.622	0.160	0.928
Spotted Gar - Occupancy	0.748	0.254	0.961
White Bass - Occupancy	0.347	0.051	0.816
Alligator Gar - Backwater	-0.005	-1.273	1.244
Alligator Gar - Drainage	-1.341	-3.006	0.286
Alligator Gar - Elevation	-0.398	-1.056	0.390
Alligator Gar - Sinuosity	-0.157	-0.919	0.469
Alligator Gar - Salinity	0.328	-0.282	0.963
Alligator Gar - W:D	-0.103	-0.999	0.762
Alligator Gar - Dam distance	-0.140	-0.741	0.625
Alligator Gar - Discharge	0.139	-0.461	0.694
Alligator Gar - Chlorophyll	-0.335	-0.827	0.118
Bighead Carp - Backwater	0.552	-0.657	2.178
Bighead Carp - Drainage	-1.407	-3.071	0.311
Bighead Carp - Elevation	-0.329	-1.014	0.515
Bighead Carp - Sinuosity	-0.172	-0.978	0.493
Bighead Carp - Salinity	0.176	-0.655	0.816
Bighead Carp - W:D	-1.011	-2.222	0.085
Bighead Carp - Dam distance	-0.300	-1.129	0.477
Bighead Carp - Discharge	0.136	-0.464	0.675
Bighead Carp - Chlorophyll	-0.286	-0.741	0.208

Bigmouth Buffalo - Backwater	0.988	-0.306	2.581
Bigmouth Buffalo - Drainage	-1.502	-3.218	0.140
Bigmouth Buffalo - Elevation	-0.433	-1.084	0.336
Bigmouth Buffalo - Sinuosity	0.015	-0.567	0.750
Bigmouth Buffalo - Salinity	0.414	-0.195	1.146
Bigmouth Buffalo - W:D	-0.917	-1.937	0.066
Bigmouth Buffalo - Dam distance	-0.069	-0.695	0.725
Bigmouth Buffalo - Discharge	0.147	-0.428	0.712
Bigmouth Buffalo - Chlorophyll	-0.245	-0.689	0.301
Black Buffalo - Backwater	0.472	-0.774	2.006
Black Buffalo - Drainage	-1.295	-2.962	0.408
Black Buffalo - Elevation	-0.393	-1.037	0.408
Black Buffalo - Sinuosity	-0.153	-0.912	0.493
Black Buffalo - Salinity	0.400	-0.230	1.134
Black Buffalo - W:D	0.079	-0.885	1.004
Black Buffalo - Dam distance	-0.284	-1.015	0.466
Black Buffalo - Discharge	0.158	-0.410	0.750
Black Buffalo - Chlorophyll	-0.319	-0.779	0.152
Blue Catfish - Backwater	-0.203	-1.771	1.085
Blue Catfish - Drainage	-1.083	-2.831	0.870
Blue Catfish - Elevation	-0.454	-1.121	0.355
Blue Catfish - Sinuosity	0.209	-0.423	1.190
Blue Catfish - Salinity	0.252	-0.432	0.866
Blue Catfish - W:D	0.361	-0.561	1.312
Blue Catfish - Dam distance	0.083	-0.614	1.081
Blue Catfish - Discharge	0.098	-0.517	0.612

Blue Catfish - Chlorophyll	-0.311	-0.758	0.147
Blue Sucker - Backwater	-0.175	-1.623	0.992
Blue Sucker - Drainage	-1.328	-2.996	0.349
Blue Sucker - Elevation	-0.477	-1.167	0.278
Blue Sucker - Sinuosity	-0.082	-0.779	0.565
Blue Sucker - Salinity	0.327	-0.293	1.010
Blue Sucker - W:D	1.987	0.766	3.338
Blue Sucker - Dam distance	-0.132	-0.773	0.644
Blue Sucker - Discharge	0.134	-0.442	0.700
Blue Sucker - Chlorophyll	-0.267	-0.712	0.219
Bluegill - Backwater	0.052	-1.164	1.240
Bluegill - Drainage	-1.689	-3.551	0.022
Bluegill - Elevation	-0.468	-1.149	0.268
Bluegill - Sinuosity	-0.070	-0.690	0.564
Bluegill - Salinity	0.239	-0.394	0.844
Bluegill - W:D	0.351	-0.490	1.236
Bluegill - Dam distance	-0.317	-1.029	0.405
Bluegill - Discharge	0.162	-0.384	0.730
Bluegill - Chlorophyll	-0.343	-0.802	0.089
Channel Catfish - Backwater	-0.111	-1.492	1.126
Channel Catfish - Drainage	-1.285	-2.913	0.386
Channel Catfish - Elevation	-0.369	-1.024	0.381
Channel Catfish - Sinuosity	-0.051	-0.678	0.595
Channel Catfish - Salinity	0.399	-0.193	1.108
Channel Catfish - W:D	0.728	-0.234	1.734
Channel Catfish - Dam distance	-0.293	-1.022	0.424

Channel Catfish - Discharge	0.146	-0.424	0.709
Channel Catfish - Chlorophyll	-0.321	-0.769	0.112
Common Carp - Backwater	0.792	-0.524	2.700
Common Carp - Drainage	-1.244	-2.915	0.528
Common Carp - Elevation	-0.476	-1.189	0.258
Common Carp - Sinuosity	-0.096	-0.814	0.610
Common Carp - Salinity	0.218	-0.553	0.875
Common Carp - W:D	-0.067	-1.274	1.072
Common Carp - Dam distance	-0.224	-0.936	0.576
Common Carp - Discharge	0.172	-0.403	0.765
Common Carp - Chlorophyll	-0.272	-0.711	0.222
Flathead Catfish - Backwater	-0.480	-2.017	0.756
Flathead Catfish - Drainage	-1.326	-2.974	0.347
Flathead Catfish - Elevation	-0.350	-1.012	0.444
Flathead Catfish - Sinuosity	-0.070	-0.720	0.587
Flathead Catfish - Salinity	0.555	-0.074	1.389
Flathead Catfish - W:D	1.419	0.428	2.526
Flathead Catfish - Dam distance	-0.241	-0.916	0.495
Flathead Catfish - Discharge	0.106	-0.499	0.633
Flathead Catfish - Chlorophyll	-0.312	-0.780	0.134
Freshwater Drum - Backwater	-0.472	-1.919	0.732
Freshwater Drum - Drainage	-1.259	-2.910	0.433
Freshwater Drum - Elevation	-0.507	-1.239	0.203
Freshwater Drum - Sinuosity	0.053	-0.520	0.763
Freshwater Drum - Salinity	0.293	-0.308	0.924
Freshwater Drum - W:D	0.248	-0.617	1.092

Freshwater Drum - Dam distance	-0.073	-0.686	0.707
Freshwater Drum - Discharge	0.074	-0.556	0.609
Freshwater Drum - Chlorophyll	-0.326	-0.781	0.101
Grass Carp - Backwater	0.222	-1.034	1.568
Grass Carp - Drainage	-1.492	-3.292	0.073
Grass Carp - Elevation	-0.475	-1.161	0.264
Grass Carp - Sinuosity	-0.038	-0.688	0.647
Grass Carp - Salinity	0.133	-0.728	0.759
Grass Carp - W:D	-0.242	-1.345	0.742
Grass Carp - Dam distance	-0.185	-0.833	0.607
Grass Carp - Discharge	0.198	-0.366	0.842
Grass Carp - Chlorophyll	-0.270	-0.708	0.216
Green Sunfish - Backwater	-0.020	-1.574	1.439
Green Sunfish - Drainage	-1.546	-3.372	0.179
Green Sunfish - Elevation	-0.487	-1.238	0.288
Green Sunfish - Sinuosity	0.004	-0.676	0.743
Green Sunfish - Salinity	0.197	-0.608	0.835
Green Sunfish - W:D	0.375	-0.716	1.497
Green Sunfish - Dam distance	-0.323	-1.164	0.435
Green Sunfish - Discharge	0.145	-0.423	0.717
Green Sunfish - Chlorophyll	-0.275	-0.730	0.211
Longear Sunfish - Backwater	-0.053	-1.442	1.160
Longear Sunfish - Drainage	-1.602	-3.447	0.035
Longear Sunfish - Elevation	-0.426	-1.078	0.345
Longear Sunfish - Sinuosity	-0.042	-0.681	0.623
Longear Sunfish - Salinity	0.327	-0.319	0.988

Longear Sunfish - W:D	0.011	-0.949	0.942
Longear Sunfish - Dam distance	-0.240	-0.910	0.522
Longear Sunfish - Discharge	0.139	-0.424	0.709
Longear Sunfish - Chlorophyll	-0.309	-0.752	0.133
Longnose Gar - Backwater	0.041	-1.331	1.356
Longnose Gar - Drainage	-1.206	-2.814	0.633
Longnose Gar - Elevation	-0.446	-1.165	0.343
Longnose Gar - Sinuosity	-0.021	-0.686	0.661
Longnose Gar - Salinity	0.266	-0.384	0.914
Longnose Gar - W:D	0.470	-0.500	1.445
Longnose Gar - Dam distance	-0.131	-0.765	0.682
Longnose Gar - Discharge	0.128	-0.481	0.659
Longnose Gar - Chlorophyll	-0.289	-0.748	0.186
Orangespotted Sunfish - Backwater	0.438	-0.793	1.947
Orangespotted Sunfish - Drainage	-1.529	-3.362	0.062
Orangespotted Sunfish - Elevation	-0.518	-1.277	0.255
Orangespotted Sunfish - Sinuosity	0.006	-0.613	0.756
Orangespotted Sunfish - Salinity	0.107	-0.737	0.769
Orangespotted Sunfish - W:D	-0.113	-1.304	0.980
Orangespotted Sunfish - Dam distance	-0.326	-1.155	0.407
Orangespotted Sunfish - Discharge	0.115	-0.492	0.665
Orangespotted Sunfish - Chlorophyll	-0.352	-0.864	0.110
Paddlefish - Backwater	0.801	-0.391	2.407
Paddlefish - Drainage	-1.539	-3.342	0.111
Paddlefish - Elevation	-0.297	-0.982	0.572
Paddlefish - Sinuosity	-0.148	-0.902	0.524

Paddlefish - Salinity	0.173	-0.530	0.819
Paddlefish - W:D	-0.470	-1.537	0.514
Paddlefish - Dam distance	-0.136	-0.789	0.679
Paddlefish - Discharge	0.097	-0.505	0.605
Paddlefish - Chlorophyll	-0.311	-0.782	0.139
River Carpsucker - Backwater	0.468	-0.810	2.115
River Carpsucker - Drainage	-1.036	-2.724	0.993
River Carpsucker - Elevation	-0.470	-1.190	0.295
River Carpsucker - Sinuosity	-0.133	-0.870	0.492
River Carpsucker - Salinity	0.392	-0.234	1.157
River Carpsucker - W:D	0.492	-0.495	1.465
River Carpsucker - Dam distance	-0.231	-0.950	0.510
River Carpsucker - Discharge	0.134	-0.480	0.664
River Carpsucker - Chlorophyll	-0.305	-0.756	0.160
Shortnose Gar - Backwater	0.044	-1.124	1.138
Shortnose Gar - Drainage	-1.395	-3.048	0.196
Shortnose Gar - Elevation	-0.355	-1.002	0.409
Shortnose Gar - Sinuosity	0.051	-0.515	0.744
Shortnose Gar - Salinity	0.545	-0.079	1.330
Shortnose Gar - W:D	-0.031	-0.900	0.816
Shortnose Gar - Dam distance	-0.129	-0.725	0.604
Shortnose Gar - Discharge	0.172	-0.400	0.756
Shortnose Gar - Chlorophyll	-0.282	-0.714	0.180
Shovelnose Sturgeon - Backwater	0.089	-1.455	1.601
Shovelnose Sturgeon - Drainage	-1.418	-3.185	0.298
Shovelnose Sturgeon - Elevation	-0.533	-1.350	0.271

Shovelnose Sturgeon - Sinuosity	-0.098	-0.858	0.590
Shovelnose Sturgeon - Salinity	0.315	-0.396	1.066
Shovelnose Sturgeon - W:D	0.906	-0.258	2.187
Shovelnose Sturgeon - Dam distance	-0.277	-1.095	0.490
Shovelnose Sturgeon - Discharge	0.124	-0.484	0.683
Shovelnose Sturgeon - Chlorophyll	-0.296	-0.775	0.188
Silver Carp - Backwater	0.433	-0.879	2.096
Silver Carp - Drainage	-1.207	-2.907	0.654
Silver Carp - Elevation	-0.380	-1.076	0.435
Silver Carp - Sinuosity	-0.167	-1.016	0.516
Silver Carp - Salinity	0.251	-0.510	0.957
Silver Carp - W:D	-0.176	-1.237	0.851
Silver Carp - Dam distance	-0.136	-0.790	0.709
Silver Carp - Discharge	0.115	-0.486	0.672
Silver Carp - Chlorophyll	-0.261	-0.736	0.281
Smallmouth Buffalo - Backwater	0.464	-0.773	2.081
Smallmouth Buffalo - Drainage	-1.335	-2.993	0.379
Smallmouth Buffalo - Elevation	-0.396	-1.040	0.412
Smallmouth Buffalo - Sinuosity	-0.062	-0.752	0.605
Smallmouth Buffalo - Salinity	0.540	-0.125	1.482
Smallmouth Buffalo - W:D	-0.405	-1.556	0.626
Smallmouth Buffalo - Dam distance	-0.097	-0.746	0.728
Smallmouth Buffalo - Discharge	0.138	-0.483	0.690
Smallmouth Buffalo - Chlorophyll	-0.283	-0.742	0.211
Spotted Bass - Backwater	-0.122	-1.452	1.025
Spotted Bass - Drainage	-1.621	-3.410	0.030

Spotted Bass - Elevation	-0.443	-1.087	0.301
Spotted Bass - Sinuosity	-0.020	-0.617	0.613
Spotted Bass - Salinity	0.288	-0.349	0.917
Spotted Bass - W:D	0.199	-0.684	1.096
Spotted Bass - Dam distance	-0.380	-1.179	0.348
Spotted Bass - Discharge	0.091	-0.520	0.612
Spotted Bass - Chlorophyll	-0.363	-0.877	0.081
Spotted Gar - Backwater	-0.184	-1.588	0.985
Spotted Gar - Drainage	-1.388	-3.016	0.309
Spotted Gar - Elevation	-0.457	-1.171	0.287
Spotted Gar - Sinuosity	0.006	-0.593	0.720
Spotted Gar - Salinity	0.417	-0.193	1.142
Spotted Gar - W:D	-0.409	-1.330	0.463
Spotted Gar - Dam distance	-0.306	-1.057	0.402
Spotted Gar - Discharge	0.147	-0.432	0.733
Spotted Gar - Chlorophyll	-0.304	-0.755	0.165
White Bass - Backwater	-0.011	-1.488	1.299
White Bass - Drainage	-1.304	-2.945	0.405
White Bass - Elevation	-0.572	-1.475	0.192
White Bass - Sinuosity	0.101	-0.521	0.957
White Bass - Salinity	0.208	-0.535	0.864
White Bass - W:D	0.363	-0.714	1.460
White Bass - Dam distance	-0.279	-1.004	0.490
White Bass - Discharge	0.104	-0.512	0.644
White Bass - Chlorophyll	-0.333	-0.829	0.128
Spotted Gar - Dam distance	-0.306	-1.057	0.402

Spotted Gar - Discharge	0.147	-0.432	0.733

Table 23. Mean back-calculated length-at-age (mm) for Silver Carp and Bighead Carp collected from May 2021 through October 2022 in the lower Red River catchment.

Age (years)	Silver Carp	Bighead Carp
1	275	272
2	465	438
3	603	569
4	694	674
5	740	746
6	759	808
7	797	862
8	833	922
9	868	963
10	891	995
11	899	1019
12	914	1040
13	917	1059
14	905	1108
15	-	1151
16	-	1216
17	-	1299

Table 24. The top ranked models with the corresponding parameter number (*K*), Akaike information criterion corrected for small sample size (AICc), model difference (ΔAIC), and model weight for models that were averaged for Bighead Carp in the lower Red River catchment. B0 is the model intercept, A is fish age, T is air temperature, and CV.Q is the coefficient of variation of discharge.

Model	K	AICc	ΔAIC	Weight
~ B0 + A + T	6	1324.39	0	0.34
~ B0 + A + T + CV.Q	7	1326.00	1.62	0.15

Table 25. The top ranked models with the corresponding parameter number (*K*), Akaike information criterion corrected for small sample size (AICc), model difference (ΔAIC), and model weight for models included in the averaged Weisberg model for Silver Carp in the lower Red River catchment. B0 is the model intercept, A is fish age, T is air temperature, Q is discharge, CV.T is the coefficient of variation of air temperature, and CV.Q is the coefficient of variation of discharge.

Model	K	AICc	ΔAIC	Weight
~ B0 + A + T + Q	7	2177.33	0	0.11
~ B0 + A + T + Q + CV.T + CV.Q	9	2177.79	0.46	0.08
~ B0 + A + T	6	2177.81	0.49	0.08
~ B0 + A + T + Q + CV.Q	8	2177.86	0.53	0.08
~ B0 + A + Q + CV.T + CV.Q	8	2177.88	0.55	0.08
~ B0 + A + T + CV.Q	7	2177.95	0.63	0.08
~ B0 + A + Q	6	2178.26	0.93	0.07
~ B0 + A + T + Q + CV.T	8	2178.42	1.09	0.06
~ B0 + A	5	2178.59	1.26	0.06
~ B0 + A+ Q + CV.T	7	2178.62	1.29	0.06
~ B0 + A + CV.Q	6	2178.88	1.55	0.05
~ B0 + A + Q + CV.Q	7	2178.92	1.59	0.05
~ B0 + A + T + CV.T + CV.Q	8	2179.12	1.79	0.04

Table 26. Averaged model estimates for evaluating the relationship between Silver Carp and Bighead Carp growth and environmental factors. The final average Weisberg model estimates with the corresponding standard error (SE), p-value (Pr>|z|), and 90% confidence intervals (90% C.I.) for Bighead Carp and Silver Carp in the lower Red River catchment.

Species	Covariate	Estimate	SE	Pr>|z|	90% C.I.
Bighead Carp	Age	-0.28	0.01	0.00	(-0.49, -0.26)
	Air temperature	0.19	0.07	0.00	(0.08, 0.30)
	CV of discharge	-0.01	0.03	0.74	(-0.06, 0.04)
Silver Carp	Age	-0.37	0.01	0.00	(-0.39, -0.35)
	Discharge	0.15	0.16	0.34	(-0.10, 0.40)
	Air temperature	0.13	0.14	0.36	(-0.01, 0.37)
	CV of temperature	0.05	0.08	0.59	(-0.09, 0.19)
	CV of discharge	-0.05	0.07	0.44	(-0.16, 0.06)

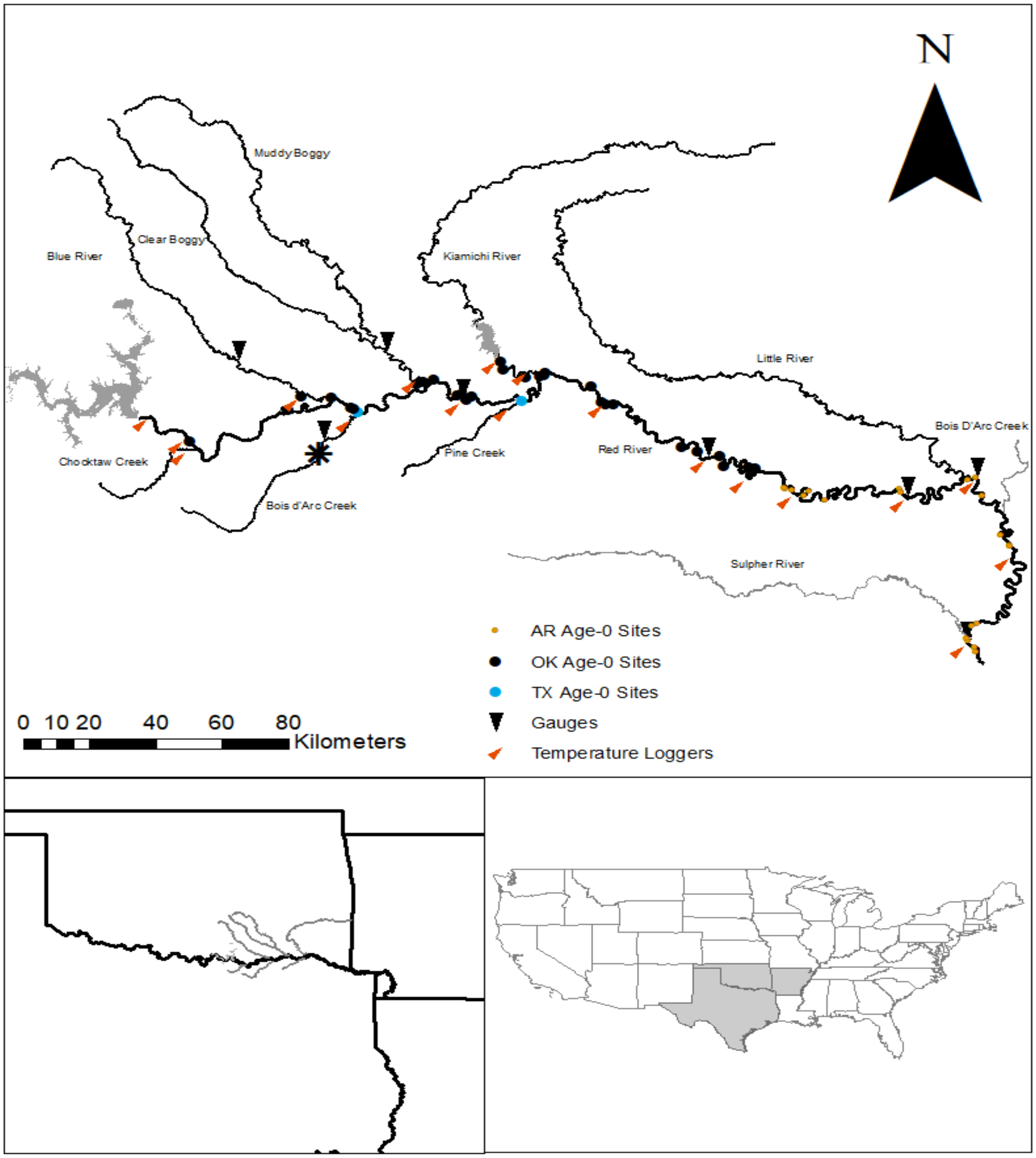


Figure 1. Age-0 fish sampling locations (circles) in the lower Red River basin. The circle colors reflect the state where the sample site was located. Sample sites in orange indicate the location of sites sampled for Arkansas. We include Texas (blue), and Oklahoma (black) sites simply to share information since the river is a continuous system. The gray lines represent major rivers with black arrows denoting U.S. Geological Survey streamgages and the red arrow denoting temperature logger locations. Each sampling reach was sampled 1-3 times May through early October 2021-2022 using seines, mini-fyke nets, and larval tows.

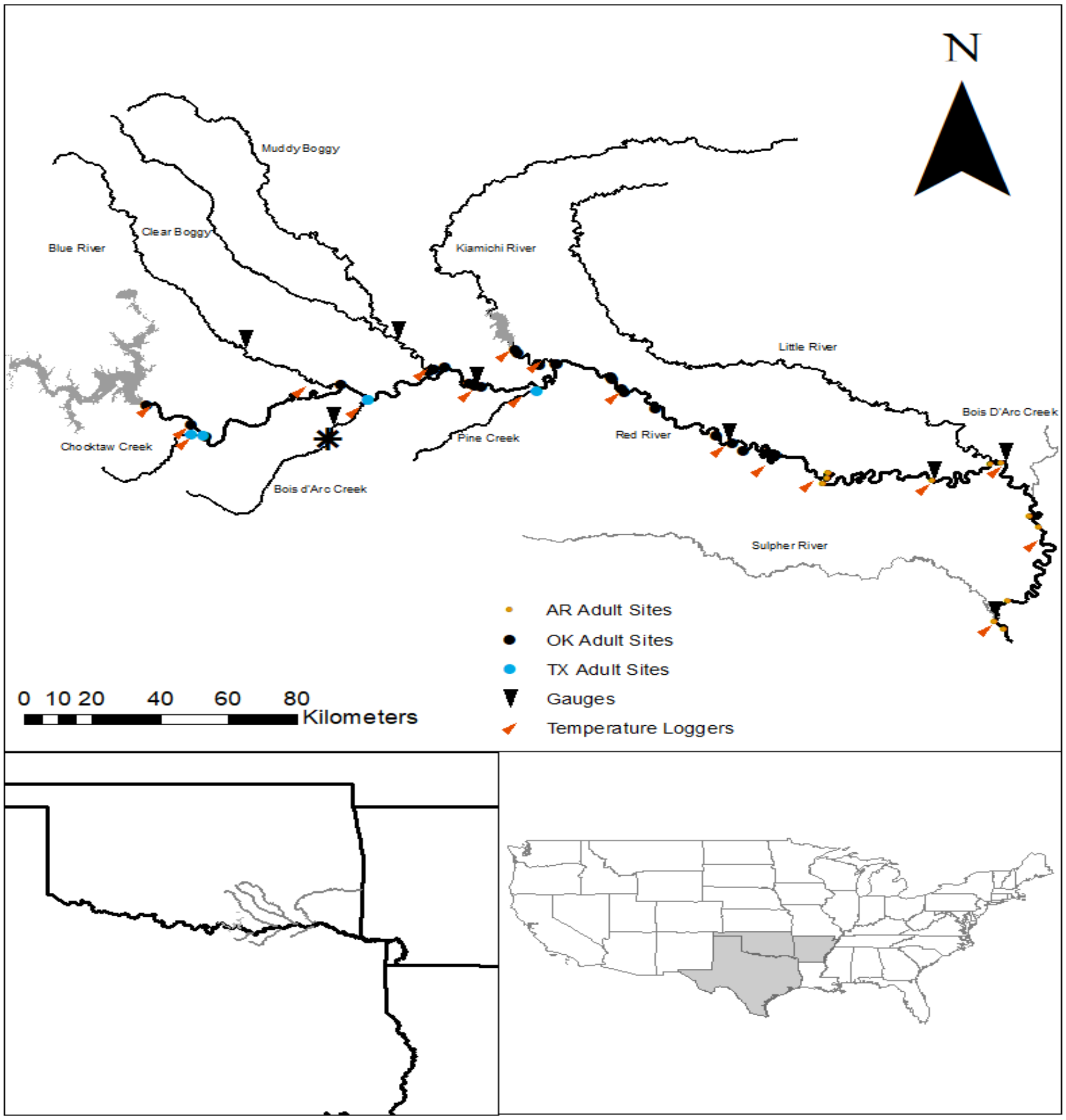


Figure 2. Adult fish sampling locations (circles) in the lower Red River basin. The circle colors reflect the state where the sample site is located. Sample sites in orange indicate the location of sites sampled for Arkansas. We include Texas (blue), and Oklahoma (black) sites simply to share information since the river is a continuous system. The gray lines represent major rivers with black arrows denoting U.S. Geological Survey streamgages and the red arrow denoting temperature logger locations. Each site was sampled 1-3 times in April through September 2021-2022 using gillnets, electrofishing, and hoop nets.

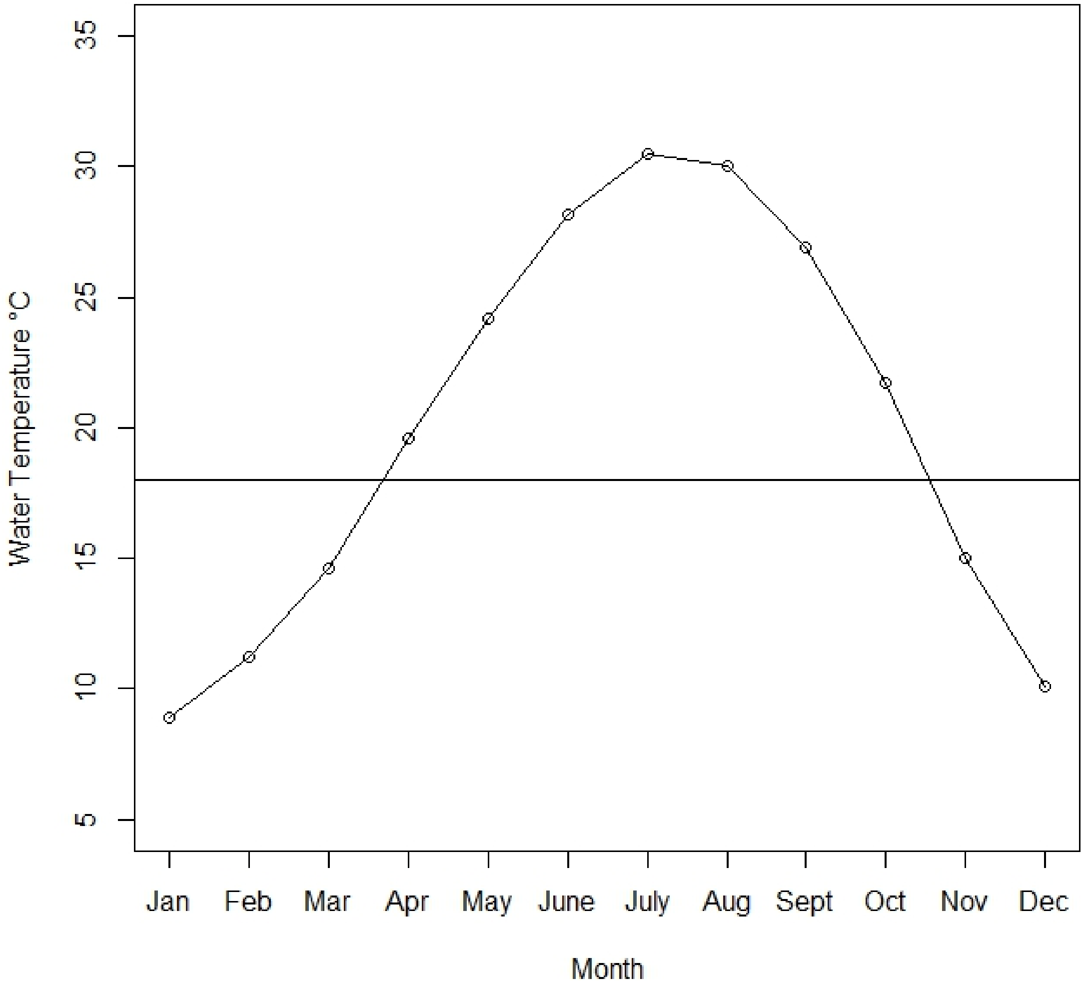


Figure 3. The mean monthly water temperature (°C) for the lower Red River (1997 to 2021) from the U.S. Geological Survey streamgage located near Index, AR (07337000). The horizontal line indicates 18 °C, which is hypothesized to be required for Carp spawning.

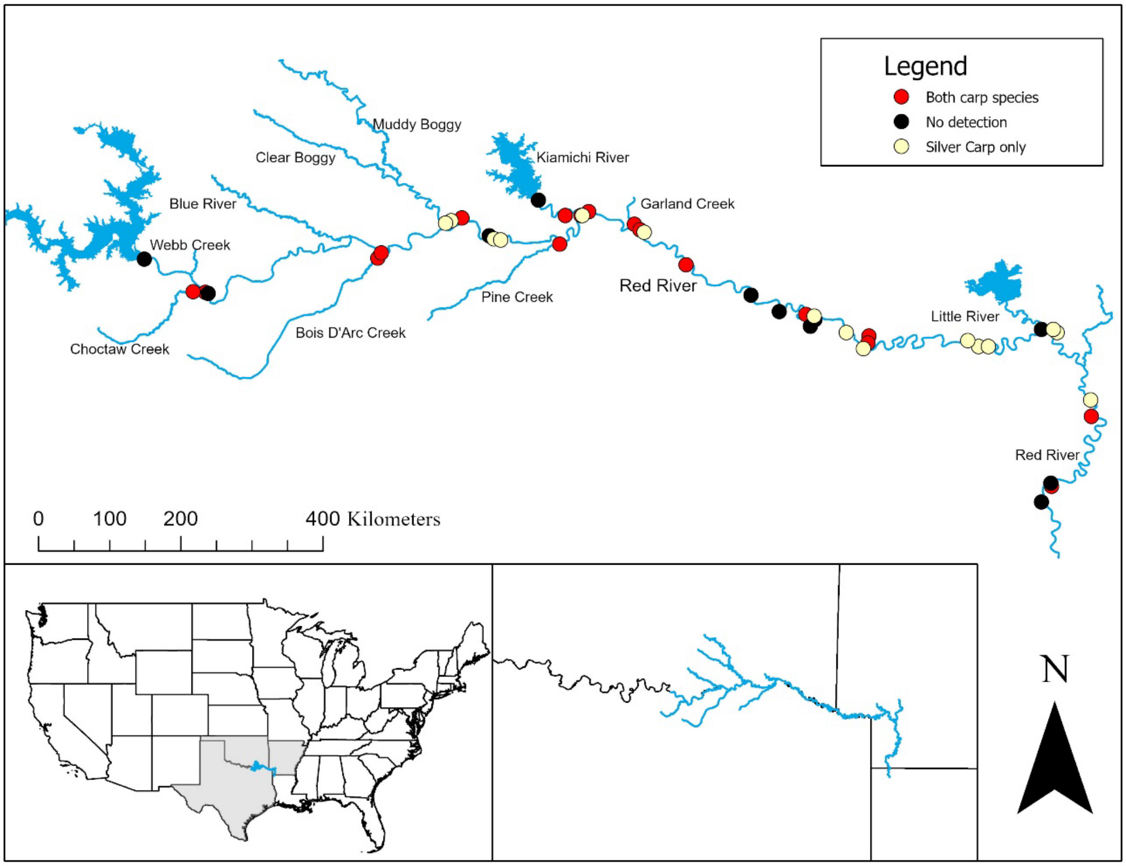


Figure 4. A map of all sites sampled in the lower Red River catchment from May 2021 through September 2022 where no carp were detected (black circle), only Silver Carp was detected (yellow circle), or both Carp (Bighead Carp and Silver Carp) were detected (red circle).

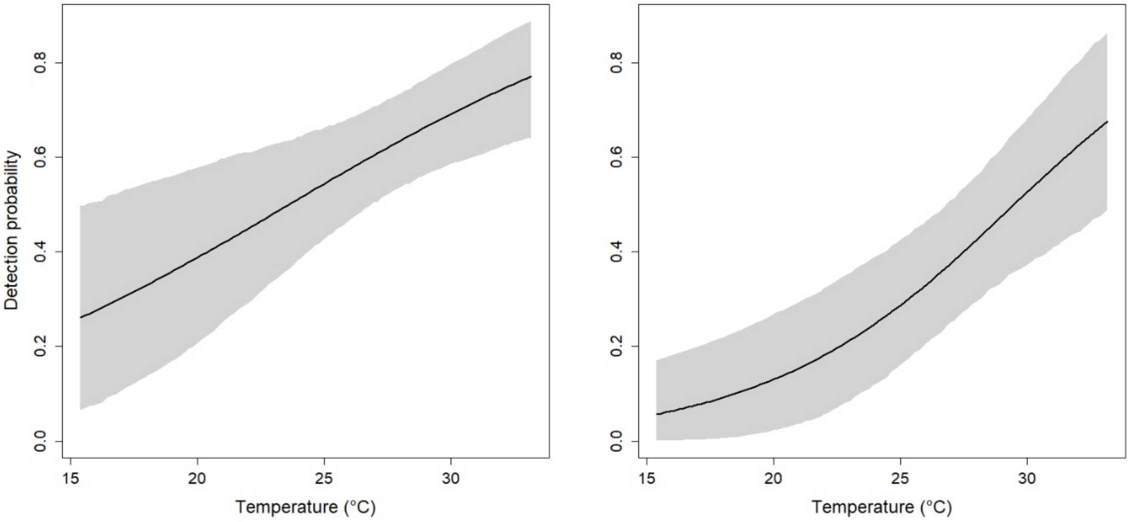


Figure 5. Silver Carp (left) and Bighead Carp (right) detection probability related to water temperature (°C) in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values.

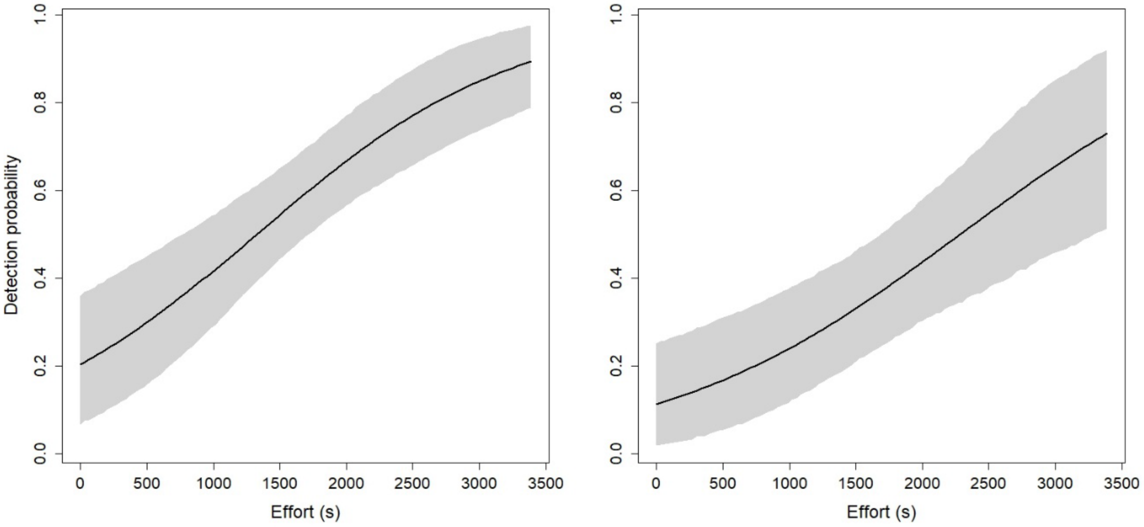


Figure 6. Silver Carp (left) and Bighead Carp (right) detection probability related to electrofishing effort (s) in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values

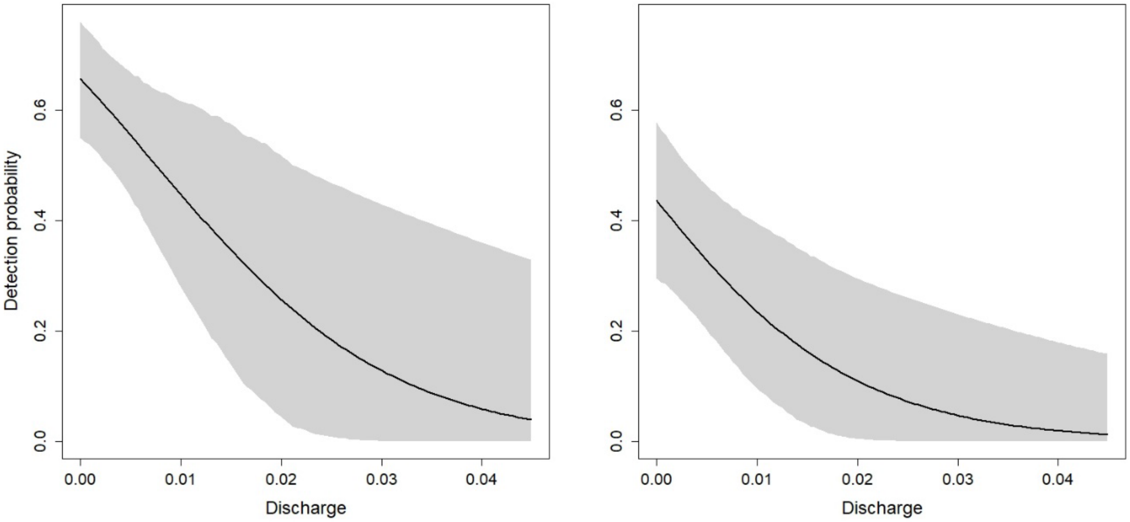


Figure 7. Silver Carp (left) and Bighead Carp (right) detection probability related to discharge (m^3/s) in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values.

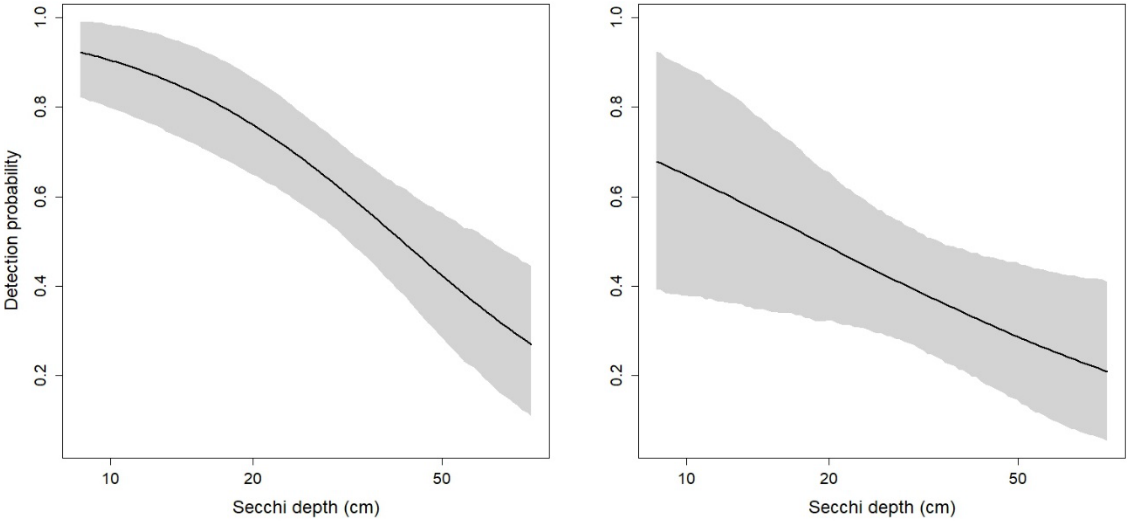


Figure 8. Silver Carp (left) and Bighead Carp (right) detection probability related to Secchi depth (cm) in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values.

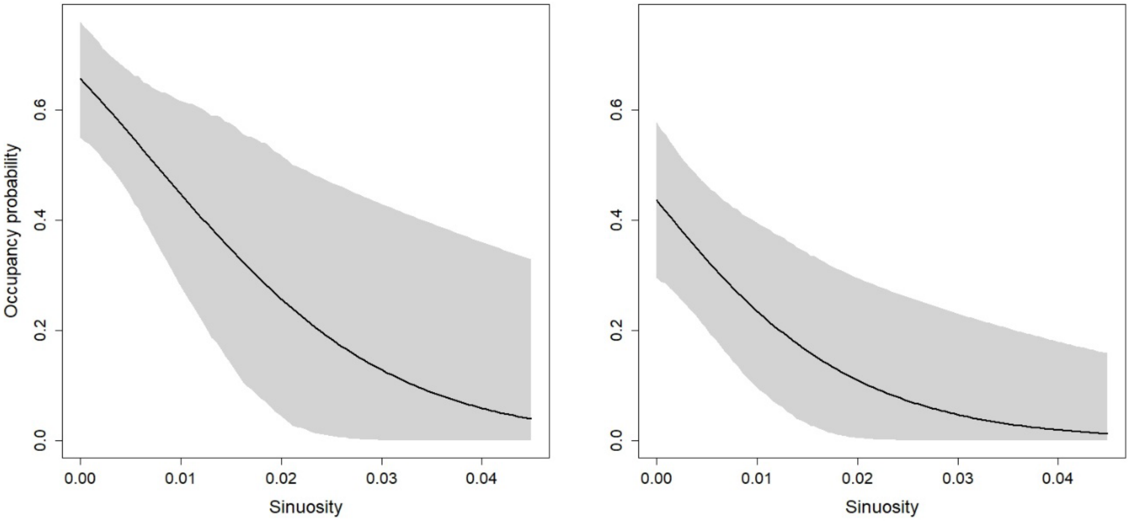


Figure 9. Silver Carp (left) and Bighead Carp (right) occupancy probability related to sinuosity in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values.

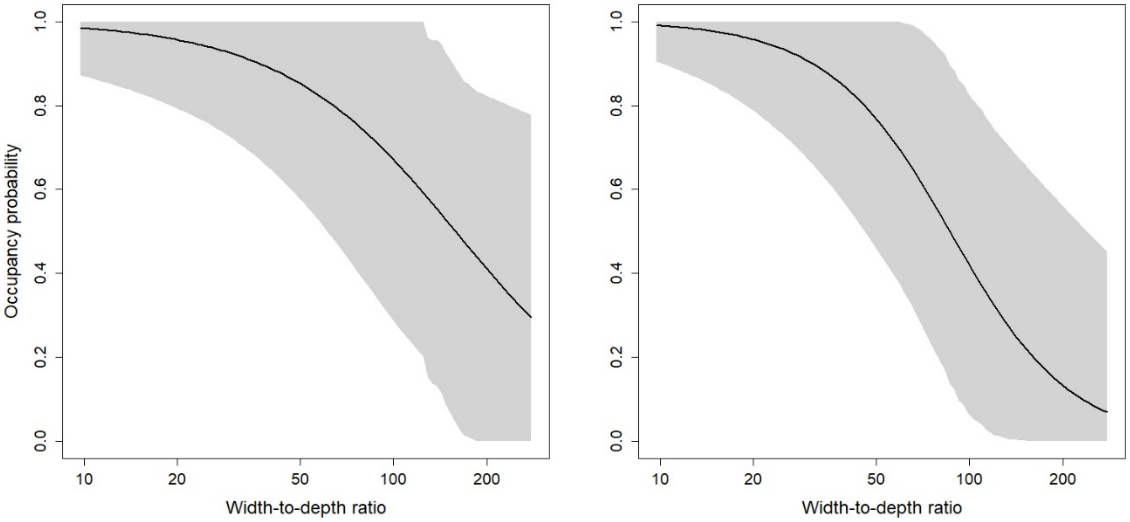


Figure 10. Silver Carp (left) and Bighead Carp (right) occupancy probability related to width-to-depth ratio in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values.

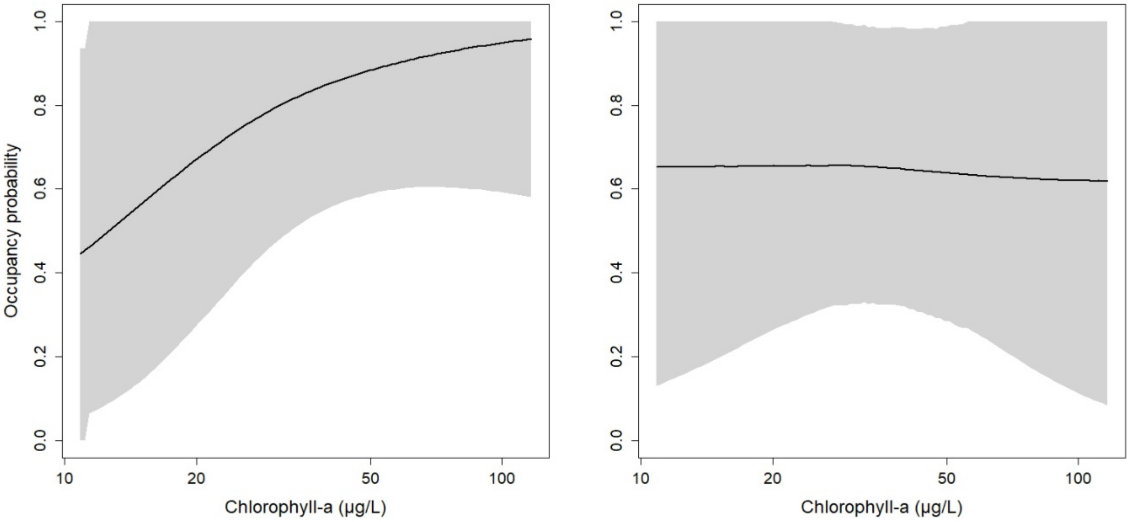


Figure 11. Silver Carp (left) and Bighead Carp (right) occupancy probability related to chlorophyll-*a* in the lower Red River catchment. The solid line is the mode estimate, and the gray polygon is the 90% highest density interval (HDI). The mode was estimated with all other model covariates held at mean values.

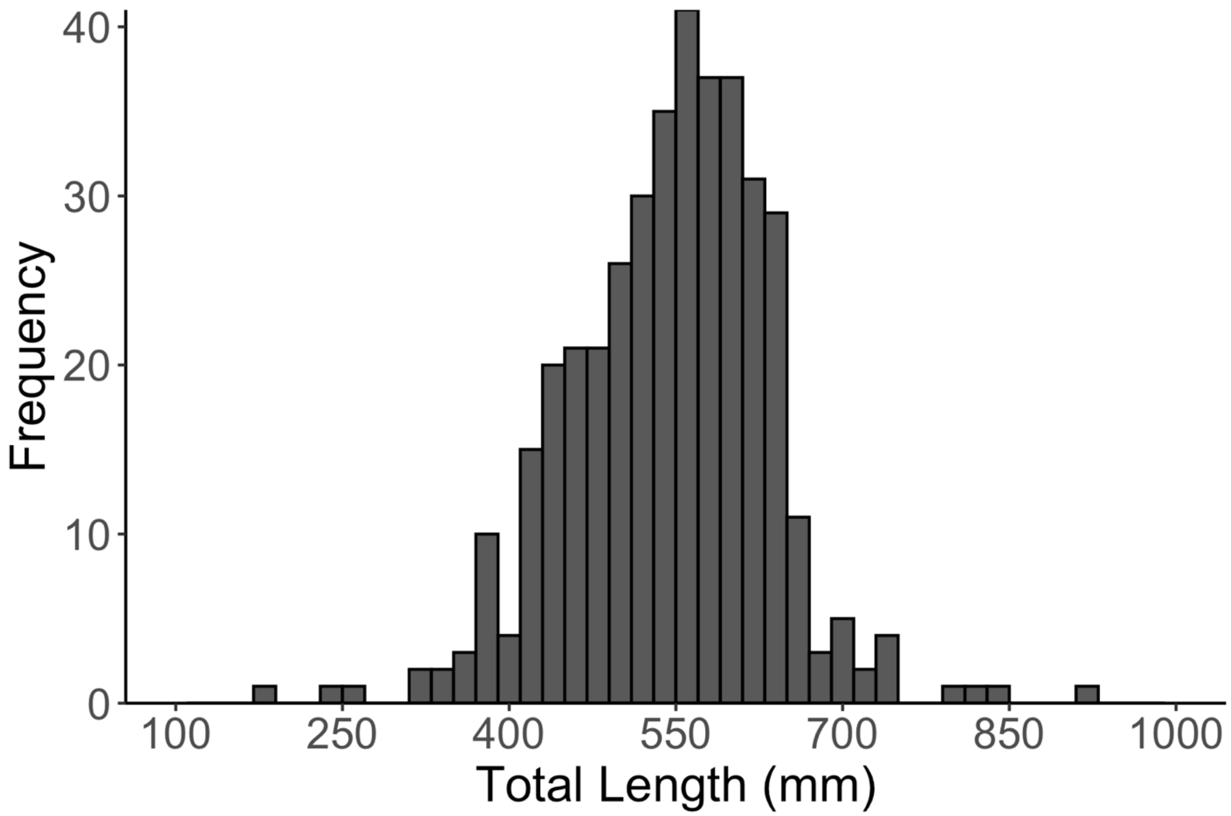


Figure 12. Length (mm) frequency histogram of Smallmouth Buffalo sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=386) in 2021-2022.

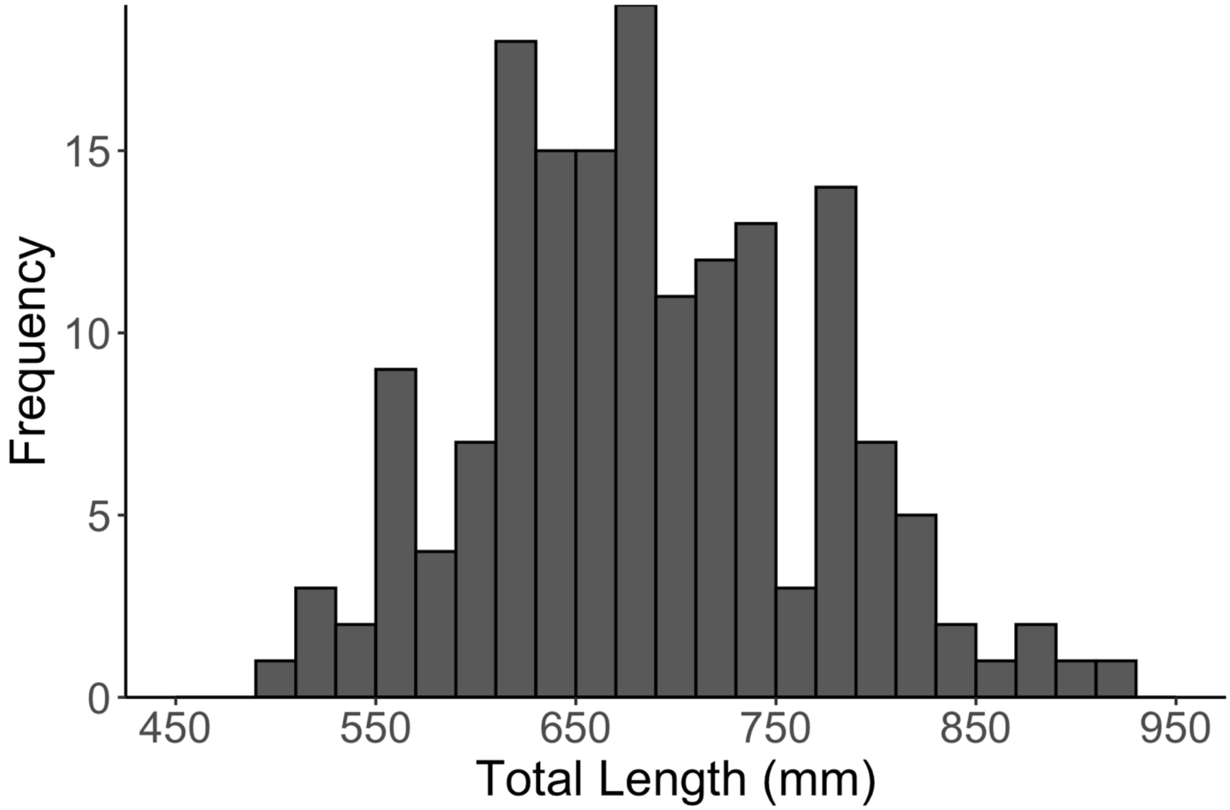


Figure 13. Length (mm) frequency histogram of Black Buffalo sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=158) in 2021-2022.

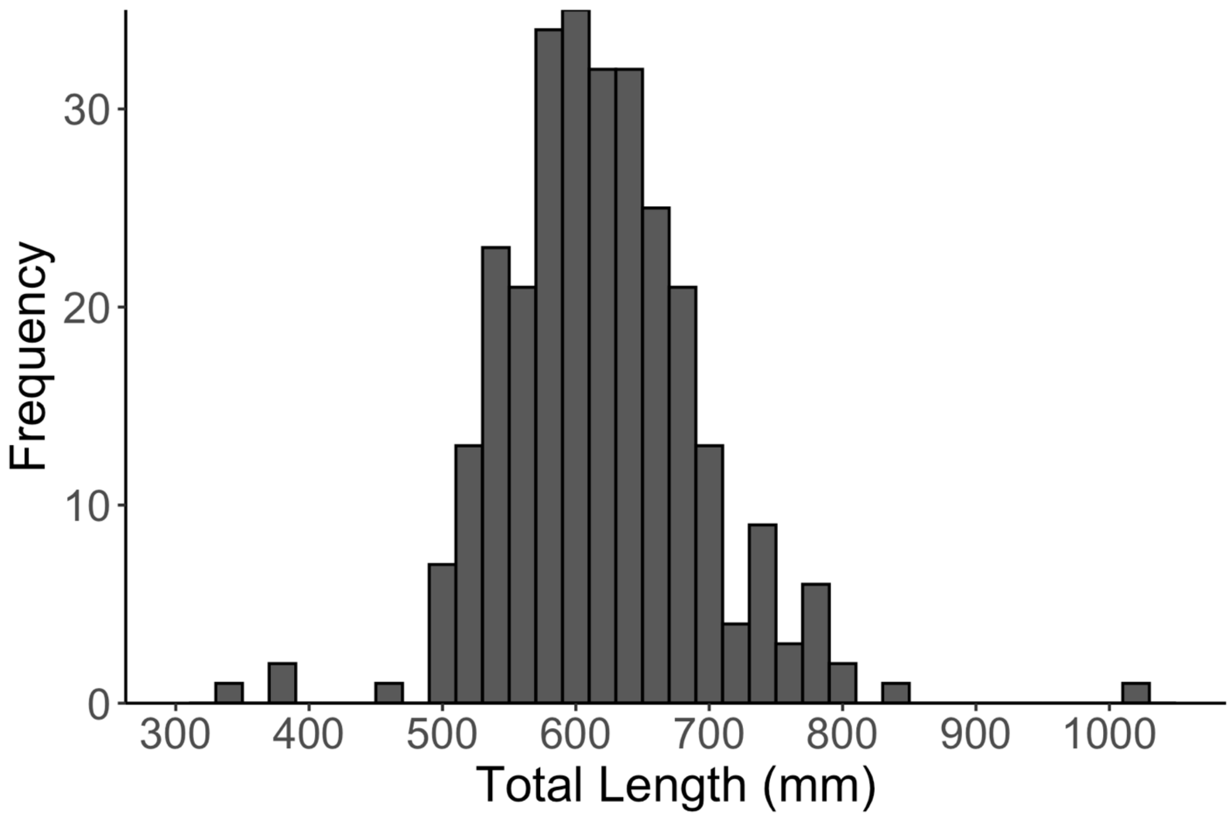


Figure 14. Length (mm) frequency histogram of Bigmouth Buffalo sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=267) in 2021-2022.

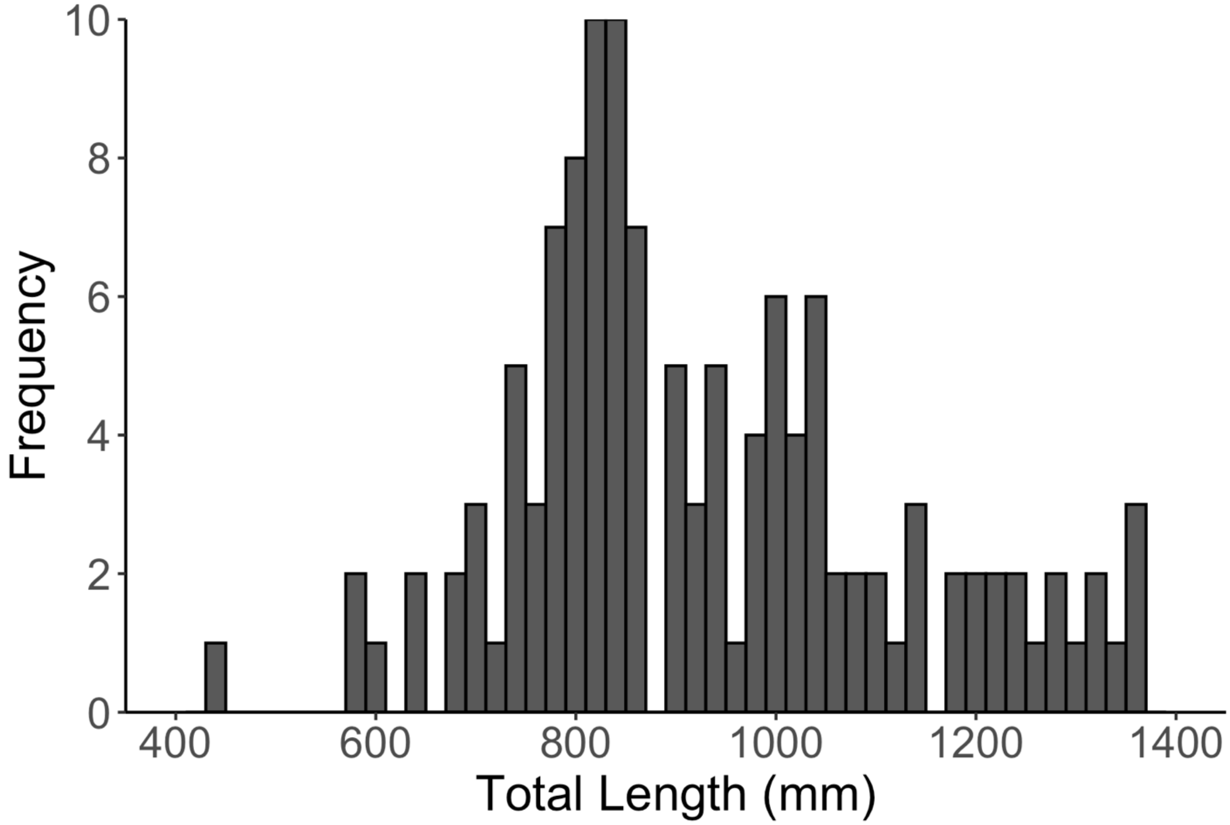


Figure 15. Length (mm) frequency histogram of Longnose Gar sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=124) in 2021-2022.

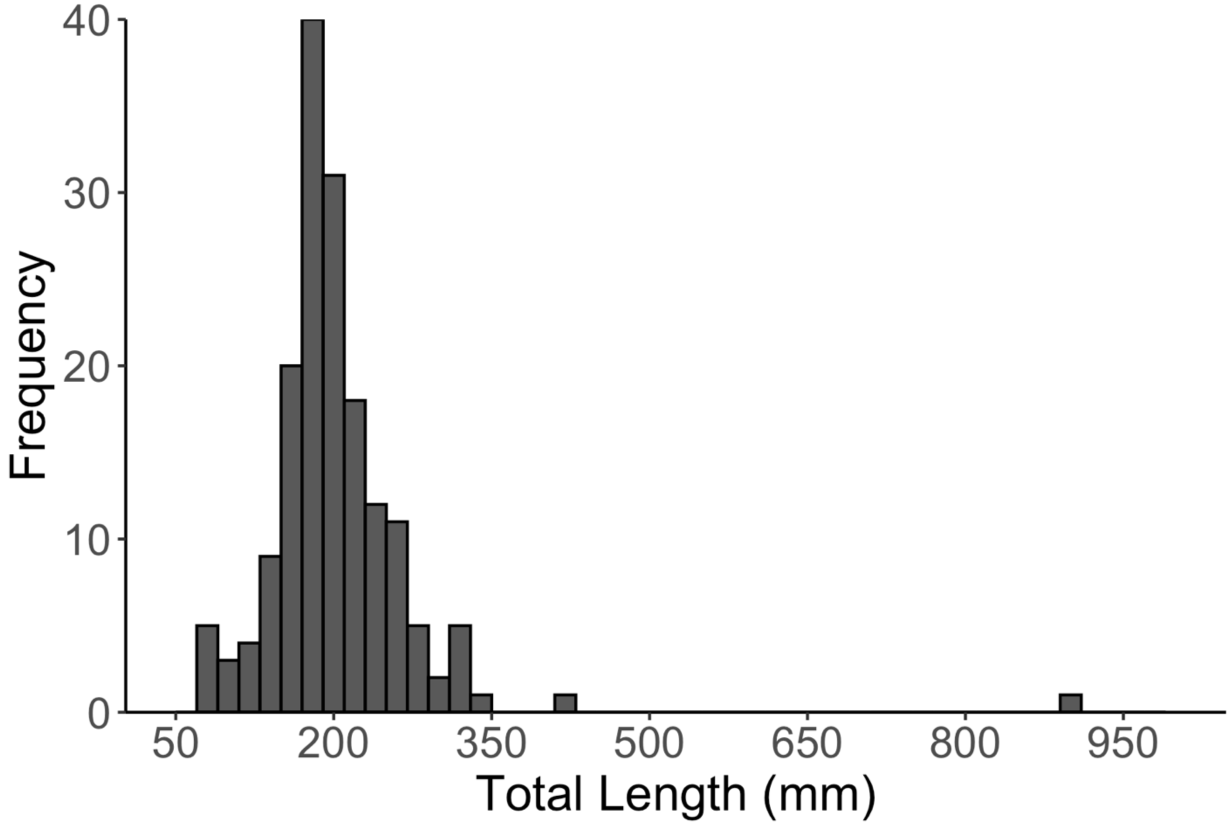


Figure 16. Length (mm) frequency histogram of Flathead Catfish sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=168) in 2021-2022.

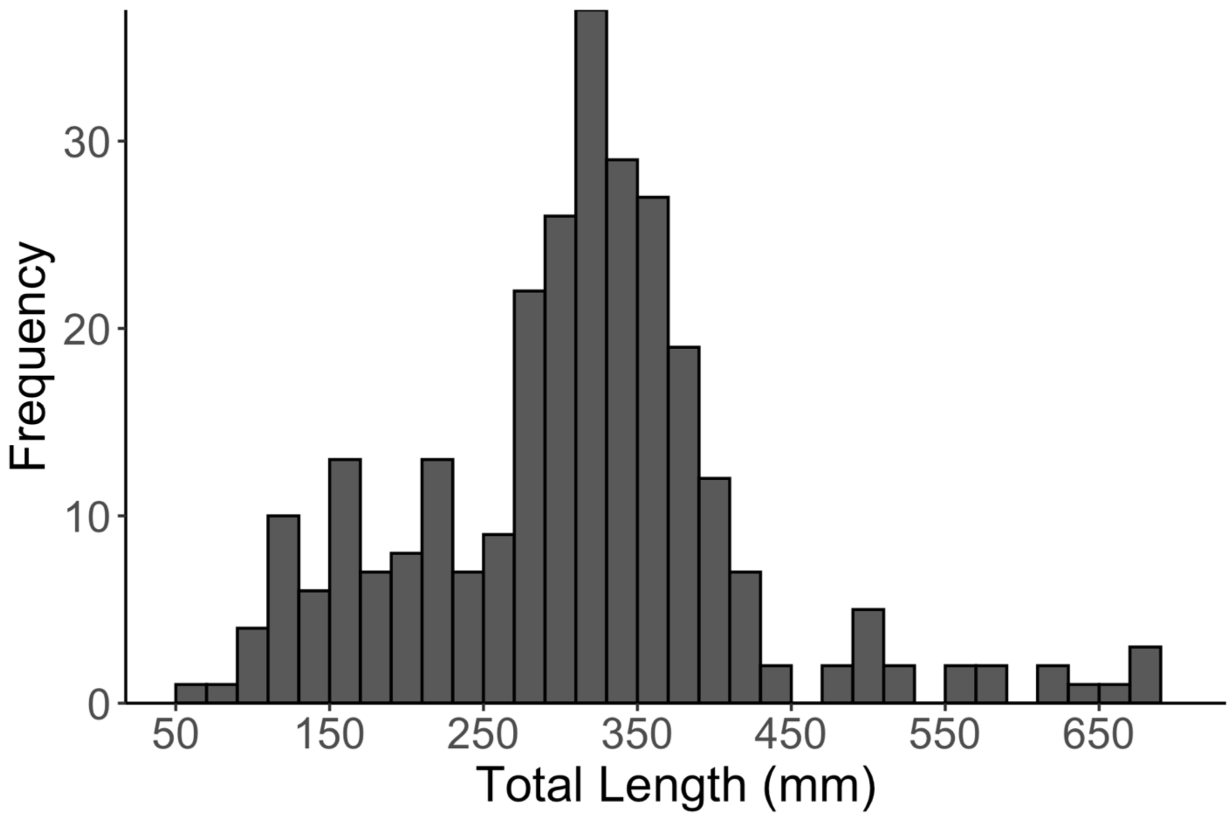


Figure 17. Length (mm) frequency histogram of River Carpsucker sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=280) in 2021-2022.

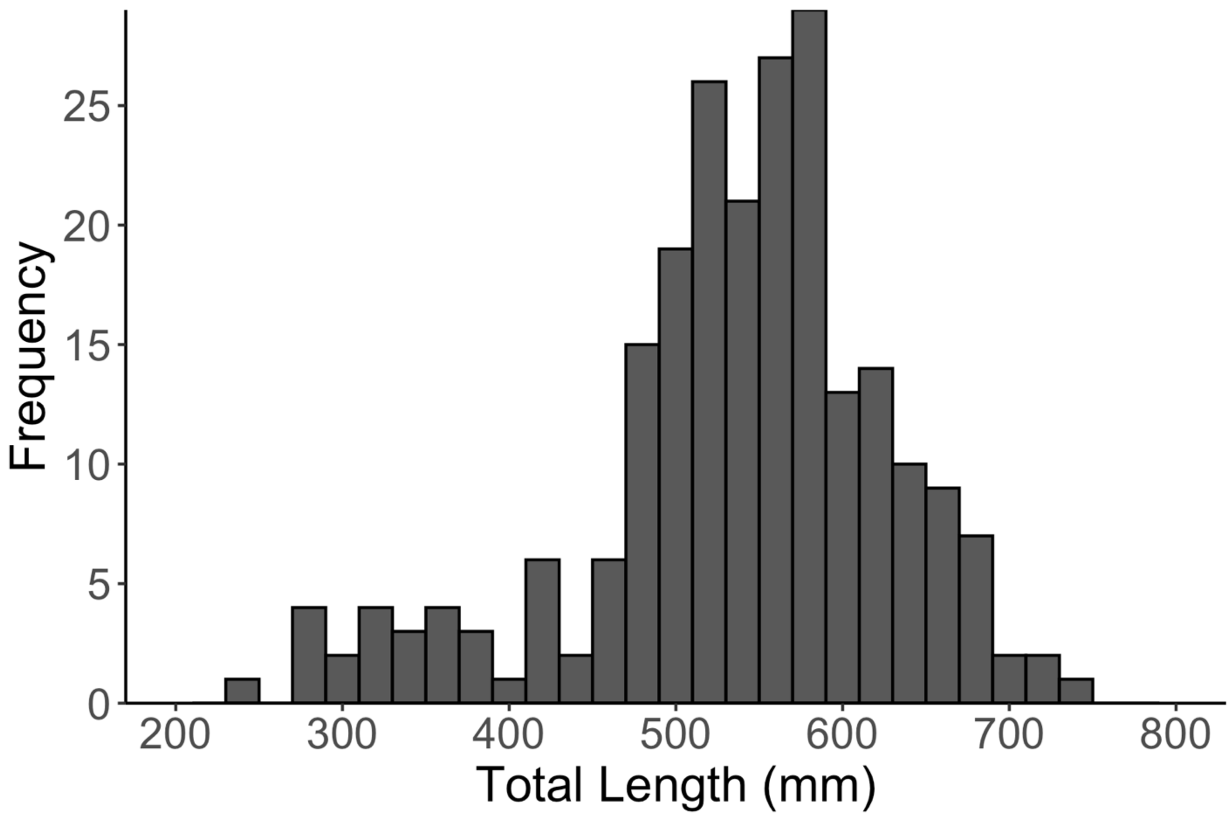


Figure 18. Length (mm) frequency histogram of Blue Sucker sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=231) in 2021-2022.

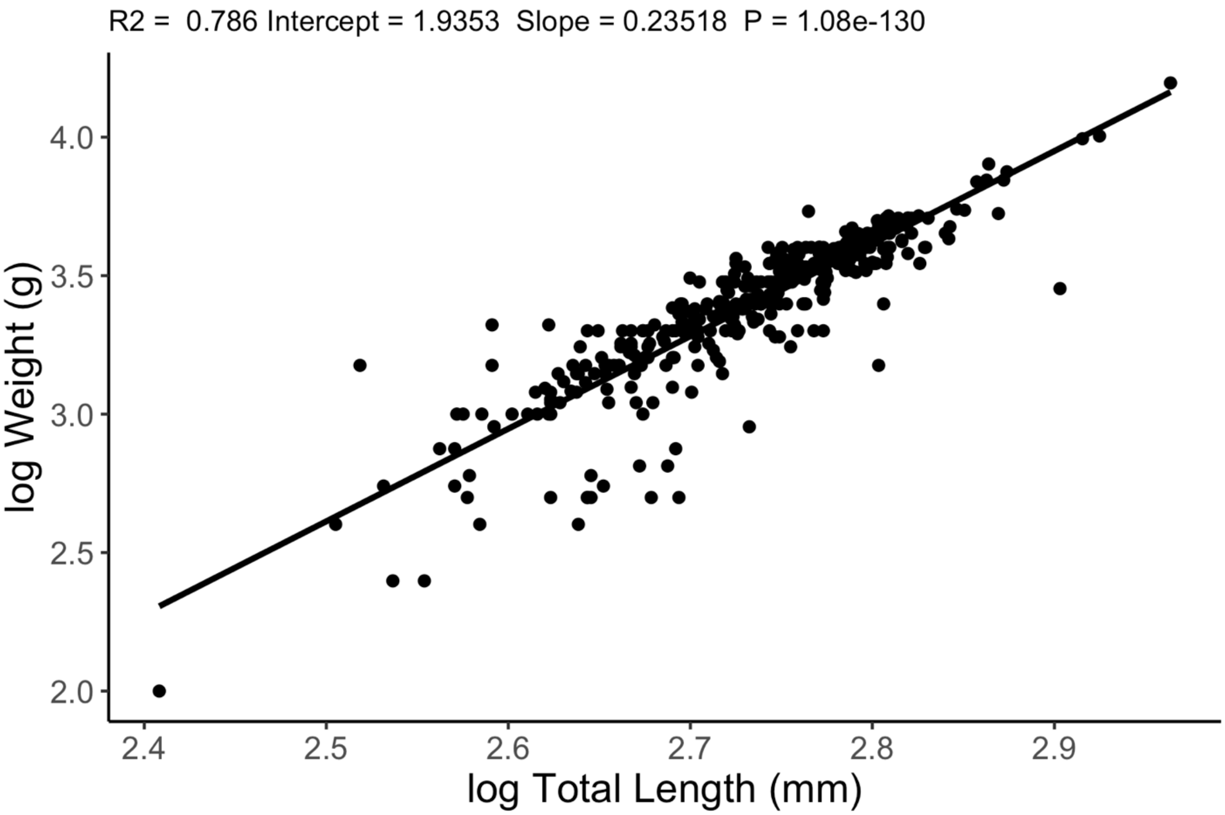


Figure 19. Relationship between the Log_{10} length (mm) and Log_{10} weight (g) for Smallmouth Buffalo sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=377) in 2021-2022.

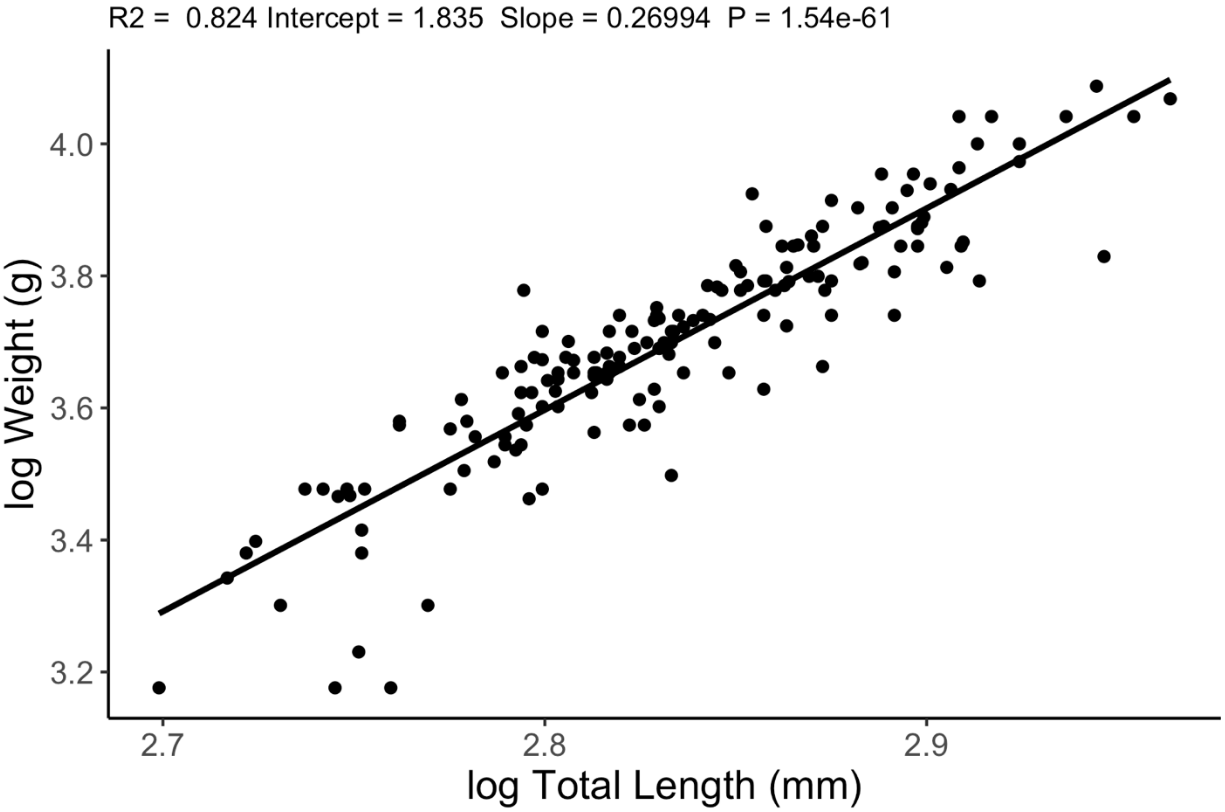


Figure 20. Relationship between the Log_{10} length (mm) and Log_{10} weight (g) for Black Buffalo sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=160) in 2021-2022.

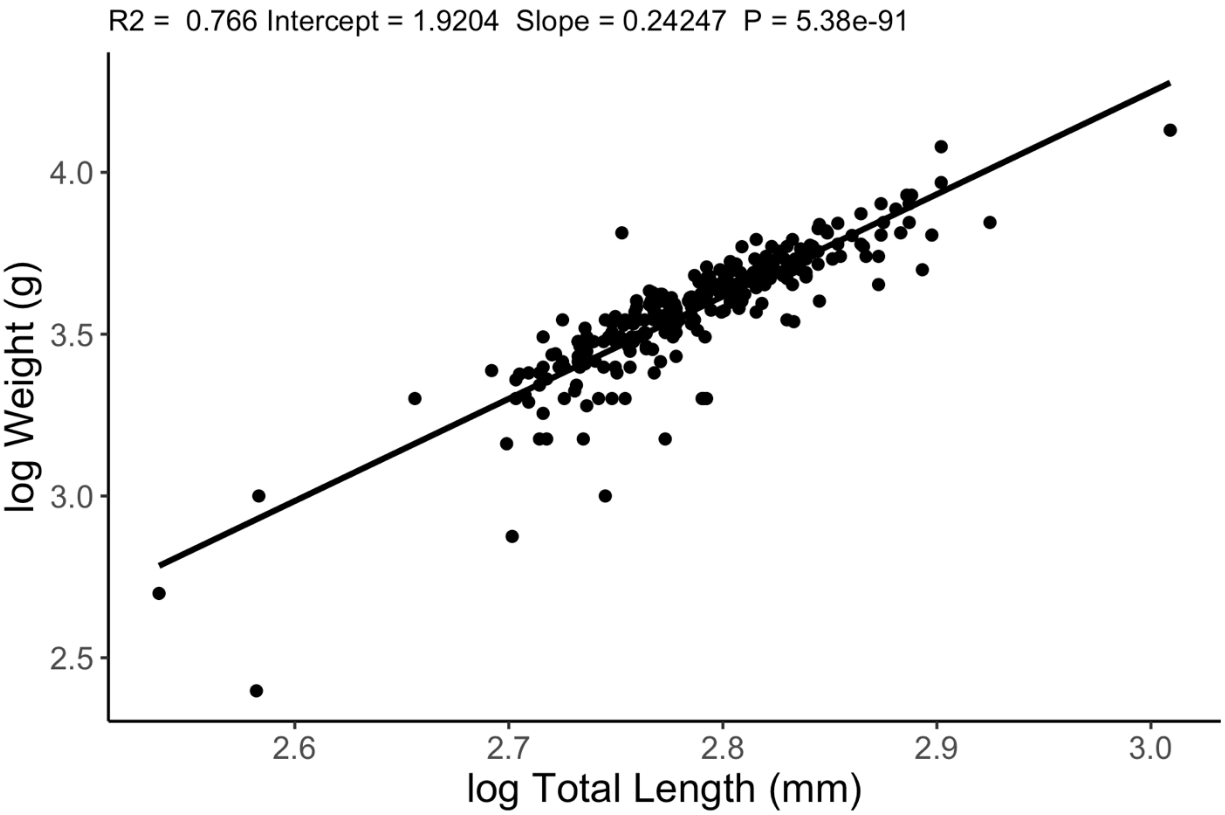


Figure 21. Relationship between the Log_{10} length (mm) and Log_{10} weight (g) for Bigmouth Buffalo sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=284) in 2021-2022.

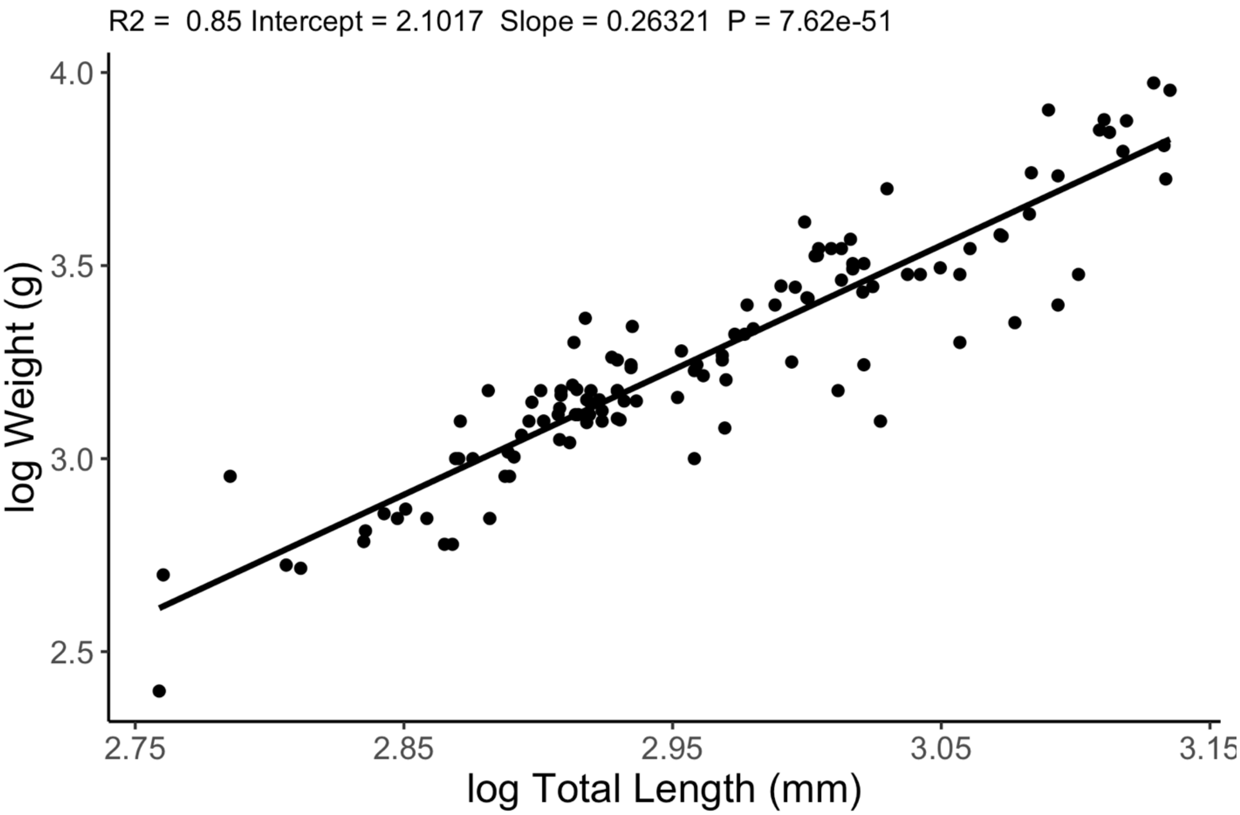


Figure 22. Relationship between the Log_{10} length (mm) and Log_{10} weight (g) for Longnose Gar sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=123) in 2021-2022.

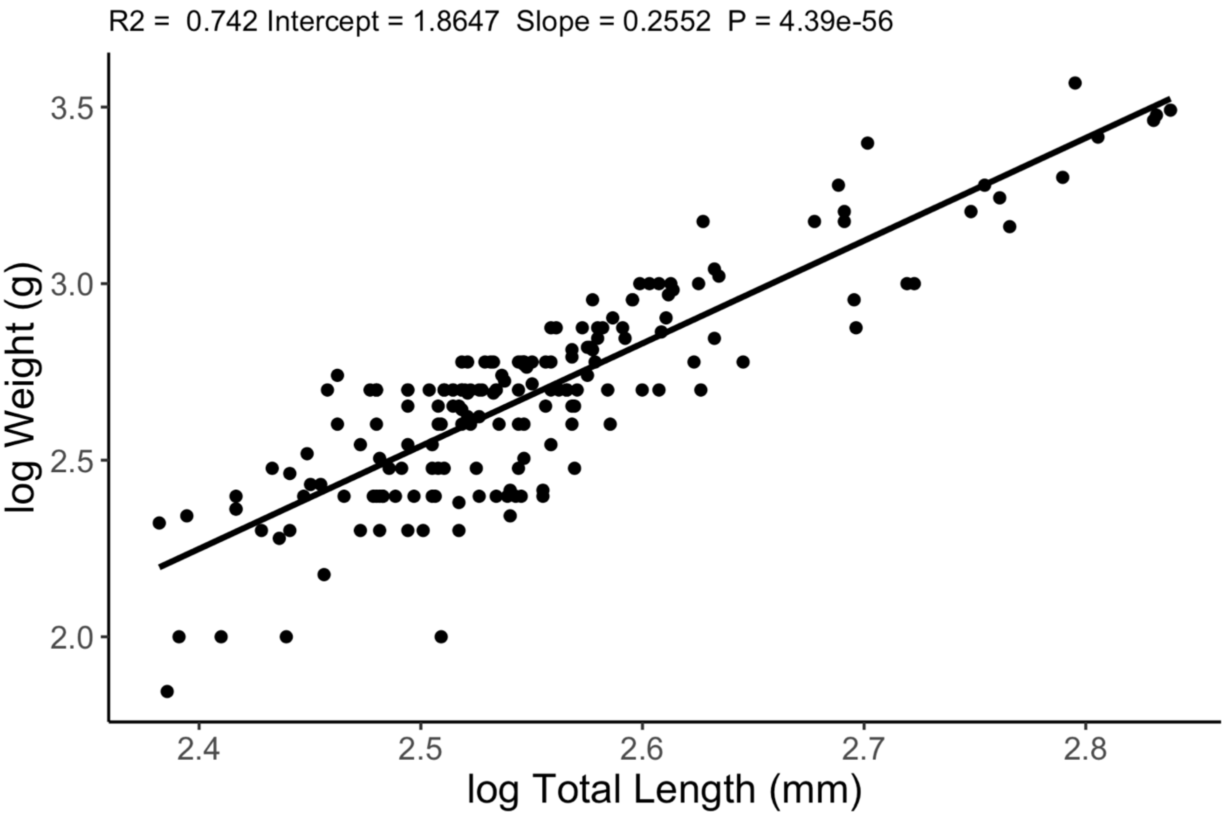


Figure 23. Relationship between the Log_{10} length (mm) and Log_{10} weight (g) for River Carpsucker sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=191) in 2021-2022.

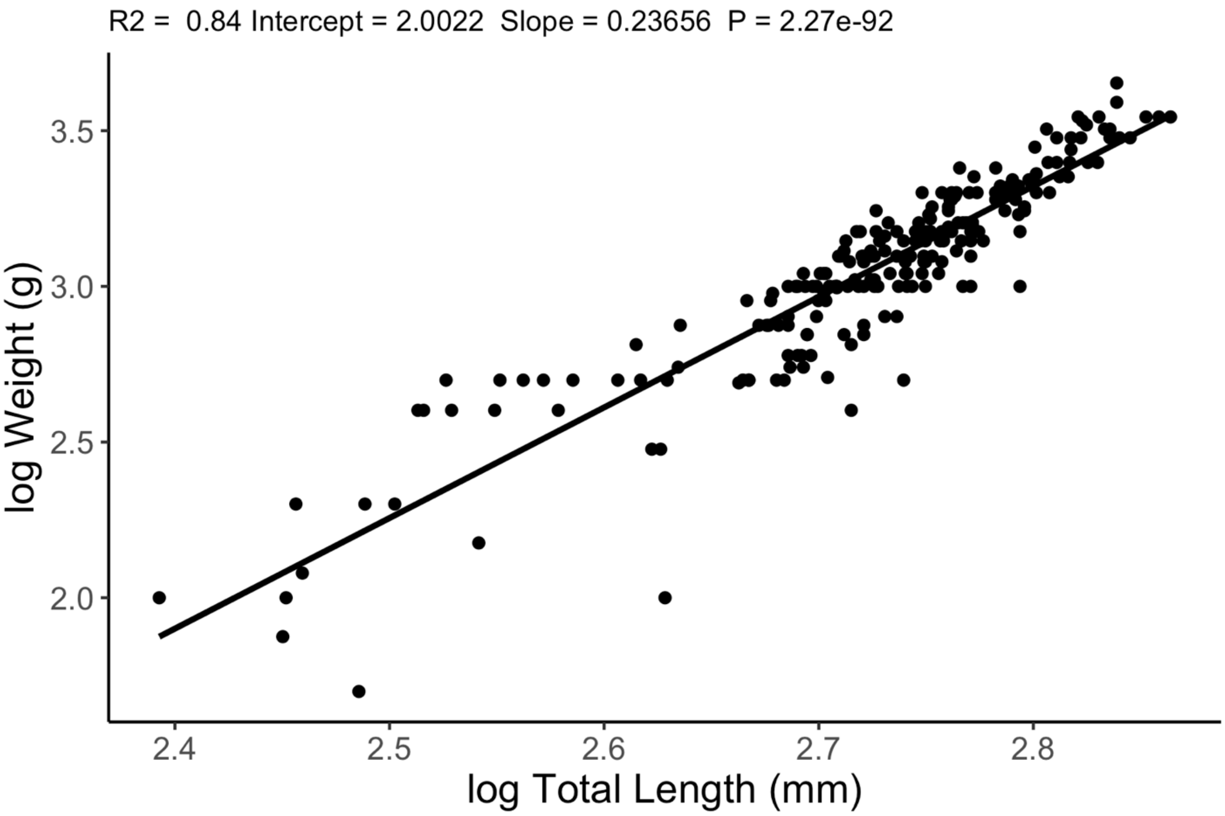


Figure 24. Relationship between the Log_{10} length (mm) and Log_{10} weight (g) for Blue Sucker sampled from the Red River basin in Arkansas using gillnets, hoop nets, and electrofishing (n=229) in 2021-2022.

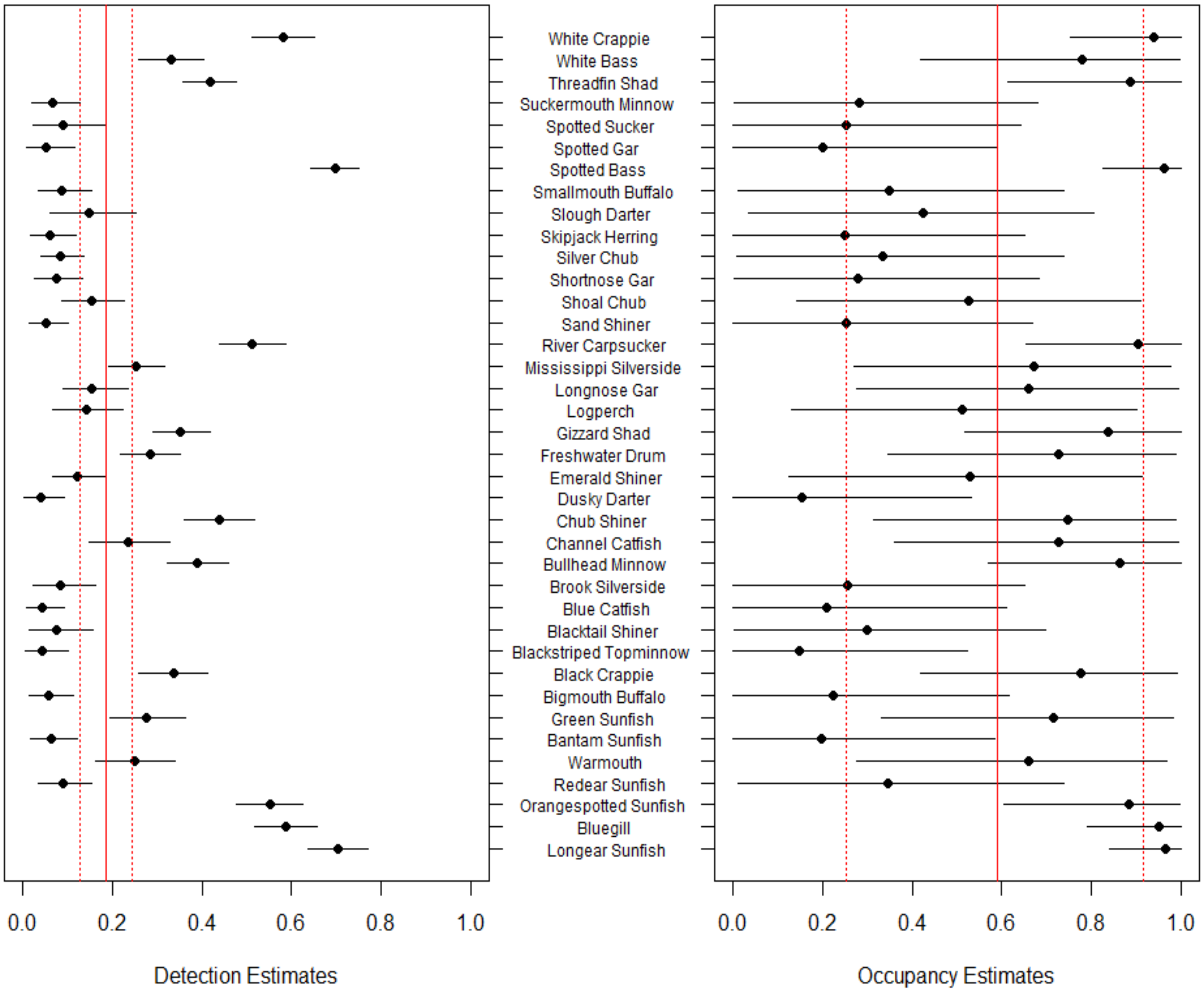


Figure 25. Juvenile native species detection and occupancy estimates from the final occupancy model for the Red River basin. The black points represent the median (most likely) values from the posterior distribution for each species. The black bars represent the 90% credible intervals for those species. The solid red line shows the group mean (all species) for both the detection and occupancy estimates and the dotted red lines show the 90% credible intervals for those estimates.

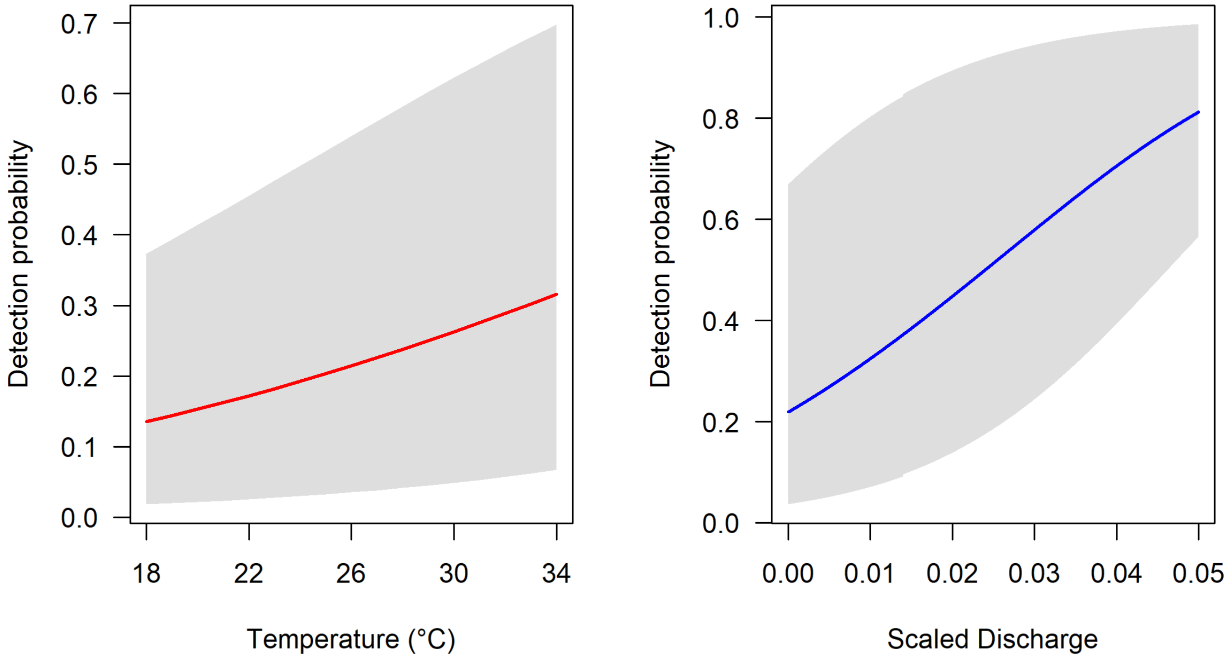
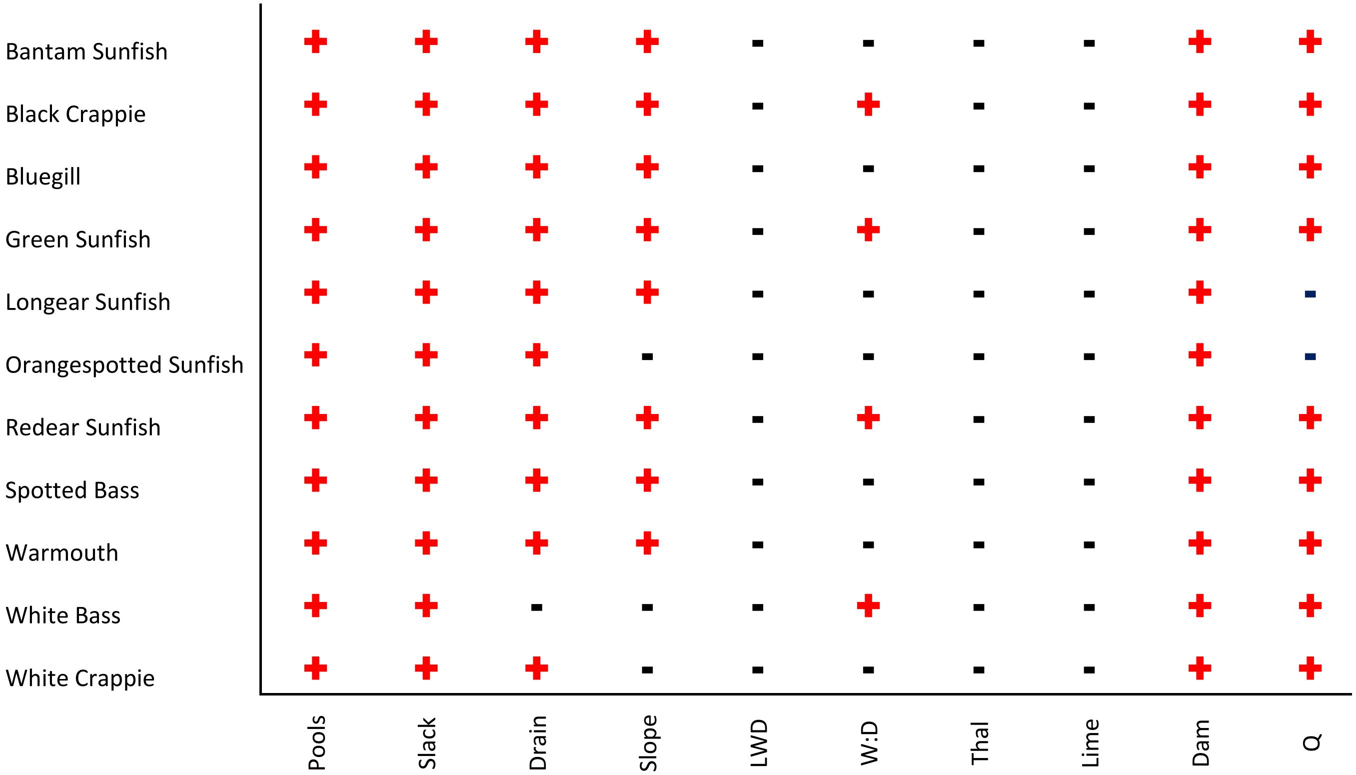


Figure 26. Relationships between water temperature, scaled discharge and the probability of detecting all fish species within the assemblage in the Red River basin in 2021-2022. The shaded gray areas represent the 90% credible intervals, and the solid line indicates the mode. The mode was estimated with all other model covariates held at mean values.



	Pools	Slack	Drain	Slope	LWD	W:D	Thal	Lime	Dam	Q
Bantam Sunfish	+	+	+	+	-	-	-	-	+	+
Black Crappie	+	+	+	+	-	+	-	-	+	+
Bluegill	+	+	+	+	-	-	-	-	+	+
Green Sunfish	+	+	+	+	-	+	-	-	+	+
Longear Sunfish	+	+	+	+	-	-	-	-	+	-
Orangespotted Sunfish	+	+	+	-	-	-	-	-	+	-
Redear Sunfish	+	+	+	+	-	+	-	-	+	+
Spotted Bass	+	+	+	+	-	-	-	-	+	+
Warmouth	+	+	+	+	-	-	-	-	+	+
White Bass	+	+	-	-	-	+	-	-	+	+
White Crappie	+	+	+	-	-	-	-	-	+	+

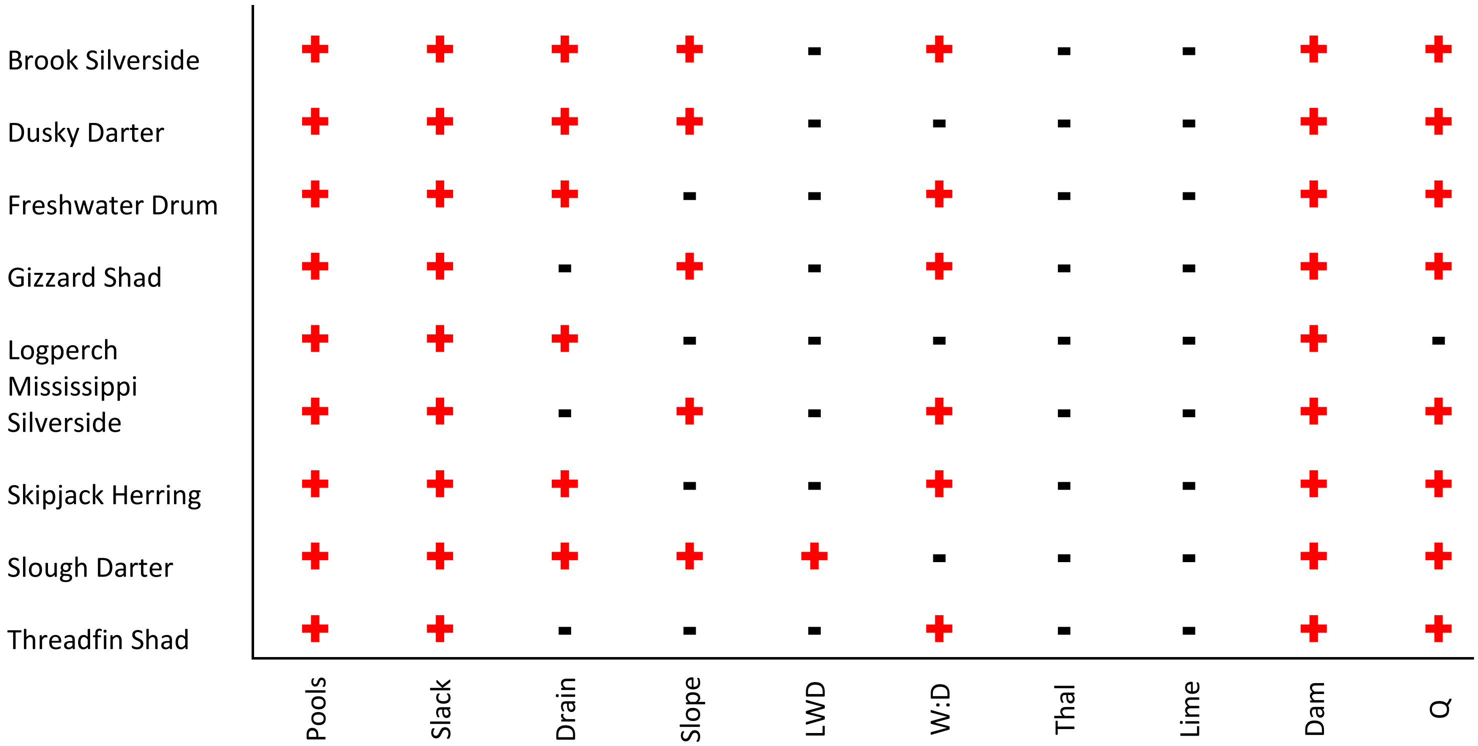
Figure 27. Occupancy relationships of Centrarchidae and Moronidae species in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is the presence of slackwater, Drain is the drainage area where low drainage area is the reference, LWD is large woody debris, W:D is width-to-depth ratio, Thal is average thalweg depth, Lime is percentage of limestone, Dam is the distance from nearest upstream dam, and Q is the median discharge value.

	Pools	Slack	Drain	Slope	LWD	W:D	Thal	Lime	Dam	Q
Blackstripe Topminnow	+	+	+	-	-	+	-	-	+	+
Blacktail Shiner	+	+	+	+	-	-	-	-	+	+
Bullhead Minnow	+	+	+	+	-	+	-	-	+	+
Chub Shiner	+	+	-	-	-	+	-	-	+	+
Emerald Shiner	+	+	+	-	-	-	-	-	+	+
Sand Shiner	+	+	+	+	-	+	-	-	+	+
Shoal Chub	+	+	+	-	-	+	-	-	+	+
Silver Chub	+	+	+	-	-	+	-	-	+	-
Suckermouth Minnow	+	+	+	+	-	-	-	-	+	-

Figure 28. Occupancy relationships of Cyprinidae species in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is the presence of slackwater, Drain is the drainage area, LWD is large woody debris, W:D is width-to-depth ratio, Thal is average thalweg depth, Lime is percentage of limestone, Dam is the distance from nearest upstream dam, and Q is the median discharge value.

	Pools	Slack	Drain	Slope	LWD	W:D	Thal	Lime	Dam	Q
Bigmouth Buffalo	+	+	+	+	-	+	-	-	+	+
Blue Catfish	+	+	+	-	-	+	-	-	+	+
Channel Catfish	+	+	+	+	+	+	-	-	+	+
Longnose Gar	+	+	+	-	+	-	-	-	+	+
River Carpsucker	+	+	+	-	-	+	-	-	+	+
Shortnose Gar	+	+	+	+	-	+	-	-	+	+
Smallmouth Buffalo	+	+	+	-	-	+	-	-	+	+
Spotted Gar	+	+	+	+	-	-	-	-	+	+
Spotted Sucker	+	+	+	-	-	+	-	-	+	+

Figure 29. Occupancy relationships of common large river fish families Catostomidae, Ictaluridae, and Lepisosteidae species in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is the presence of slackwater, Drain is the drainage area, LWD is large woody debris, W:D is width-to-depth ratio, Thal is average thalweg depth, Lime is percentage of limestone, Dam is the distance from nearest upstream dam, and Q is the median discharge value.



	Pools	Slack	Drain	Slope	LWD	W:D	Thal	Lime	Dam	Q
Brook Silverside	+	+	+	+	-	+	-	-	+	+
Dusky Darter	+	+	+	+	-	-	-	-	+	+
Freshwater Drum	+	+	+	-	-	+	-	-	+	+
Gizzard Shad	+	+	-	+	-	+	-	-	+	+
Logperch	+	+	+	-	-	-	-	-	+	-
Mississippi Silverside	+	+	-	+	-	+	-	-	+	+
Skipjack Herring	+	+	+	-	-	+	-	-	+	+
Slough Darter	+	+	+	+	+	-	-	-	+	+
Threadfin Shad	+	+	-	-	-	+	-	-	+	+

Figure 30. Occupancy relationships of remaining fish families Atherinidae, Clupidae, Percidae, and Sciaenidae in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is the presence of slackwater, Drain is the drainage area, LWD is large woody debris, W:D is width-to-depth ratio, Thal is average thalweg depth, Lime is percentage of limestone, Dam is the distance from nearest upstream dam, and Q is the median discharge value.

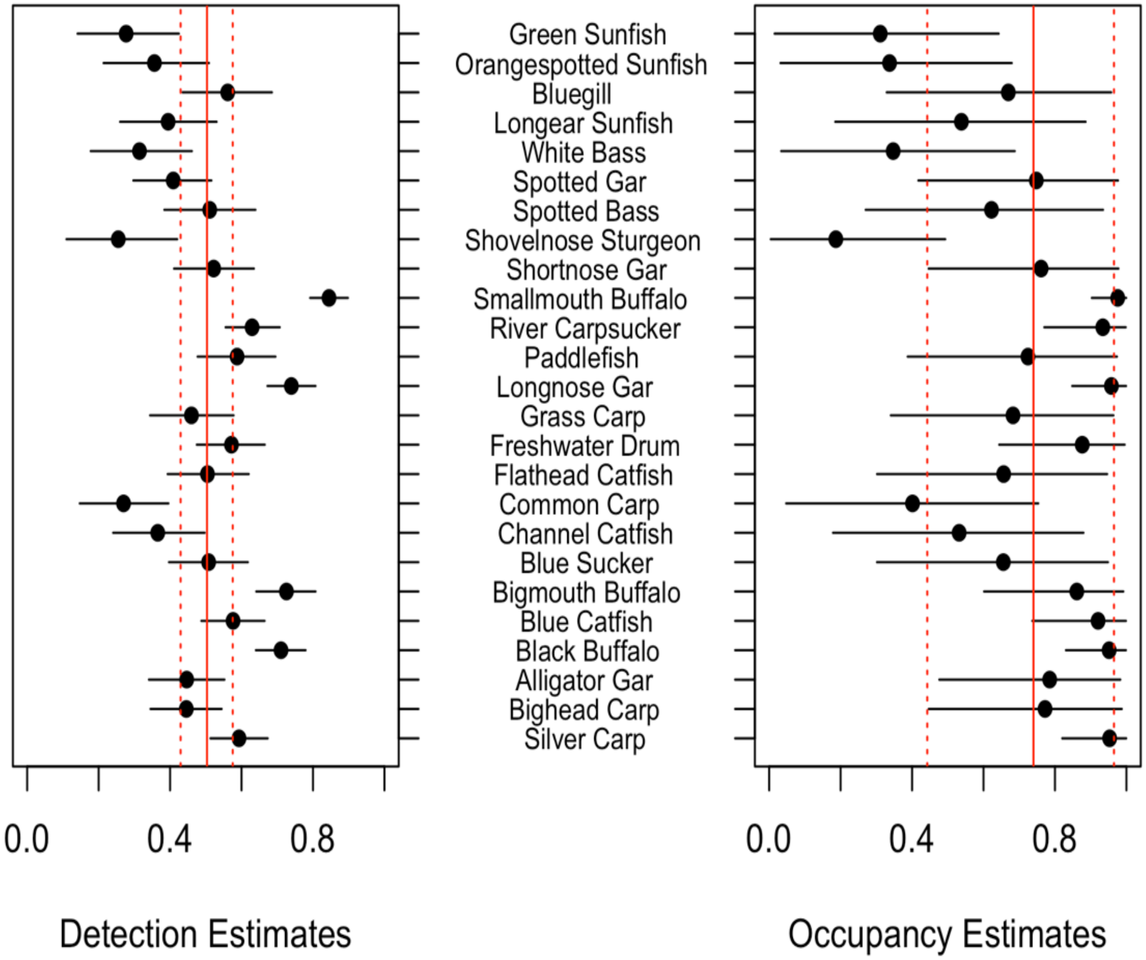
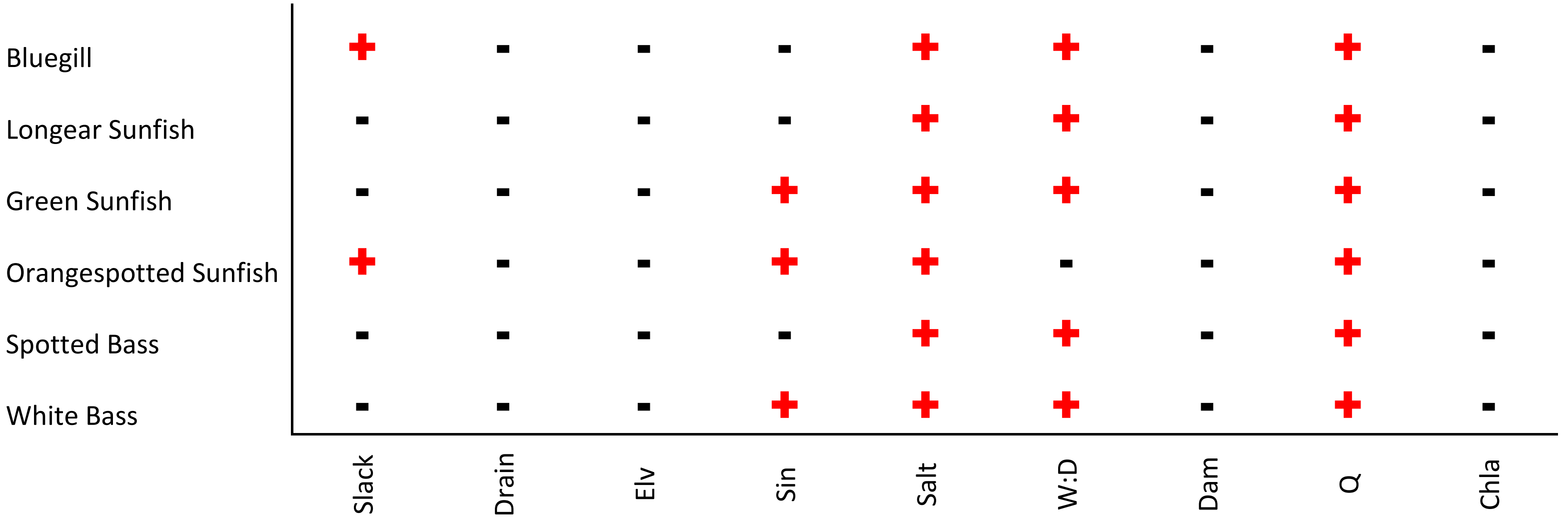
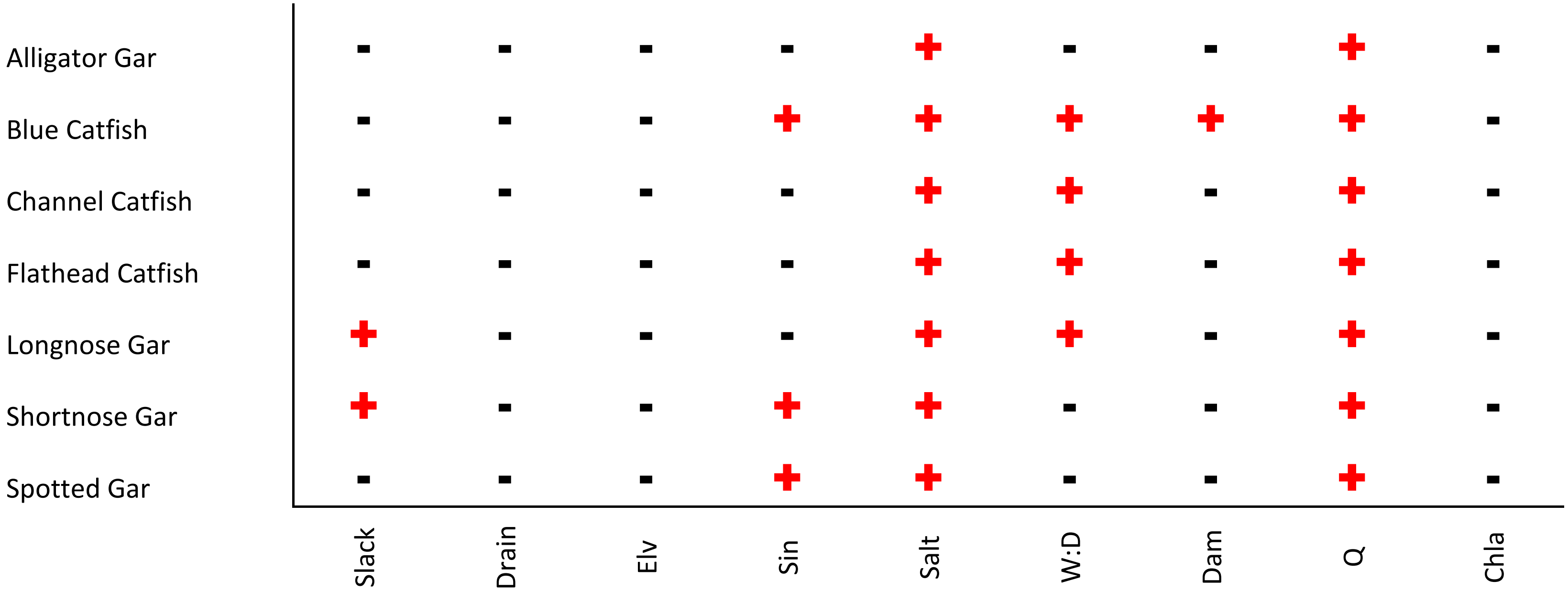


Figure 31. Adult large-bodied fish species detection and occupancy estimates from the final occupancy model for the Red River basin in 2021-2022. The black points represent the median (most likely) values from the posterior distribution for each species. The black bars represent the 90% credible intervals for those species. The solid red line shows the group mean (all species) for both the detection and occupancy estimates and the dotted red lines show the 90% credible intervals for those estimates.



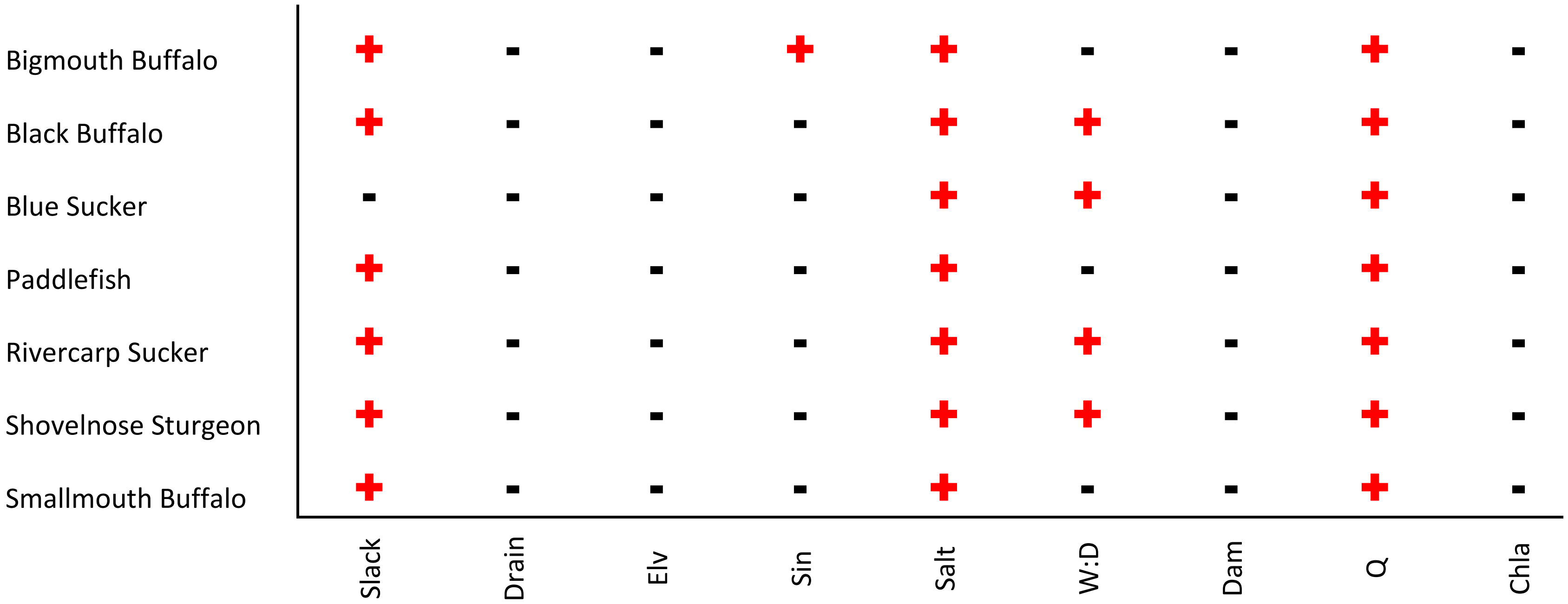
	Slack	Drain	Elv	Sin	Salt	W:D	Dam	Q	Chla
Bluegill	+	-	-	-	+	+	-	+	-
Longear Sunfish	-	-	-	-	+	+	-	+	-
Green Sunfish	-	-	-	+	+	+	-	+	-
Orangespotted Sunfish	+	-	-	+	+	-	-	+	-
Spotted Bass	-	-	-	-	+	+	-	+	-
White Bass	-	-	-	+	+	+	-	+	-

Figure 32. Occupancy relationships of Centrarchidae and Moronidae in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is greater than 1% of slackwater, Drain is the drainage area, Elv is elevation, Sin is the segment sinuosity, Salt is the salinity, W:D is width-to-depth ratio, Dam is the distance from nearest upstream dam, Q is the median discharge value, and Chla is the chlorophyll-a concentration.



	Slack	Drain	Elv	Sin	Salt	W:D	Dam	Q	Chla
Alligator Gar	-	-	-	-	+	-	-	+	-
Blue Catfish	-	-	-	+	+	+	+	+	-
Channel Catfish	-	-	-	-	+	+	-	+	-
Flathead Catfish	-	-	-	-	+	+	-	+	-
Longnose Gar	+	-	-	-	+	+	-	+	-
Shortnose Gar	+	-	-	+	+	-	-	+	-
Spotted Gar	-	-	-	+	+	-	-	+	-

Figure 33. Occupancy relationships of Lepisteidae and Ictaluridae species in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is greater than 1% of slackwater, Drain is the drainage area, Elv is elevation, Sin is the segment sinuosity, Salt is the salinity, W:D is width-to-depth ratio, Dam is the distance from nearest upstream dam, Q is the median discharge value, and Chla is the chlorophyll-a concentration.



	Slack	Drain	Elv	Sin	Salt	W:D	Dam	Q	Chla
Bigmouth Buffalo	+	-	-	+	+	-	-	+	-
Black Buffalo	+	-	-	-	+	+	-	+	-
Blue Sucker	-	-	-	-	+	+	-	+	-
Paddlefish	+	-	-	-	+	-	-	+	-
Rivercarp Sucker	+	-	-	-	+	+	-	+	-
Shovelnose Sturgeon	+	-	-	-	+	+	-	+	-
Smallmouth Buffalo	+	-	-	-	+	-	-	+	-

Figure 34. Occupancy relationships of Catostomidae species, Paddlefish, and Shovelnose Sturgeon in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is greater than 1% of slackwater, Drain is the drainage area, Elv is elevation, Sin is the segment sinuosity, Salt is the salinity, W:D is width-to-depth ratio, Dam is the distance from nearest upstream dam, Q is the median discharge value, and Chla is the chlorophyll-a concentration.

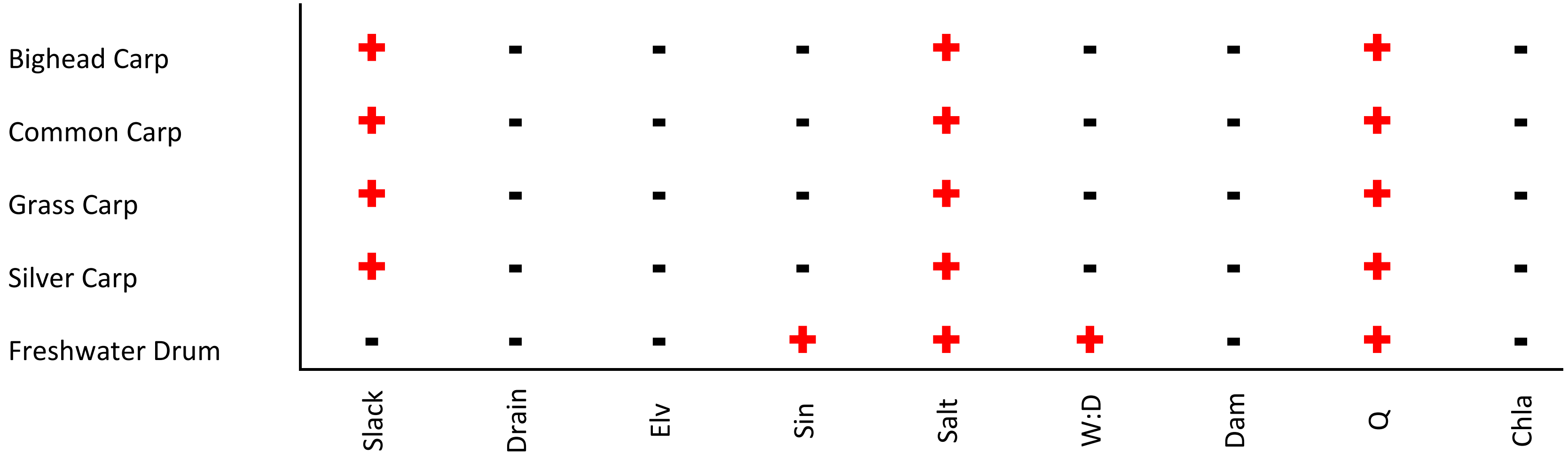


Figure 35. Occupancy relationships of Sciaenidae (native) and invasive species in the Red River basin in 2021-2022. Positive relationships are indicated with a red plus sign (+). Negative relationships are indicated with a black negative sign (-). Slack is greater than 1% of slackwater, Drain is the drainage area, Elv is elevation, Sin is the segment sinuosity, Salt is the salinity, W:D is width-to-depth ratio, Dam is the distance from nearest upstream dam, Q is the median discharge value, and Chla is the chlorophyll-a concentration.

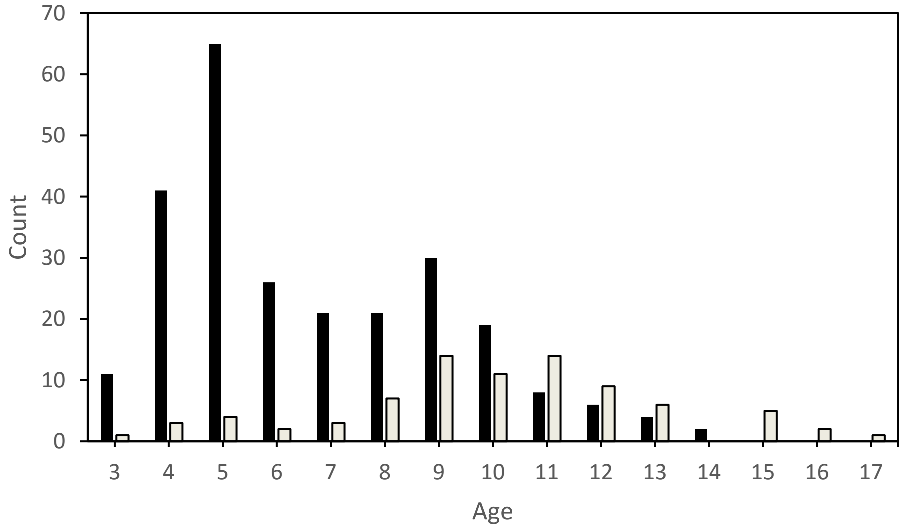


Figure 36. Age frequency histogram for Silver Carp (black bars) and Bighead Carp (gray bars) sampled from the lower Red River catchment from 2021 and 2022.

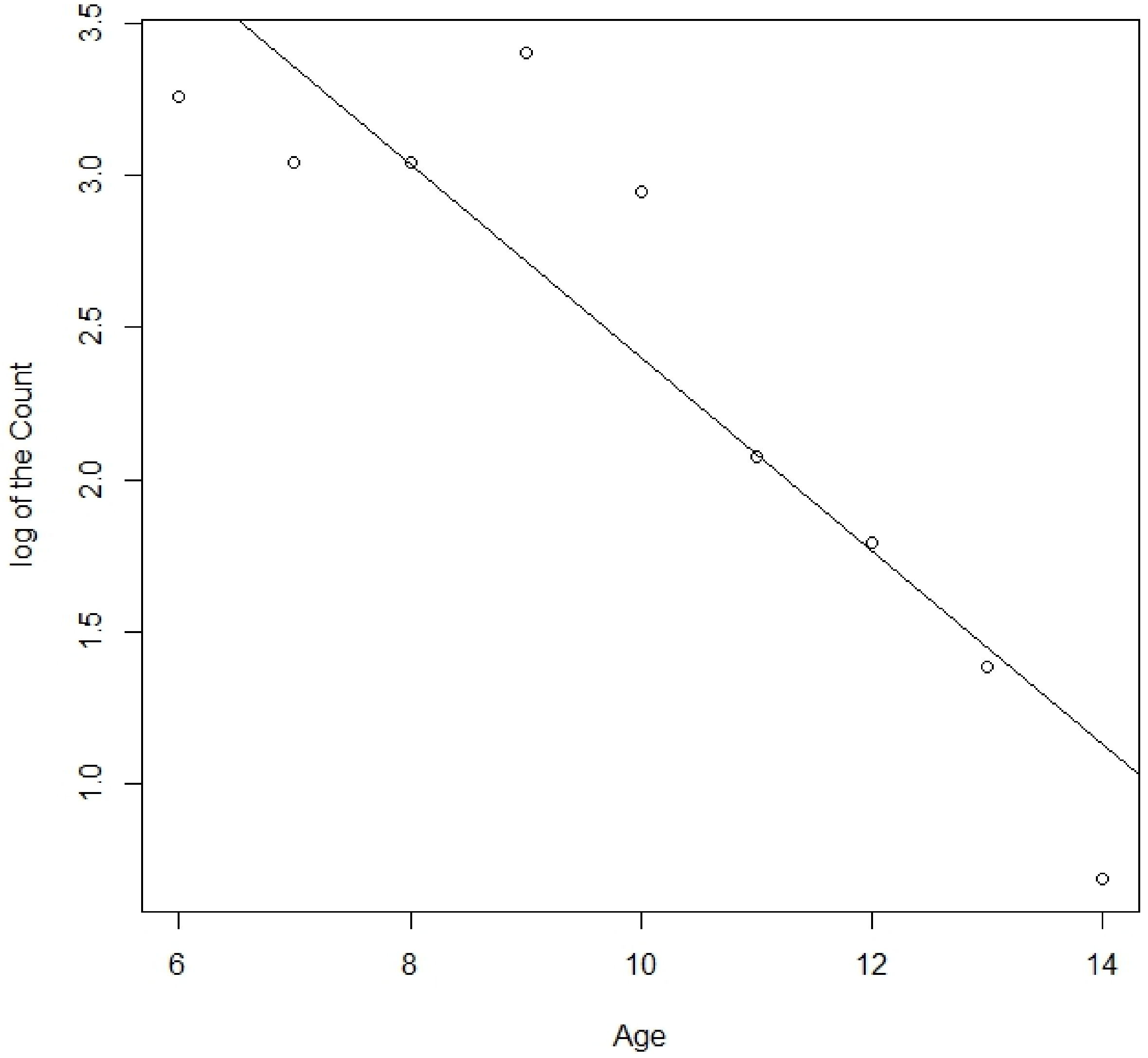


Figure 37. A catch-curve assessing mortality and recruitment variability of Silver Carp in the lower Red River catchment in 2021-2022.

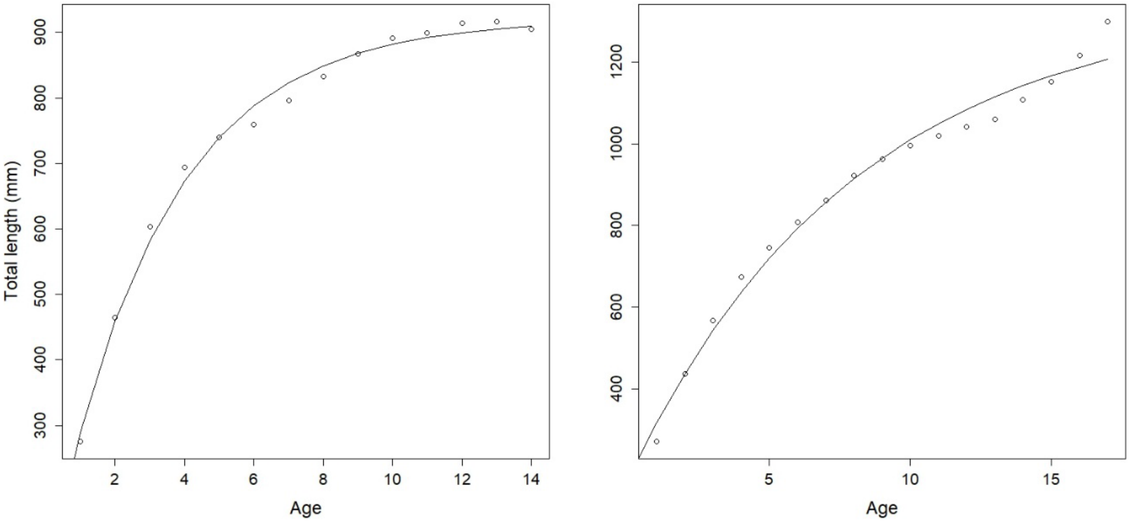


Figure 38. A von Bertalanffy growth curve fit to the mean back-calculated length-at-age for Silver Carp (left) and Bighead Carp (right) in the lower Red River catchment in 2021-2022.

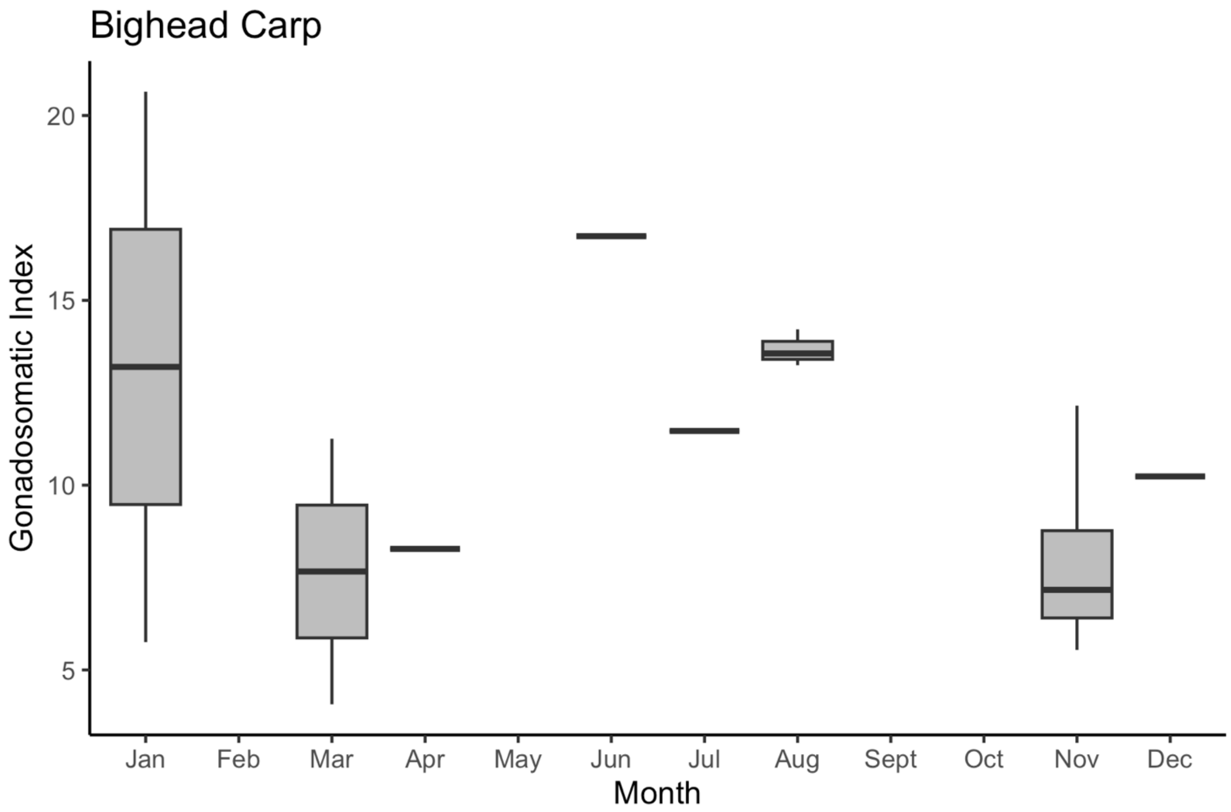


Figure 39. Bighead Carp gonadosomatic index by month captured from the lower Red River catchment from June 2021 through December 2022. Box plots depict the minimum, first quartile, median, third quartile, and maximum.

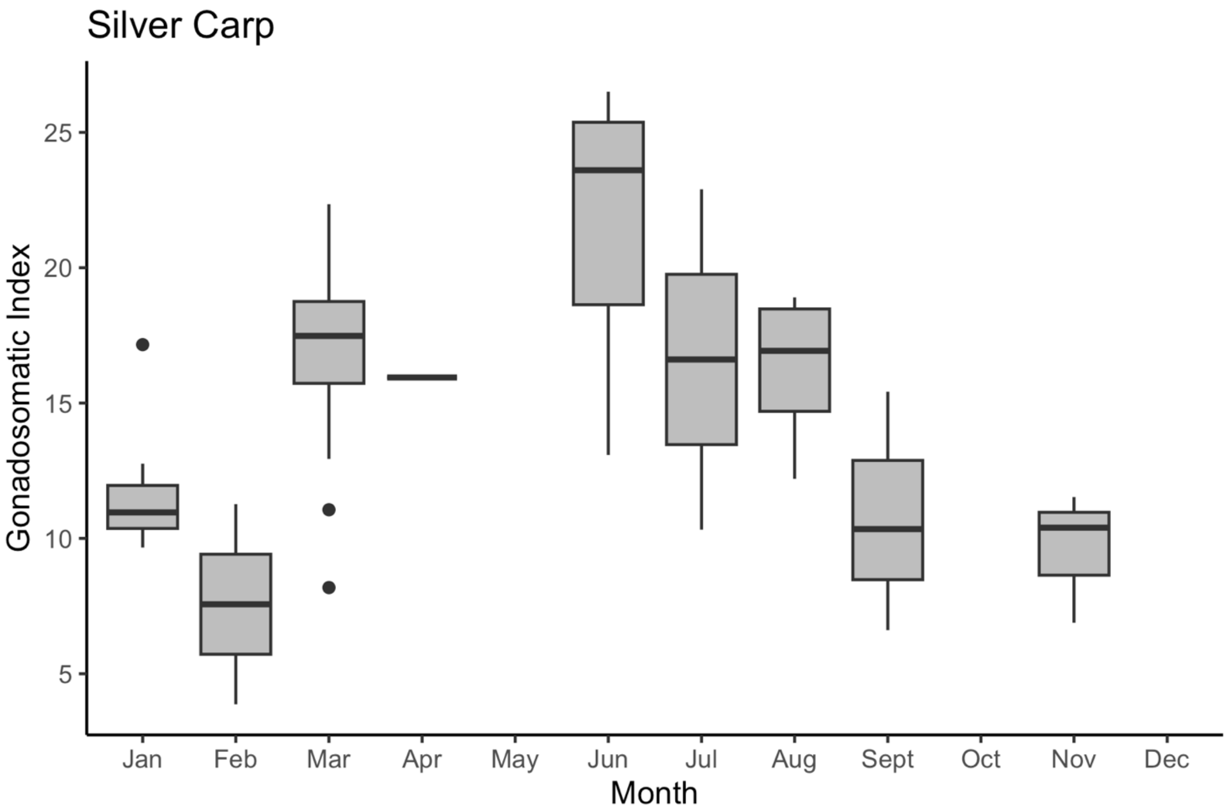


Figure 40. Silver Carp gonadosomatic index by month captured from the lower Red River catchment from June 2021 through December 2022. Box plots depict the minimum, first quartile, median, third quartile, and maximum with outliers depicted as single points.

Appendix A.

Table 1. Catch-per-unit-effort data for Bighead Carp (BHC) and Silver Carp (SVC) sampled in the Red River in Arkansas from June 2021 through December 2022. Latitude (Lat.) and Longitude (Long.) represent the coordinates from the most upstream end of the sample site. Gillnet effort is the number of fish collected per hour set of our gillnet complex (three, 180ft long gillnets). Electrofishing effort is the number of fish collected per hour of button time. Season reflects our warm sampling season (April through September) and our cold sampling season (October through March). Although we are providing these data, we did not meet the assumptions associated with catch-per-unit effort data (e.g., equal detection, see detection probability sections within the report; detection varies with the environment); thus, these data should not be used as a comparison to future sampling efforts (i.e., should not be used to reflect trends in fish abundance). However, these data may provide insight to locations where it is simply easier to catch fish under the sampling conditions at that time (e.g., a low flow period during the cold season).

	Lat.	Long.	Season	BHC Gillnet (fish/hr)	BHC- E-fishing (fish/hr)	SVC- Gillnet (fish/hr)	SVC-E-fishing (fish/hr)
ARR04	33.55708	-94.04868	Warm	0.00	0.00	0.04	0.00
ARR08	33.60915	-93.8242	Warm	0.00	0.00	0.00	0.63
ARR10	33.56842	-94.38122	Warm	0.16	0.00	0.16	4.90
ARR11	33.58881	-94.37804	Warm	0.03	0.98	0.28	4.56
ARR12	33.43524	-93.73965	Warm	0.00	NA	0.00	NA
ARR13	33.09082	-93.85964	Warm	0.00	0.00	0.00	0.00
ARR15	33.5515	-94.39453	Warm	0.00	0.00	0.00	0.00
ARR22	33.60932	-93.85986	Warm	0.00	0.00	0.00	0.00

ARR25	33.39703	-93.71171	Warm	0.00	0.00	0.00	0.00
ARR26	33.06602	-93.83293	Warm	0.00	0.00	0.00	0.00
ARR27	33.1568	-93.81832	Warm	0.00	0.00	0.00	0.00
ARR30	33.57537	-94.08128	Warm	0.00	0.00	0.00	0.00
ARR31	33.5998	-94.44686	Warm	0.00	0.00	0.00	0.00
ARR37	33.55718	-94.0195	Warm	0.00	0.00	0.00	1.13
ARR38	33.34793	-93.71021	Warm	0.00	0.00	0.00	0.00
ARR41	33.14741	-93.83134	Warm	0.00	0.00	0.00	0.00
ARR42	33.13784	-93.82909	Warm	0.00	0.00	0.00	0.00
ARR44	33.59898	-93.81232	Warm	0.00	0.00	0.00	0.00
ARR04	33.55708	-94.04868	Cold	0.00	0.00	0.06	0.78
ARR08	33.60915	-93.8242	Cold	0.00	0.00	0.00	0.00
ARR10	33.56842	-94.38122	Cold	0.22	0.00	0.99	23.21
ARR11	33.58881	-94.37804	Cold	0.09	0.00	1.21	10.47
ARR12	33.43524	-93.73965	Cold	0.00	NA	0.00	NA
ARR13	33.09082	-93.85964	Cold	0.00	0.00	0.00	0.00
ARR15	33.5515	-94.39453	Cold	0.07	0.00	0.07	1.51
ARR22	33.60932	-93.85986	Cold	0.00	NA	0.00	NA

ARR25	33.39703	-93.71171	Cold	0.00	0.00	0.00	0.00
ARR30	33.57537	-94.08128	Cold	0.00	NA	0.00	NA
ARR31	33.5998	-94.44686	Cold	0.00	NA	0.00	NA
ARR32	33.07597	-93.8387	Cold	0.00	0.00	0.11	0.00
ARR34	33.59526	-94.42342	Cold	0.00	0.00	0.00	0.00
ARR36	33.55226	-94.04026	Cold	0.00	0.00	0.00	0.00
ARR37	33.55718	-94.0195	Cold	0.00	0.00	0.06	0.00
ARR38	33.34793	-93.71021	Cold	0.00	0.00	0.00	0.54

Appendix B. The common name with the corresponding scientific name for fish species sampled in the lower Red River catchment of Arkansas, Oklahoma, and Texas.

Common Name	Scientific Name
Alligator Gar	*Atractosteus spatula*
American Eel	*Anguilla rostrata*
American Paddlefish	*Polyodon spathula*
Bantam Sunfish	*Lepomis symmetricus*
Bigeye Shiner	*Notropis boops*
Bighead Carp	*Hypophthalmichthys nobilis*
Bigmouth Buffalo	*Ictiobus cyprinellus*
Black Buffalo	*Ictiobus niger*
Black Crappie	*Pomoxis nigromaculatus*
Blackstripe Topminnow	*Fundulus notatus*
Blacktail Shiner	*Cyprinella venusta*
Blue Catfish	*Ictalurus furcatus*
Blue Sucker	*Cycleptus elongatus*
Bluegill	*Lepomis macrochirus*
Bluntnose Darter	*Etheostoma chlorosomum*
Bluntnose Minnow	*Pimephales notatus*
Brook Silverside	*Labidesthes sicculus*
Bullhead Minnow	*Pimephales vigilax*
Channel Catfish	*Ictalurus punctatus*
Chestnut Lamprey	*Ichthyomyzon castaneus*
Chub Shiner	*Notropis potteri*
Common Carp	*Cyprinus carpio*
Dusky Darter	*Percina sciera*
Emerald Shiner	*Notropis atherinoides*
Flathead Catfish	*Pylodictis olivaris*
Flier	*Centrarchus macropterus*
Freshwater Drum	*Aplodinotus grunniens*
Ghost Shiner	*Notropis buchanani*
Gizzard Shad	*Dorosoma cepedianum*
Golden Shiner	*Notemigonus crysoleucas*
Golden Topminnow	*Fundulus chrysotus*
Goldeye	*Hiodon alosoides*
Grass Carp	*Ctenopharyngodon idella*
Green Sunfish	*Lepomis cyanellus*
Highland Stoneroller	*Campostoma spadiceum*
Hybrid Sunfish	*Lepomis spp.*
Largemouth Bass	*Micropterus salmoides*
Logperch	*Percina caprodes*
Longear Sunfish	*Lepomis megalotis*

Longnose Gar	*Lepisosteus osseus*
Mississippi Silverside	*Menidia audens*
Mississippi Silvery Minnow	*Hybognathus nuchalis*
Mooneye	*Hiodon tergisus*
Mosquitofish	*Gambusia affinis*
Orangespotted Sunfish	*Lepomis humilis*
Pallid Shiner	*Hybopsis amnis*
Pirate Perch	*Aphredoderus sayanus*
Plains Killifish	*Fundulus zebrinus*
Pugnose Minnow	*Opsopoeodus emiliae*
Quillback	*Carpiodes cyprinus*
Red Shiner	*Cyprinella lutrensis*
Redear Sunfish	*Lepomis microlophus*
Redspot Darter	*Etheostoma artesiae*
Ribbon Shiner	*Lythrurus fumeus*
River Carpsucker	*Carpiodes carpio*
River Darter	*Percina shumardi*
Sand Shiner	*Notropis stramineus*
Scaly Sand Darter	*Ammocrypta vivax*
Shoal Chub	*Macrhybopsis hyostoma*
Shortnose Gar	*Lepisosteus platostomus*
Shovelnose Sturgeon	*Scaphirhynchus platorynchus*
Silver Carp	*Hypophthalmichthys molitrix*
Silver Chub	*Macrhybopsis storeriana*
Silverband Shiner	*Notropis shumardi*
Skipjack Herring	*Alosa chrysochloris*
Slenderhead Darter	*Percina phoxocephala*
Slough Darter	*Etheostoma gracile*
Smallmouth Buffalo	*Ictiobus Bubalus*
Spotted Bass	*Micropterus punctulatus*
Spotted Gar	*Lepisosteus oculatus*
Spotted Sucker	*Minytrema melanops*
Striped Bass	*Morone saxatilis*
Suckermouth Minnow	*Phenacobius mirabilis*
Tadpole Madtom	*Noturus gyrinus*
Threadfin Shad	*Dorosoma petenense*
Warmouth	*Lepomis gulosus*
Western Sand Darter	*Ammocrypta clara*
Western Starhead Topminnow	*Fundulus blairae*
White Bass	*Morone chrysops*
White Crappie	*Pomoxis annularis*
Weed Shiner	*Notropis Texanus*
Yellow Bullhead	*Ameiurus natalis*