Using distribution and movement of invasive channel catfish *Ictalurus punctatus* in the San Juan River to inform removal efforts

by

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Abstract

The invasion of nonnative fishes has homogenized regionally endemic communities with species in the American West being disproportional impacted. In the San Juan River, New Mexico, Colorado, and Utah, invasive channel catfish *Ictalurus punctatus* may harm the native fish community through predation and competition. Because of this perceived threat, a removal program was implemented in the 1990s; however, exploitation rates have suggested that these efforts were insufficient to cause population declines necessitating reexamination of this management action. Quantifying aggregations and movements of channel catfish might allow managers to optimize the timing and location of removal efforts. We used active and passive radio telemetry to assess seasonal patterns in the distribution, aggregation, and movement of adults, and used temperature and activity sensors in some transmitters to identify behavior associated with channel catfish spawning which we corroborated through the back calculation of young-of-year otoliths to estimate hatch dates. We implanted 100 channel catfish in 2023 and 96 in 2024 with either a coded radio transmitter or a coded archive radio transmitter equipped with daily activity and temperature sensors. Tracking efforts occurred monthly outside of the spawning season and weekly during the expected spawning season (June-July) with raft-based tracking surveys. Despite a transmitter loss rate of 59% (n=116/196), we observed limited movement (< 5 river kilometers [rkm]) in spring/early summer followed by upstream movement in July in 2023 and May in 2024. Upstream movement coincided with warming water temperatures and largely occurred when the daily average water temperature reached 21°C, which is reported to initiate spawning for this species. Net movement was lower for fish < 440 mm TL (4.2 rkm) than for fish > 440 mm TL (14.4 rkm, $p < 0.05$). Linear mixed effects model results confirmed a positive relationship between movement rate and total length and a modal relationship between movement rate and a quadratic term for temperature with a predicted maximum movement rate identified at 22.1°C. Additionally, movement rate was 30.0% lower in 2024 compared to 2023 suggesting annual variability in movement patterns. Regression of activity as a function of temperature indicated that ten of twelve individuals displayed a modal activity pattern with predicted activity peaking in late-spring/early-summer at an average of 21.3°C. While our results do not suggest channel catfish have a propensity to aggregate, synchronized upstream movement likely cued by water temperatures near 21°C may provide the

opportunity for resource managers to use passive sampling techniques to remove channel catfish during upstream spawning movements.

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Chapter 1 - Evaluating adult channel catfish movement, aggregation, and activity patterns

Introduction

Species invasions are one of the most influential drivers in biodiversity loss in freshwater ecosystems (Sala et al. 2000, Dudgeon et al. 2006). Invasive fishes impact native communities by increasing predation pressure (Brown and Moyle 1997; Findlay et al. 2000; Weyl and Lewis 2006), increasing interspecific competition (Fisher Huckins et al. 2000; Zimmerman and Vondracek 2006; Grabowska et al. 2015), modifying habitats (Ribeiro and Leunda 2012; Gallardo et al. 2016), increasing the frequency of disease transmission (Gozlin 2008; Peeler et al. 2011), and suppressing native reproduction through hybridization (Weigel et al. 2003; Costedoat et al. 2005; Hänfling et al. 2005). These impacts are particularly strong in regions characterized by low native fish diversity such as in the American Southwest (Fitzgerald et al. 2016). The susceptibility to invasion paired with high endemism in this region highlights both the fragility and importance of these native fish communities (Minckley and Deacon 1968).

Removing an invasive species once established is difficult, and the probability of success often depends on the life history of target species and the complexity of the invaded habitat (Gozlan 2008; Simberloff 2009; Gozlan et al. 2010). A variety of non-native removal techniques are available, including chemical treatments (e.g., rotenone), mechanical removal, and biological control (Rytwinski et al. 2018). Despite the options available to resource managers, removal efforts in large rivers targeted at eradication are often ineffective (Franssen et al. 2014; Zelasko et al. 2016; Healy et al. 2022). The implementation of chemical treatments, such as rotenone, may be more likely to achieve eradication success, but its use is often constrained due to its negative impacts on non-target species (Vinson et al. 2000; Rytwinski et al. 2018). In general, the likelihood of successfully eradicating a non-native species is highest during early stages of invasion or in small, isolated habitats; once established, eradication is likely unattainable (Gozlan 2008; Gozlan et al. 2010). Regardless, suppression of an invasive species may still benefit natives, making it a desirable management tool (Klein et al. 2023). Identifying vulnerabilities in the life cycle of these fishes may increase the likelihood of successful suppression or eradication (Rytwinski et al. 2018). Consequently, sufficient knowledge of life cycle requirements, habitat preferences, and distribution patterns is a necessary component of any non-native species management protocol (Simberloff 2009).

The San Juan River in New Mexico, Colorado, and Utah has been invaded by several species, including the channel catfish *Ictalurus punctatus*, where they now co-occur with the federally endangered razorback sucker *Xyrauchen texanus* and Colorado pikeminnow *Ptychocheilus lucius.* Given that channel catfish are piscivorous, the threat of this invader to these endangered fishes warrants concern. Hedden et al. (2021) analyzed the stomach contents of 4,649 channel catfish from the San Juan River and found that 356 (7.7%) contained fish, of which 54% of that total fish biomass were native species including two individual Colorado pikeminnow. Although smaller channel catfish tend to be more insectivorous, they have the potential to predate on younger life stages (Evelyn et al. 2021). For example, in a laboratory study, small channel catfish (average = 74 mm total length [TL]) were capable of consuming larval razorback sucker (14.4 mm TL; Carpenter and Mueller 2008), while a diet analysis of channel catfish in the Gila River found that 55% (16/29) of stomachs contained razorback sucker juveniles following stocking (Marsh and Brooks 1989). The impact of small channel catfish on larval and juvenile life stages for the native fishes of the San Juan River has not been quantified making it difficult to quantify this potential threat to the population. Furthermore, competition threats caused by channel catfish are unknown; however, given that both channel catfish and razorback sucker are benthic species, displacement and competition for resources may be impacting recovery.

Mechanical removal of channel catfish in the San Juan River, via raft-mounted electrofishing, began in the late 1990s, with effort and spatial coverage varying over time (Franssen et al. 2014; Pennock et al. 2018). Intensive, river-wide non-native removal began in 2006, and results from later years (2011-2015) suggested a reduction in the abundance of larger individuals (Pennock et al. 2018). However, population exploitation rates of 0.14 from those intensive, river-wide efforts (i.e., 2011-2015) were ultimately insufficient to cause population declines. According to model estimates, efforts would need to be increased to obtain exploitation rates of 0.21-0.34 to achieve growth overfishing or 0.26-0.29 to achieve recruitment overfishing (Pennock et al. 2018). Contrary to expectations, catch per unit effort (CPUE) of channel catfish during long-term annual monitoring, although variable, increased following the initiation of the mechanical removal program (Pennock et al. 2018). The compensatory response created high levels of uncertainty in the efficacy of this management action, warranting the need to identify innovative and strategic removal approaches.

Quantifying distribution and movement patterns of channel catfish in the San Juan River can help to increase the efficacy of removal efforts. Limited floy tag and recapture data suggest that in some years fish can undergo extensive migrations with some individuals moving greater than 80 river kilometers (Duran et al. 2018). In other systems, channel catfish make relatively large migrations with individuals generally making upstream movements in the spring, localized movements in the summer, and downstream movements in the fall (Newcomb 1989; Pellett et al. 1998; Wendle and Kelsch 1999). However, the temporal scale of current tagging and recapture data in the San Juan River is too coarse to infer spawning movements and areas. A more temporally intensive investigation into individual movements both during and outside the spawning season, such as through the use of radio telemetry, could help determine where individuals spawn and if they aggregate in particular reaches. Further, the use of archive radio transmitters equipped with activity sensors can reveal patterns in daily and seasonal activity of a fish. For nest building species, activity patterns may indicate approximately when an individual initiated spawning activities (Hedden and Gido 2016). For example, a spike in activity may indicate nest-building and/or mating rituals, while depressed activity patterns following a spike may result from the nest-guarding period exhibited by male channel catfish (Bates and Tiersch 1998; Tatarenkov et al. 2006). Thus, the combination of activity and locality data could inform both when and where individuals spawn. Identifying seasonal movements and aggregation patterns might help focus removal efforts on spawning adults and potentially reduce the number of fish contributing to reproduction (Coulter et al. 2016; Hedden and Gido 2016).

Our objectives were to 1) assess patterns of seasonal distribution, aggregations, and movement; 2) use activity sensors to identify channel catfish spawning timing as related to water temperature and discharge; and 3) use back calculated hatch dates from young-of-year channel catfish otoliths to validate the use of activity sensors to identify spawning timing. We hypothesize that channel catfish in the San Juan River make relatively localized movements in early spring and begin to move upstream as water temperatures increased to 21°C, which has been suggested to be the lower spawning temperature threshold for this species (Newcomb 1989; Pellett et al. 1998; Small 2006; Pawiroredjo et al. 2008). We also hypothesize a peak in spawning activity around 21°C, which is typically associated with channel catfish spawning-related activity such as nest-building and mating ritual in other systems.

Methods

Study Site

The San Juan River is a major tributary of the Colorado River that originates in the San Juan Mountains of Colorado and drains into Lake Powell, Utah. The San Juan River watershed measures 99,200 km^2, and extends into Colorado, New Mexico, Utah, and Arizona (Carlson and Carlson 1982). The river is impounded in northern New Mexico by Navajo Dam, which alters its' flow and temperature regime relative to historic pre-dam conditions (Miller and Swaim 2017). Locations in the river are designated by river kilometer (rkm) upstream of Piute Farms Waterfall (rkm 0.0) which serves as a barrier to upstream fish passage (Figure 1). Silt-sand runs interspersed with cobble bars make up the majority of substrate within the study area. The river morphology in the upstream portion of our study reach is characterized by broad, braided channels that result in a relatively high diversity of habitat types (e.g., secondary channels, backwaters, riffles). The system becomes largely canyon bound downstream of rkm 107.2. Riparian vegetation is dominated by invasive Russian olive (*Eleangnus angustifoliI*) and saltcedar (*Tamarix spp.*), with dispersed native cottonwood (*Populus fremontii*) and willows (*Salix exiqua* and *Salix gooddingii*) present throughout.

Fish Capture and Transmitter Implantation

Using raft-mounted electrofishing, adult channel catfish were captured and tagged in February of 2023 and April of 2024. Capture efforts were concentrated within sub-reaches between rkm 199.6 (Powerline) and rkm 123.0 (Sand Island Boat Launch). One hundred adult channel catfish were surgically implanted with an Advanced Telemetry Systems (Isanti, Minnesota) coded VHF radio transmitter with external whiptail antennas in 2023. Sixty fish received a coded transmitter (model F1850C), while the other 40 received a transmitter equipped with daily activity and temperature sensors (model ARC400-AA). Both transmitter types had a minimum estimated battery life of 397 days. In 2024, we used smaller transmitters with shorter battery lives to improve transmitter retention. Fifty-six transmitters had an internal coil antenna (model F1250C), 40 received a transmitter equipped with daily activity and temperature sensors and an external whiptail antenna (n = 20 model ARC400-10) or an internal coil antenna (n = 20, model ARC400-10). All transmitter types used in 2024 had a minimum estimated battery life of 130 days. All transmitters were equipped with an inactivity switch. Following 8 consecutive hours of inactivity, the switch trips and lowers the emitted pulse rate of the transmitter which is subsequently recorded by the radio receiver as an inactive transmitter. In 2023, all radio transmitters were ≤ 6% (range: 1.1-6.0%; mean: 3.3%) of the individual body mass. In 2024, transmitter models were adapted to reduce tag burden to < 4% (range: 0.9-3.9%; mean: 2.4%).

Captured fish were held in net pens submerged in the river before being individually transferred to a livewell where they were anesthetized using tricaine methanesulfonate (MS-222; Syndel Syncaine®) prior to surgery. To implant each transmitter, we made an incision of about 10-20 mm (depending on transmitter type) into the peritoneal cavity, adjacent to the left pelvic fin (Hart and Summerfelt 1975). Incisions were closed with 3 to 4 external interrupted sutures (absorbable monofilament, 5-0, FS-2; non-absorbable monofilament, 1-0, CP; absorbable braided 3-0, PS-2; Ethicon, Inc., Sommerville, NJ). In 2024, the incision site was swabbed with antiseptic liquid bandage to reduce the risk of infection. Following surgery, fish were held in an approximately 190 L aerated livewell to recover before being released; in 2024 the recovery livewell was increased to a 375 L tank placed in the river to stabilize water temperature. In addition, the recovery tank in 2024 was treated with a 1% salt solution and 0.02 mL/L of oxytetracycline. In 2024, fish were held for at least 20 minutes (20 – 180 minutes) in the recovery tank before being released back into the river. Because fish movement and aggregation patterns may differ among adult age classes and between sexes, transmitters were divided between two size classes (2023: n = 50 340-440 mm TL, n = 50 ≥440 mm TL; 2024: n = 69 340-440 TL, n = 27 ≥440 TL). Sex was determined through genetic analysis (Ninwichian et al. 2011) of caudal fin clips taken prior to surgery (2023: n = 45 female; n = 54 male; n = 1 unknown; 2024: n = 40 female, n = 55 male; n =1 unknown). Additionally, each radio-tagged fish was measured for total length and implanted with both a Floy tag (Floy Tag & Mfg., Inc., Seattle, Washington) and passive integrated transponder (PIT) tag (12 mm, Biomark, Inc., Boise, Idaho). These tags served as secondary methods for obtaining additional encounter histories through fish handling (e.g., community monitoring) or from tag detections using the PIT antennas deployed throughout the San Juan River (Figure 1).

Telemetry Efforts

Tracking of channel catfish was conducted using a combination of passive and active receivers. In 2023, passive receivers (Advanced Telemetry Systems, Isanti, Minnesota, 4 Element Fixed Yagi; R4500CD Coded Receiver Datalogger) were located at rkm 199.6 (Powerline) and 123.0 (Sand Island Boat Launch; Figure 1). In 2024, three additional remote telemetry stations were established at rkm 255.2 (Hogback Diversion), 161.6 (McElmo Creek), and 85.8 (Mexican Hat) to increase the spatial resolution of passive stations. Stationary receiver detections were used to identify upstream movements of individuals to help confirm non-shed active transmitters as we assumed upstream movement confirmed the presence of a live, tagged fish. Stationary receiver detections were also used to identify emigration from the upper and lower bounds of our study reach.

Active telemetry tracking efforts were conducted by raft using a 3-element folding Yagi antenna. Surveys varied in duration and spatial extent but were concentrated on an approximately 76.6 rkm reach that extends from rkm 199.6 (Powerline) – 123.0 (Sand Island Boat Launch; Table 1; Figure 1) near Bluff, Utah. To identify individual locations of tagged fish during each survey, the maximum signal strength of detections on the receiver (model R4500DC) was paired with recorded GPS coordinates. Tracking surveys were conducted every 3-5 weeks outside of the expected spawning season (2023: March-May and August-October; 2024: May and August) and were conducted weekly during June and July when mean water temperatures were presumed to be optimal for spawning (Table 1).

The shedding of telemetry transmitters is common in telemetry studies and is especially common in ictalurids (Summerfelt and Mosier 1984; Marty and Summerfelt 1986; Jepsen et al. 2002; Holbrook et al. 2012). Because of the relatively high rate of observed transmitter loss, we developed a systematic approach to decipher live tagged fish from shed transmitters. We used the identification of shed transmitters, the presence of upstream movement, and inactivity sensors to distinguish shed transmitters from live fish (Figure A.1). Identification of shed transmitters involved tracking on foot to identify the precise location (within 2m) of individual transmitters. Transmitters that were either located on land or showed no movement once the area was disturbed were confirmed to be shed. We confirmed transmitter retention if a fish moved upstream. Inactivity sensors integrated in each transmitter were the least reliable method, likely due to continued downstream movement of transmitters expelled into the river, and thus were used as a last resort to decipher transmitter status.

Following the expected spawning season (June-July) searches for shed archive transmitters occurred concurrently with active tracking efforts. The locations of transmitters suspected to have been shed were triangulated on foot and locations were excavated using a shovel if buried in sediment. Along with the retrieval of shed transmitters, to capture archive-tagged fish we used a combination of capture methods (seining, backpack electrofishing, raft-mounted electrofishing) to target triangulated locations of these fish. Efforts to capture live channel catfish were concentrated during low flow conditions in September and October 2023 and August and September of 2024.

Data Analysis

Aggregations

To identify patterns of channel catfish distributions, we first located tagged fish based on the coordinates when the strongest signal strength occurred in each survey. Locations were rounded to the nearest 0.16 rkm. Next, we calculated the average rkm of channel catfish locations during each mobile telemetry survey. To test for aggregations throughout the study period, we developed a metric that used the number of fish detected at distinct rkms and defined an aggregation as any rkm with greater than one fish. We analyzed these aggregations across time to investigate the temporal trends in the spatial distributions of channel catfish and their propensity to aggregate. Because the proportion of aggregations during a telemetry survey was a function of the rkms tracked we restricted aggregation calculations to include rkms 123-200 since this reach was covered during all tracking surveys across both years.

Movement

To examine longitudinal movement of channel catfish, the difference between detection locations and the last known location (rkm) was calculated, thus positive values indicated upstream movement and negative values indicated downstream movement. Additionally, we calculated a directional movement rate as the difference in river locations divided by the number of days between detections. We used a linear mixed effects model in Program R (R Core Team 2023) using packages “lme4” (Bates et al. 2015) and “AICcmodavg” (Mazerolle, 2023) to test the associations of environmental and individual-level covariates with channel catfish movement rates. To approach a normal distribution, we cube root transformed movement rate. Only upstream movement rates with detection intervals shorter than 22 days were included in the analyses, as movements were generally upstream, and rates calculated over longer intervals were more difficult to match with environmental conditions. Our resulting dataset was thus largely restricted to movements occurring during June and July. Total length at time of surgery (mm), sex, and year were included as fixed effects. We used temperature and discharge obtained from the stream gage near Four Corners, CO (USGS #09371010) to calculate average temperature and discharge values for the time between telemetry detections (days at large; Vine et al. 2019). Average temperature and discharge for days at large were included as continuous fixed effects. Polynomial terms for both temperature and discharge were included as continuous fixed effects as we expected peaks in movements at intermediate temperature and discharge. We included individual as a random effect to account for multiple detections of the same individuals. To approximate normality of model residuals, all continuous variables were log transformed.

Prior to model creation, we assessed covariates for correlation using Pearson's correlation coefficients and determined a value > |0.4| to indicate significant multicollinearity issues. Average discharge was highly correlated with average temperature (Pearson's correlation coefficient = -0.85), and thus average discharge was removed from models as we sought to validate the 21°C spawning threshold proposed in previous study (Small 2006; Pawiroredjo et al. 2008). We used Akaike's Information Criteria corrected for small sample sizes (AICc) to compare a null (intercept only) and all nested models with no multicollinearity issues to the global model. We assessed AICc model weights and models with a ΔAICc < 2 were considered valid. To assess model performance, we used the package MuMIn (Barton, 2010) to calculate marginal and conditional R^2 values which represent the variance explained by the fixed effects and by both the fixed and random effects, respectively (Nakagawa et al. 2017).

Activity

To evaluate seasonal patterns of activity and to identify the timing of channel catfish spawning, we calculated daily and monthly averages of activity and daily averages of temperature obtained from archival transmitters. Activity sensors composed of multi-axis accelerometers detect variations in motion every 15 minutes and records activity as the percentage of a 60-second interval in which the transmitter was in motion. We used regression analysis to assess statistical relationships between activity and temperature. We predicted that a spike in daily activity may correlate with active spawning behavior such as nest building and mating ritual (Bates and Tiersch 1998; Tatarenkov et al. 2006). To validate the use of archive transmitter activity measurements to identify spawning timing, we compared predicted peaks in daily average activity patterns to back-calculated spawning dates from larval channel catfish otoliths (Grey et al. 2024).

Results

Transmitter Loss

In 2023, 15 mobile telemetry surveys were conducted between March-October resulting in 371 unique detections of tagged fish. In 2024, 10 mobile telemetry surveys between May-August resulted in 732 detections of tagged fish (Table 1). Fewer detections of tagged fish in 2023 was largely a result of transmitter loss. Of the 100-channel catfish tagged in 2023, 87 were determined to have shed their transmitter, with nearly half (41/87) of those shed prior to July 04 when mean daily water temperature first reached 21°C. In 2024, 29 of the 96 tagged fish were determined to have shed their transmitter during the study period. Four of these fish shed their transmitters prior to June 19, the first day on which the daily water temperature reached 21°C. Ten of the 116 individuals with shed transmitters were detected on upstream stationary PIT antennas after radio transmitter loss occurred, suggesting that transmitter loss is partially attributable to transmitter shedding as opposed to mortality.

Aggregations

Prior to the first day in which daily average water temperatures reached 21°C, July 04, 2023, and June 19, 2024, relatively few channel catfish exhibited patterns of upstream movement exceeding five rkms (n = 40/181; Figure 2). Channel catfish distributions during the initial 30 days following surgical release were largely dominated by small downstream movements (< 5 rkm) in 2023 and small upstream movements (< 5 rkm) in 2024. Over half (n = 94/181) of the channel catfish that were detected during this time period were located within 5 rkms from their release locations. Average location of catfish during telemetry surveys showed an increasing trend towards upstream reaches throughout the study period. The proportion of rkms containing > 2 channel catfish was the highest in the beginning of the season for both 2023 and 2024 (Figure 3). In both years, the proportion of aggregations peaked approximately 60 days after transmitter implantation (2023: 30%; 2024: 23%) as fish dispersed. The proportions of aggregations declined to 0% in 2023. In 2024, following an initial decline, proportions of aggregations remained at an average of 15% from mid-June through the end of the study period in September.

Movement

A spike of upstream movement of individuals occurred in July of 2023 following daily average water temperatures reaching 21°C and a simultaneous decline in discharge from approximately 226 to 85 m^3s^{-1} (CMS; Figure 2). A more gradual progression of upstream movement occurred in 2024, with some individuals making substantial upstream movements beginning in May (Figure 2). Channel catfish movement patterns varied across individuals. Nineteen fish exhibited highly localized movement patterns and despite 7-10 detections, were never detected further than 2 rkms from their release location. Alternatively, 21 fish exhibited net upstream movement >50 rkms with seven individuals making upstream movements >90 rkms.

Linear mixed effects models were fit to 403 observations of movement rates. The most supported model was the global model which included year, a quadratic term for temperature, total length, and sex (AICc weight = 0.57; Table 2). The second most supported model excluded sex and included year, a quadratic term for temperature and total length (AICc weight = 0.42, ΔAICc = 0.60). According to the most supported model, movement rate increased with total length of individuals and was lower in 2024 than in 2023. Channel catfish with a total length of 550 mm were predicted to have a movement rate more than 4x greater than those with a total length of 400 mm (400 mm TL: predicted movement rate = 0.09 rkm day^{-1}; 550 mm TL: predicted movement rate = 0.37 rkm day^{-1}). The 2023 predicted movement rate was more than three-fold greater than 2024 (2023: predicted movement rate = 0.31 rkm day^{-1}; 2024: predicted movement rate = 0.09 rkm day^{-1}). Our most supported model indicated a quadratic term for average temperature, and movement rate was predicted to peak at a temperature of 22.1°C. Female channel catfish were predicted to have an approximate 2.3x greater movement rate compared to males (females: predicted movement rate = 0.23 rkm day^{-1}; males: predicted movement rate = 0.1 rkm day^{-1}). The inclusion of individual as a random effect explained a greater proportion of the variance when compared to fixed effects alone (marginal $R^2 = 0.16$; conditional $R^2 = 0.41$), suggesting substantial variation in movement among individuals.

Activity

Seven archive transmitters were recovered in 2023, of which one transmitter malfunctioned, and five transmitters were shed prior to August 1 and thus offered little insight into activity patterns during the spawning season. In 2024, 12 archive transmitters were recovered, of which one was shed prior to August 1. All subsequent analyses are restricted to transmitters that were confirmed to have remained in live fish through the end of July (n=12). Activity patterns were variable among individuals (Figure 4); however, 67% of the individuals exhibited their highest monthly activity in the expected spawning season of June and July (n=8; Figure 5). Regression analysis indicated that all daily activity patterns were quadratically related to daily average temperature ($P < 0.01$; $R^2 = 0.07$-0.39). Ten of twelve individuals displayed a modal activity pattern with predicted activity peaking at an average of 21.3°C (range: 17.5-24.9 °C; Figure 6). The one transmitter from 2023 included in regression analysis had a predicted peak in activity at 23.5 °C, which first occurred on July 12. In 2024, individuals included in regression analysis predicted activity peaks at 17.5 to 24.9 °C. The first days on which the daily temperature reached these temperatures ranged from April 23 to July 11.

Discussion

Aggregation and Movement

Although past research has explored the social nature of channel catfish spawning and their tendency to visit nest sites of other adult mating pairs (Tatarenkov 2006), we found little evidence they aggregate during or outside of the spawning season. Initially, channel catfish were aggregated as a result of the grouped release of fish following surgical implantation of radio transmitters, but those aggregations declined throughout the study period. The lack of aggregations during the presumed spawning season may indicate the broad availability of channel catfish spawning habitat throughout the San Juan River. Nevertheless, our observed pattern of upstream movement may be driven by advantages related to genetic contribution, such as retention of young-of-year or access to more productive habitats (Brown and Armstrong 1985; Gido et al. 2006; Lechner et al. 2016).

Based on previous study of channel catfish in other systems, we hypothesized channel catfish movement towards upstream reaches in the spring and early summer as water temperatures approached 21°C (Newcomb 1989; Pellett et al. 1998; Small 2006; Pawiroredjo et al. 2008). Linear mixed effects model results support this hypothesis with a peak movement rate at 22.1°C, confirming that water temperature is an important environmental cue for channel catfish to begin upstream spawning movements. Observed movements in 2023 largely occurred after the first day in which the daily average water temperature reached 21°C and after a simultaneous drop in discharge. In 2024, observed movements were more variable with some individuals making upstream movements shortly after surgical release. Our model results indicated that movement rates in 2023 were 3-fold higher than in 2024, suggesting that interannual variability plays a major role in dictating movement patterns. These differences in movement rates may be partially explained by contrasting environmental conditions across the two years.

Because high discharge is negatively associated with water temperature in the San Juan River (Gido and Propst 2012), we considered both discharge and temperature as simultaneous environmental cues for prompting the initiation of upstream spawning movements. Despite our exclusion of discharge in our models due to multicollinearity it is impossible to rule out its influence on movement rates. Moreover, the influence of flow regime on movement of siluriforms has been examined in other studies (Hahn et al. 2019; Vidal et al. 2021). Enders et al. (2011) found that channel catfish movements in the Red River appeared to be triggered by peak flows and that movement typically occurred near the peak and during the descending limb of the hydrograph, providing further support for our prediction that discharge may play a role in determining movement patterns of the species. The pattern of reserved movement we observed during rising and peak flows, which was especially prevalent in 2023, may be due to increased energy expenditure associated with higher discharge (Hinch and Rand 1998; Kemp et al. 2006; Rand et al. 2006).

Our results also suggest a higher movement rate for larger individuals. Although we did not explicitly make *a priori* predictions regarding the influence of total length on movement patterns, our model results align with those from several other studies which have shown a positive relationship between movement distances and fish size (Schaffer and Elson 1975; Auer 1996; Keefer et al. 2013). Siddons (2015) showed that large channel catfish (TL > 600 mm) in the Red River made greater upstream movements when compared to smaller individuals. The increased movement rate we observed for larger fish may be a function of increased swimming ability (Hammer 1995) or greater thermal tolerance of large fish (Stewart and Allen 2014) moving upstream into cooler water released from the reservoir. Past research has explored the swimming performance of channel catfish (Beecham et al. 2007; Yoshida et al 2016, Gerhart et al. 2024), but to our knowledge no studies have examined adult channel catfish swimming ability as a function of body size. Limited swimming performance research has been conducted on siluriforms in general, however, in a laboratory experiment, Shiau et al. (2020) found that the endurance of eel-tailed catfish (*Tandanus tandanus*) was greater for larger individuals when tested in sufficiently deep water (>15 cm). Despite the limited physiological evidence for the correlation between channel catfish movement rates and body size, it seems plausible that the correlation may exist given the prevalence in other riverine fishes (Webb et al. 1984; Ojanguren and Braña. 2003; Rubio-Gracia et al. 2020). Alternatively, differences in thermal tolerance may drive differences in movement patterns between size classes. Stewart and Allen (2014) showed that in laboratory experiments, channel catfish survival was positively related with total length following water temperature manipulations. Hypolimnetic releases from Navajo Dam have depressed water temperatures in the San Juan River when compared to natural pre-dam conditions (Miller and Swaim 2017). For example, in June and July of 2023, the mean water temperature at rkm 192.0 was 20.5°C (USGS #09371010), while nearly 100 rkm upstream, the mean water temperature was 16.6°C (USGS #09365000). These depressed temperatures in upstream reaches may inhibit the movement of smaller channel catfish if they exhibit a narrower temperature tolerance.

Following spawning, male channel catfish may spend up to two weeks defending and tending to their nests (Bates and Tiersch 1998; Tatarenkov et al. 2006). We expected that this period may lead to sedentary behaviors resulting in depressed movement patterns when compared to females. Model results indicated females exhibited movement rates that more than doubled those of males. Given that most upstream movements occurred following the suspected initiation of spawning season, we expect this pattern to be indicative of sexually dimorphic spawning behaviors. Differences in spawning movement patterns of male and female catfish has been observed in other studies. Koster et al. (2014) used radio telemetry to examine movement of eel-tailed catfish during spawning season in Tahbilk Lagoon, Australia and found that female catfish moved greater distances than their male counterparts likely due to nest-guarding behavior exhibited by male eel-tailed catfish. It is possible that similar behavioral differences drove the differences we found in our study.

The relatively large conditional R^2 of our mixed effects models suggests a great deal of individual variation in movement patterns. This variation was especially prevalent in 2024, in which catfish displayed greater variation in movement consistency and movement rate. For example, one individual in 2024 displaying a relatively consistent upstream movement pattern, moved an average of 8.5 rkm between detections at an average rate of 0.93 rkm day^{-1}. Another individual exhibited a much more abrupt movement pattern in which a large upstream movement of 38.3 rkm (movement rate = 1.1 rkm day^{-1}) occurred shortly following release and a movement of 52.0 rkm (movement rate = 2.6 rkm day^{-1}) occurred suddenly following approximately 60-day residence in a 0.16 rkm region. Along with variability in movement patterns for mobile fish, our data also suggests the presence of resident fish that make highly localized movements not exceeding 2 rkms from release locations. Total linear homeranges, defined as the distance between the most upstream and downstream detection for an individual ranged from 0 to 126.0 rkm. The presence of behavioral syndromes such as sedentary and mobile individuals has been observed in several other populations of catfish (Funk 1957; Garrett and Rebeni 2011; Godinho et al 2017). In addition to intrinsic factors discussed above, such as sex or total length, this variation in life-history strategies may be determined by genetic pre-disposition or extrinsic factors (forage opportunity, competition, risk of predation, etc.), or more likely, by interactions among these factors (Chapman et al. 2012). Examining the role of genetic pre-disposition and extrinsic factors are beyond the scope of this study, however quantifying inter- and intraspecific interactions and abiotic resource gradients throughout the San Juan River may aid in further examining the variability of channel catfish movement patterns. Alternatively, mobile and sedentary behavior may be a plastic trait in which environmental conditions play a role in influencing an individual's decision to remain sedentary or exhibit mobile behavior (Chapman et al. 2012). Given the relatively short battery life of our radio transmitters ($\geq$ 397 days), we were unable to examine the movement patterns of an individual across years, and thus our ability to examine plasticity of movement patterns was limited. Future work may be needed to explore the mechanisms for determining movement patterns within individuals. Given the existing infrastructure of PIT tag antennas, evaluation of the movements of PIT-tagged channel catfish may provide valuable insights into movement plasticity in the San Juan River.

Activity

Activity patterns derived from archive-tagged fish resulted in variable monthly averages. Of the 12 fish, eight experienced their maximum monthly average of activity in the expected spawning season of June and July (June: n=6; July: n=2; Figure 5). Of these individuals, five fish exhibited monthly activity levels that exceeded twice their maximum from 60-days prior, indicating a considerable increase in activity compared to the period before the expected spawning season. We predicted to see a modal pattern in daily activity peaking at 21°C associated with spawning related activity such as nest-building and mating ritual (Bates and Tiersch 1998; Small 2006; Tatarenkov et al. 2006). This prediction was generally supported, but there was also notable individual variation in peak activity occurring at temperatures from 17.5 to 24.9°C. In 2023, spawning dates as determined via simultaneous study of larval channel catfish otoliths indicated a spawning window from June 26 through July 22 (Grey et al. 2024). The one individual from 2023 that was included in activity transmitter regression analysis had an associated predicted peak in activity at 23.5°C which occurred within the suggested spawning window (July 12). This may indicate that spikes in daily activity correspond to spawning activities, although more data is needed to examine this trend. Spawning dates and the suggested spawning window obtained via larval otoliths for 2024 are still under evaluation.

Implications for Resource Managers

Channel catfish exploitation rates from current removal regimes are ultimately too low to cause a population level decline, and thus alternative non-native removal approaches are needed to suppress the populations and limit their impacts on native species (Pennock et al. 2018). Our results indicate that channel catfish do not aggregate in summer months, but they make synchronized upstream movements as water temperatures increase towards 21°C. The lack of aggregations limits the opportunity to concentrate removal efforts in regions characterized by relatively high densities; however, synchronized upstream movement may allow for the interception of adult catfish during spawning movements. Of the catfish that made upstream movements greater than 10 rkm, 66% (23/35) made upstream movements past rkm 200 (Figure 1). Thus, the implementation of removal efforts such as hoop nets or a fish weir to capture fish at this location might be effective. Hoop nets are an efficient method for capturing catfish in other lotic systems including the Mississippi River, the Missouri River, and the Minnesota River (McCain et al. 2011; Sindt 2018; Gebhard et al. 2021). Eder et al. (2016) used hoop nets in the Missouri River, Nebraska to capture channel catfish and achieved estimated exploitation rates of 18-41%. Adapting hoop netting approaches to removal regimes in the San Juan River may lead to exploitation rates exceeding current levels achieved by electrofishing alone (14%; Pennock et al. 2018). The use of hoopnets during upstream spawning movements may provide an alternative removal gear to electrofishing during the spring and early summer when many native fishes spawn and thus may be more vulnerable to negative effects of electrofishing (Farrington et al. 2017; Clark Barkalow et al. 2020). Additionally, the removal of individuals prior to spawning may aid in reducing reproductive contribution by adults.

While the timing and duration of upstream movements of channel catfish can be variable, increasing capture efficiency may be feasible in some years. While in 2024 upstream movements of individuals was temporally variable occurring between April and the end of July, spawning movements in 2023 largely occurred in a window of < 30 days beginning in June. Thus, in some years the economic feasibility of passive capture techniques may be more suitable than others and its effectiveness may largely be a function of flow and temperature regime. Grey et al. (2024) found that channel catfish spawning between 2009-2012 and 2014-2021 varied between mid-June and mid-July and was influenced by photoperiod, temperature, and flow with spawning typically occurring on the descending limb of the hydrograph or during baseflow conditions. These results suggest that managing flow releases from Navajo Dam to align the descending limb of the hydrograph with photoperiod or temperature cues may allow resource managers to concentrate spawning activities and optimize exploitation rates. Although manipulation of flow regimes has the potential to increase capture efficiency, water availability may limit the degree to which flows can be manipulated. Additionally, future work may be needed to ensure that altered flow regimes do not have unintended consequences on populations of Colorado pikeminnow and razorback suckers during their potentially simultaneous spawning activities.

Figures

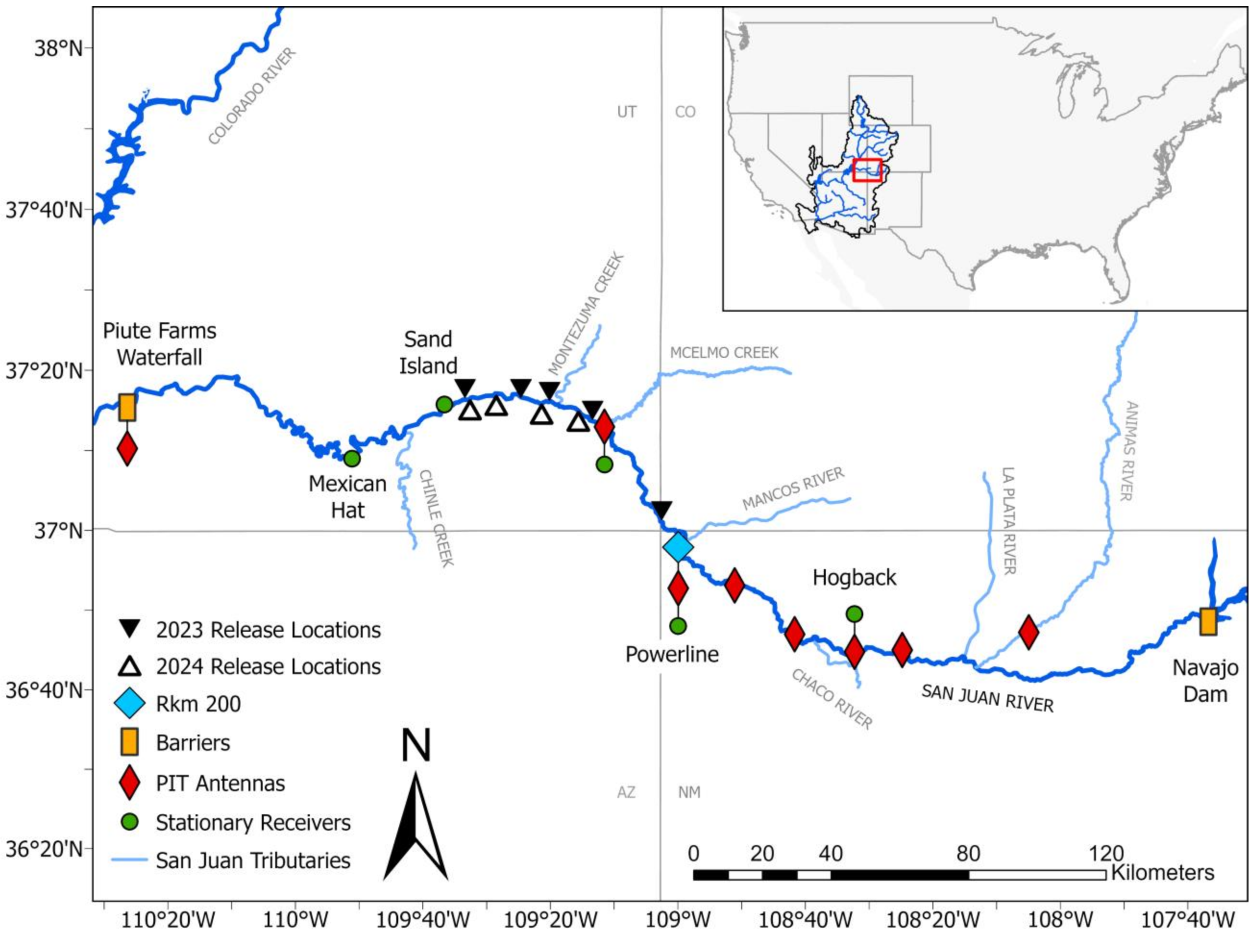

Figure 1. Locations of radio telemetry stationary receivers (green circles) and passive integrated transponder (PIT) antennas used to assess channel catfish *Ictalurus punctatus* movement and aggregation patterns in the San Juan River. Release locations of channel catfish following surgical implantation of radio transmitters are denoted as black triangles for 2023 and white triangles for 2024. Barriers to fish passage include the Navajo Dam (rkm 358.9) and the Piute Farms Waterfall (rkm 0.0) which are denoted by orange rectangles. A blue diamond denotes rkm 200 which may be a location that offers the opportunity for passive removal of channel catfish during upstream spawning movements.

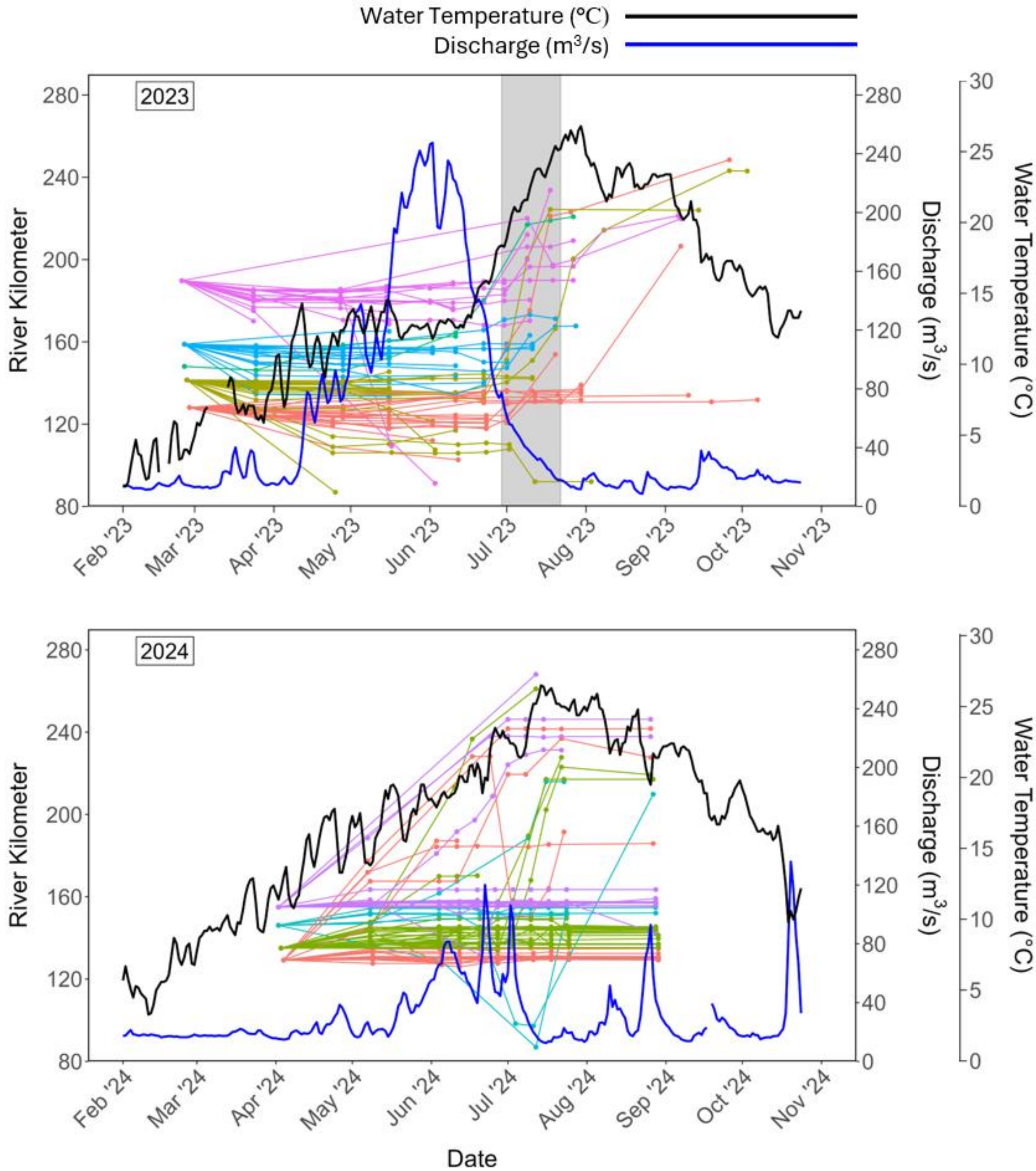

Figure 2. Locations of radio-tagged channel catfish *Ictalurus punctatus* determined via raft-based telemetry surveys in the San Juan River from 2023 and 2024. Individual locations are depicted by points connected by line segments. The color of points and lines denote release locations of channel catfish following surgical implantation of radio transmitters. Daily average water temperature (°C; black) and daily average discharge (m^3 s^{-1}; blue) were obtained from Four Corners, CO (USGS #09371010). The gray box denotes the back-calculated spawning period (June 29, 2023 – July 22, 2023) as informed by age-0 channel catfish otolith analysis (Grey et al. 2024). The spawning window in 2024 is omitted, as otoliths are still under evaluation.

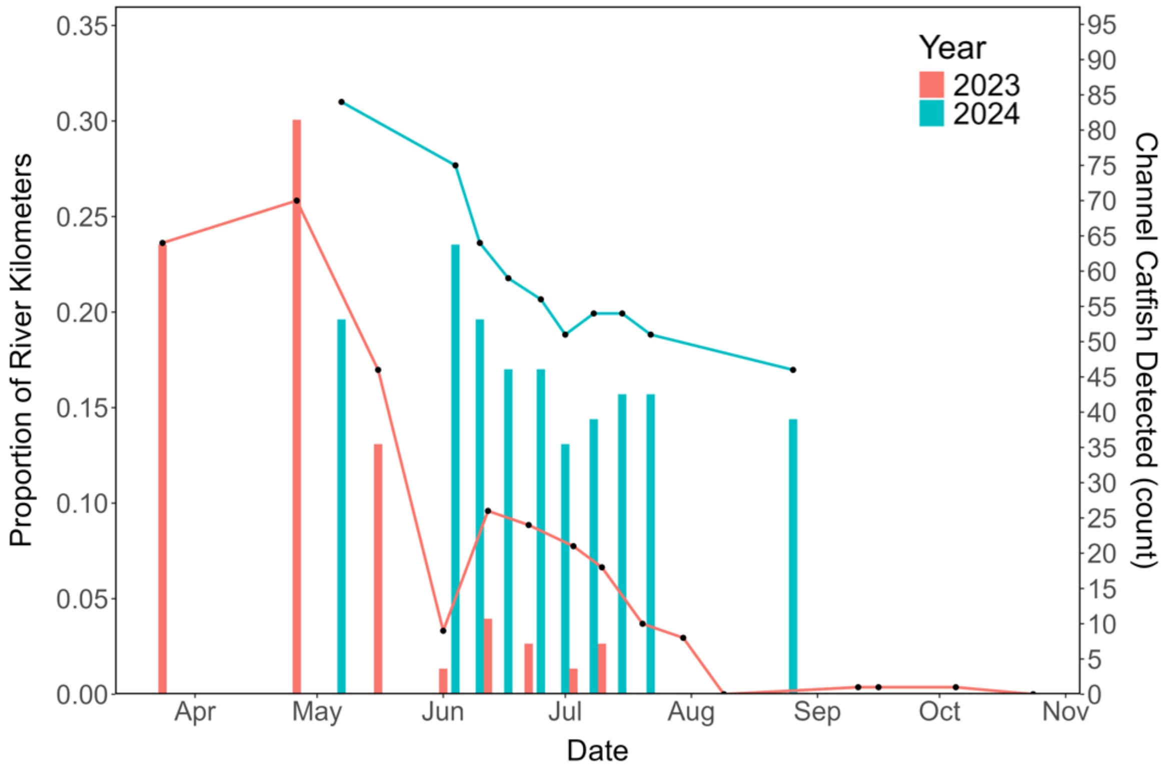

Figure 3. Proportion of river kilometers from a 77 rkm reach (rkm 123-200) that contained channel catfish *Ictalurus punctatus* aggregations (2 or more channel catfish; bars) and number of channel catfish detected during mobile telemetry surveys (black points). Lines between points are included for 2023 (pink) and 2024 (blue) to distinguish between detections among years.

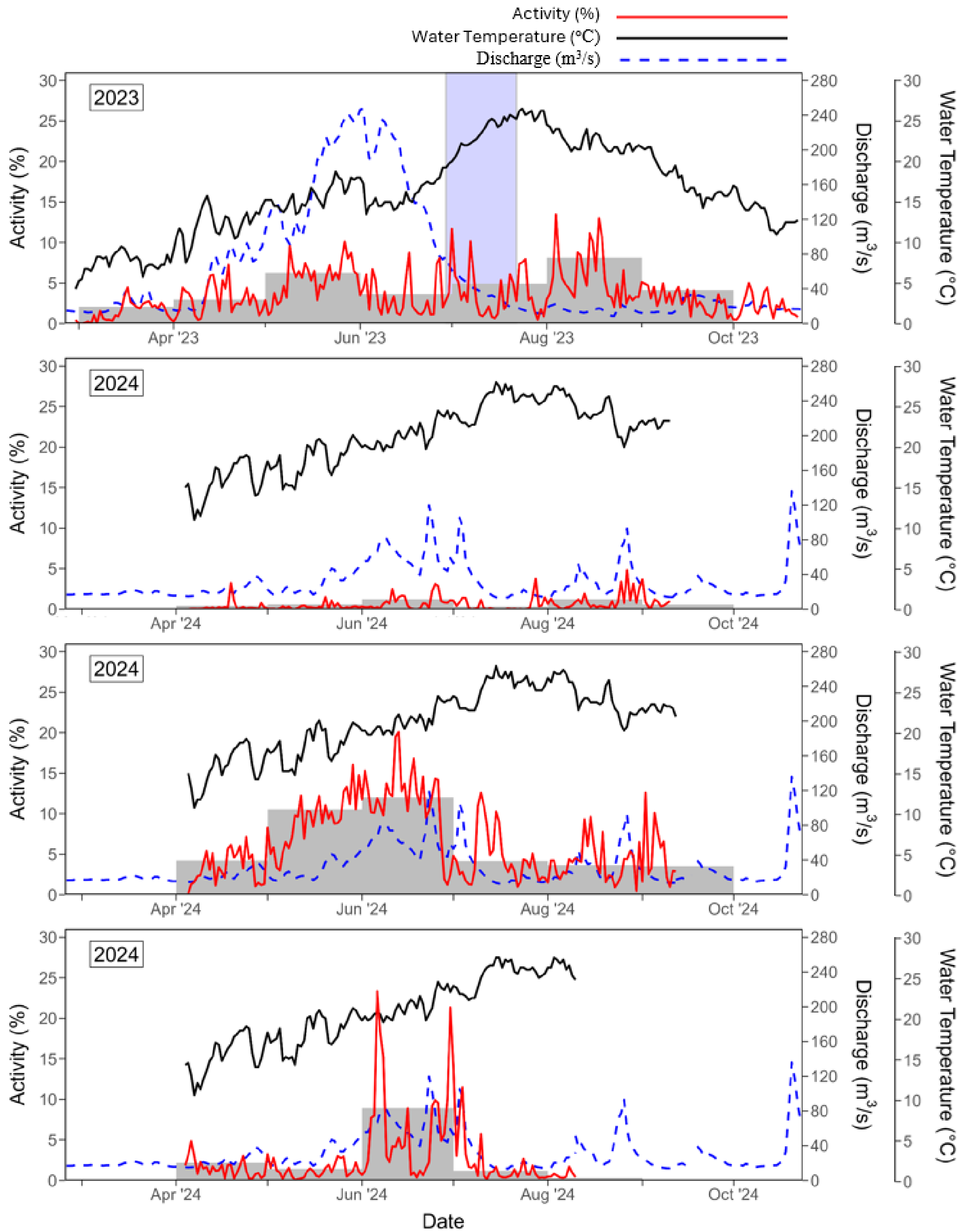

Figure 4. Average daily activity (red lines), average monthly activity (gray bars), and water temperature (°C; black lines) obtained via activity and temperature sensors from four archive radio-tagged channel catfish *Ictalurus punctatus* in the San Juan River in 2023 and 2024. Activity was recorded at 15-minute intervals as the proportion of time a transmitter was in motion in a 60-second interval. Blue dotted lines represent average daily discharge from Four Corners, CO (m^3s^{-1}; USGS #09371010). The blue box in 2023 represents the spawning period (June 29, 2023-July 22, 2023) as determined via back-calculated spawning dates from larval channel catfish otoliths (Grey et al. 2024). Spawning windows from 2024 are omitted as otoliths are still under evaluation.

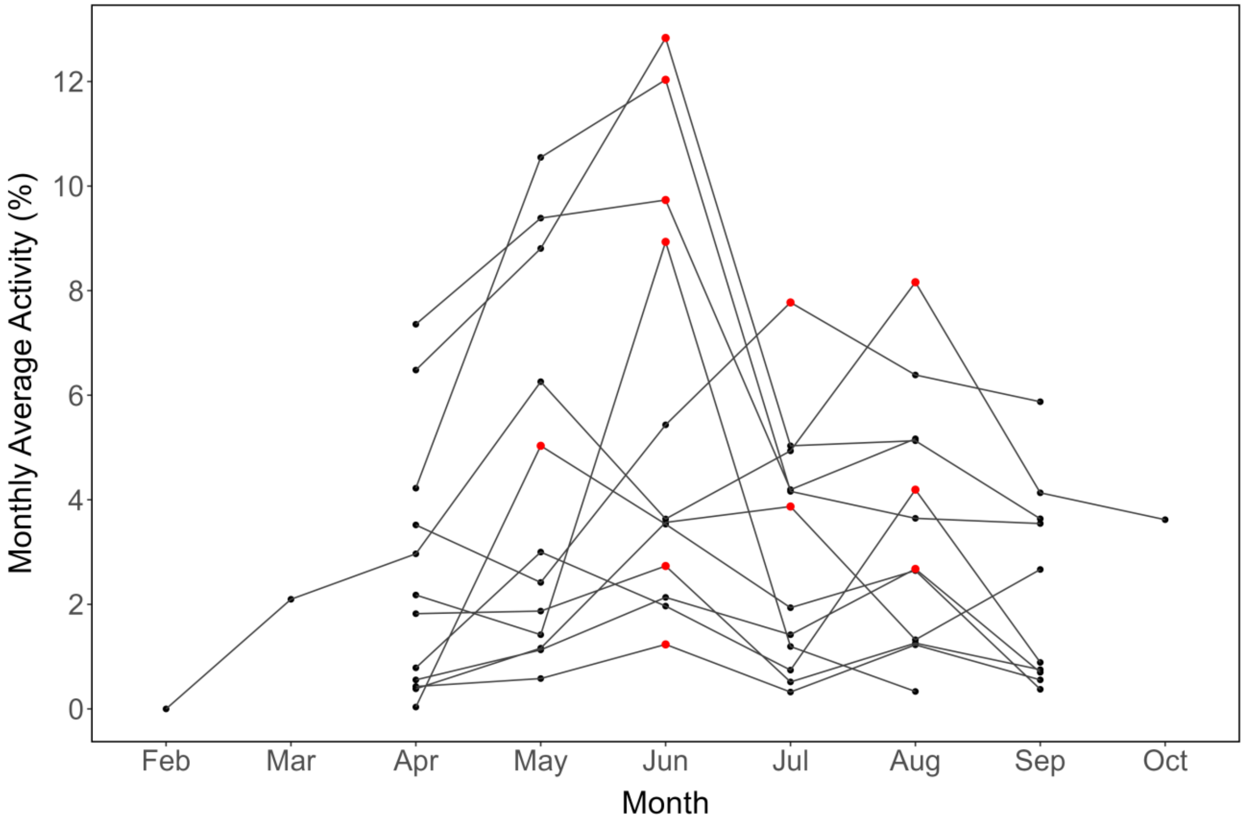

Figure 5. Monthly average activity reading obtained from twelve archive-tagged channel catfish *Ictalurus punctatus*. Activity was recorded at 15-minute intervals as the proportion of time a transmitter was in motion in a 60-second interval. Points indicate reading from twelve catfish across 2023 (n=1) and 2024 (n=11), red points indicate the peak monthly activity for each individual.

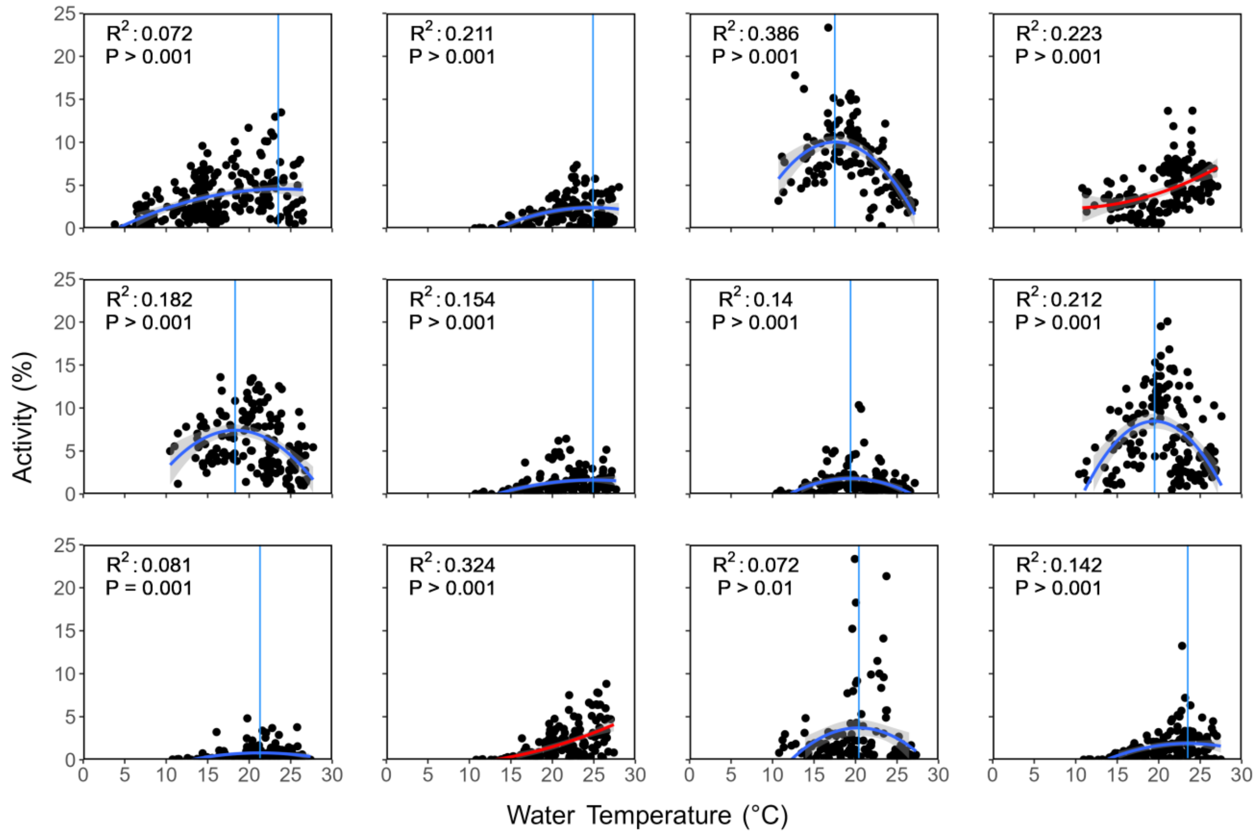

Figure 6. Relationship between daily average water temperature (°C) and daily average activity for twelve channel catfish *Ictalurus punctatus* in the San Juan River. Temperature and activity were recorded via archive radio transmitters at 15-minute intervals. Activity is the proportion of time a transmitter was in motion in a 60-second interval. Second-order polynomial functions were fit to all relationships ($P < 0.01$; $R^2 = 0.07$-0.39). Trendlines are plotted in blue if they displayed a unimodal pattern or red if they did not. Light blue vertical lines are provided for unimodal patterns at the maximum predicted activity level.

Tables

Table 1. Channel catfish *Ictalurus punctatus* detections by mobile telemetry survey in 2023 and 2024. Asterisks: (*) indicates surveys in which equipment malfunctioned; (**) indicates surveys in which tracking occurred across discontinuous days. Start rkm and End rkm denote survey starting and ending locations (rkm). Detected (count) is the number of unique channel catfish detected. Live-tagged (count) is the number of detected channel catfish after the removal of shed transmitters.

Year	Telemetry Survey	Date Start	Start rkm	End rkm	Detected (count)	Live-tagged (count)
2023	1	03/23/23	255.4	123.0	66	64
	2**	04/24/23	123.0	85.3	83	79
	3	05/15/23	199.6	85.3	58	53
	4	06/01/23	199.6	85.3	20	15
	5	06/10/23	199.6	85.3	57	33
	6	06/22/23	199.6	85.3	69	32
	7	06/30/23	199.6	85.3	68	25
	8	07/09/23	238.0	85.3	71	25
	9	07/18/23	238.0	123.0	53	15
	10**	07/26/23	255.4	4.8	74	14
	11*	08/07/23	207.6	217.3	3	2
	12**	09/06/23	268.1	85.3	41	7
	13	09/14/23	77.1	123.0	49	2
	14	10/03/23	255.4	123.0	59	2
	15	10/20/23	268.1	160.9	21	3
2024	1	05/07/24	199.6	85.0	84	84
	2	06/03/24	218.5	123.0	77	75
	3	06/10/24	218.5	123.0	68	65
	4	06/17/24	238.0	123.0	67	61
	5	06/24/24	238.0	123.0	69	59
	6	07/01/24	255.2	85.1	66	57
	7	07/08/24	268.1	85.1	76	63
	8	07/15/24	255.2	123.0	80	61
	9	07/22/24	255.2	123.0	79	59
	10	08/29/24	255.2	123.0	76	53

Table 2. Model selection statistics for linear mixed effects models relating channel catfish *Ictalurus punctatus* movement rate to individual-level and environmental covariates in the San Juan River from 2023 and 2024. AICc = Akaike's Information Criterion corrected for small sample sizes, ΔAICc = difference in AIC compared to top ranked model, AICcWt = weight of AIC model, CumWt = cumulative AIC weight from model and all models ranked higher than it. LL = Log-likelihood value of the model. Year denotes movement rates from 2023 or 2024, Temp is daily average water temperatures obtained from Four Corners, CO (°C; USGS #09371010), TL is the total length (mm) of channel catfish at time of surgical implantation of radio transmitters, and Sex denotes the sex of channel catfish determined via genetic analysis of fin clips. Only the null model and models with ΔAICc < 2.0 are reported.

Model	K	AICc	ΔAICc	AICcWt	CumWt	LL
Year + $Temp^2$ + TL + Sex	8	211.46	0.00	0.57	0.57	-97.55
Year + $Temp^2$ + TL	7	212.05	0.60	0.42	0.99	-98.88
			...			
Null	3	251.29	39.83	0.00	1.00	-122.61

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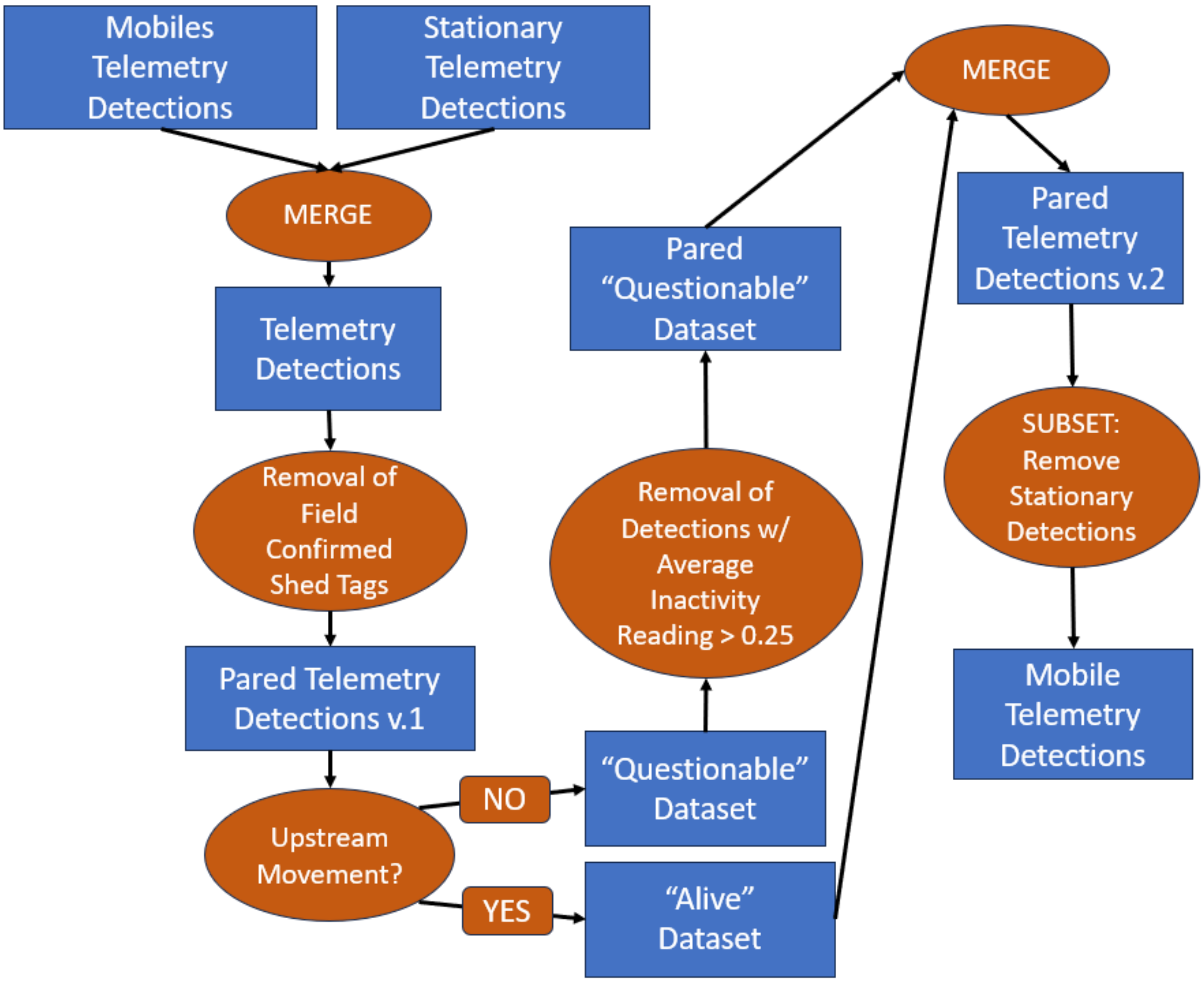
Appendix A - Appendix



Appendix Figure A.1 Flow chart used to filter all telemetry detections to remove observations suspected to be associated with shed transmitters. Filtering of detections consisted of 1) removing detections that occurred following field confirmation of a shed transmitter, 2) creating a "questionable" dataset of the detections obtained since the last occurrence of upstream movement (as we assumed upstream movement to indicate a live-tagged fish), and 3) removing detections from the "questionable" dataset using average inactivity readings obtained from radio transmitters. Inactivity readings obtained from all detections of a transmitter are registered as a 0, 1, or 2 (0: active within 4 hours; 1: no activity from previous 4 hours; 2: no activity from previous 8 hours). A threshold of 0.25 was used to remove suspected shed transmitters based on comparisons between average activity reading and transmitters with a known fate.