Movement and home range of the Sickle Darter (*Percina williamsi*) in the upper Emory River of Tennessee, USA. (**Hydrobiologia**)

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Abstract: Understanding movement patterns and home range of rare species is challenging, especially aquatic fauna like fishes. The Sickle Darter *Percina williamsi* is a rare fish species endemic to the upper Tennessee River basin in eastern Tennessee, southwestern Virginia, and western North Carolina (USA). It has been listed as threatened by the states of Tennessee and Virginia and is being petitioned for federal listing under the United States Endangered Species Act. Little is known about the movement and home range of this species. A total of 8 Sickle Darters from the upper Emory River system were implanted with 8-mm PIT tags and released at the point of capture. The mean (±SD) total length and weight of all fish PIT tagged was 70.1 ±3.4 mm and 3.08 ±1.4 g. Movement of individuals was tracked every two weeks for 6 months (September-March) with a Biomark® HPR Plus reader and BP Plus portable antenna. Associated environmental data were collected throughout the study. Mean total effort for all the tracking events was 70 ±39.4 min, mean catch-per-effort was 9.3 ±6.6 (min/detection) and mean (±SE) detection was 69.5 ±12 %. Mean (±SD) distanced moved of all individuals throughout the study was 7.1 ±4.5 m. Best sub-sets regressions modelling suggest that Sickle Darter movement is related to discharge (m/sec^3) at multiple temporal levels (1, 3, or 7-day). Home range for individuals varied in size. Median home range size was 157.5 (86.0-312.5) m^2) and median (range) degree of overlap for estimated home range was 23.3 (6.2-34.0) %. The results from this study suggest that Sickle Darters exhibit strong site fidelity except when discharge is extremely high. Therefore, conservation measures that protect or attempt to reconnect fragmented habitats will need to factor in the low dispersal ability of this species.

Keywords: Conservation, movement, rivers, ecology, modeling

Declarations

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Introduction

Understanding movement patterns and home range of rare species is challenging, especially aquatic fauna such as fishes. (Holden, 1978; Rodriguez, 2002). Movement of large-bodied sport fishes, like salmonids, has been widely documented on multiple scales (Holden, 1978; Rodriguez, 2002), however within-habitat, within-reach and among system movements of small-bodied rare species are poorly understood. There are multiple reasons why species move, such as seasonal spawning migrations, short-term movement to minimize stress (e.g., movement to a thermal refugium), locating forage, or movement to another reach in response to a habitat disturbance (e.g., flood) or loss of resources (e.g., food, cover; Hall, 1972; Rodriguez, 2002). Understanding the movement of a rare species can improve the efficacy of monitoring its population trajectory. In addition, movement studies allow researchers to understand how individuals respond behaviorally to environmental change, and how they may utilize available habitat at various spatiotemporal scales (Holden, 1978; Rodriguez, 2002; Baxter, 2015; Cooke et al., 2016; Baker et al., 2017; Pennock et al., 2018). This is important when determining conservation measures needed to preserve rare species (Cooke et al. 2015). Movement studies on rare species can help determine critical habitat requirements (Cathcart et al., 2017), which is important when considering that many freshwater species (~700) are considered imperiled in North America as of 2008 (Jelks et al., 2008). Studies on fish movement allow for estimates of home range in a particular system or habitat (Hill & Grossman, 1987). The size of a fish's home range is dependent on multiple factors, such as life-history, biotic interactions, and abiotic factors. Fish size (total length) has been found to have a positive relationship with home range size. This relationship has been observed in large-bodied species like Largemouth Bass *Micropterus salmoides* (Lacépède, 1802) and small-bodied species like the European Bullhead *Cottus gobio* (Linnaeus, 1758; (Minns, 1995). However, this relationship has not been observed within the family Percidae, which include many imperiled, small-bodied darter species and larger-bodied common species like Walleye *Sander vitreus* (Mitchill, 1818; Minns, 1995). Minns (1995) surmised that fish home range size was linked to the metabolic activity of a fish, suggesting that larger fish have greater energetic demand. Consequently, these fish will move greater distances to locate sufficient prey or refugia. This is important when considering the conservation of small-bodied, imperiled fish species like darters, because species with small home ranges will be less likely to disperse and colonize new habitat patches. Thus, population extirpation is more likely to occur when their local habitat becomes unsuitable.

There have been many recent advancements in the applications of telemetry to small-bodied fishes (< 150 mm total length) to help assess movement patterns and home range (Ruetz et al., 2006; Knaepkens et al., 2007; Baxter, 2015). Passive integrated transponder (PIT) tags have been used for decades to track many fish species from all types of environments (Smyth & Nebel, 2013; Baxter, 2015). However, most species that are PIT tagged are prized commercially or recreationally, are species that are easily recognized and valued by society (e.g., sharks) or they are invasive (e.g., carps in North America). Recent telemetry studies have used PIT tags to track small-bodied stream fishes that tend to be rare or of conservation value (Baxter, 2015; Baker et al., 2017; Cary et al., 2017; Kelly et al., 2017; Allan et al., 2018; Pennock et al., 2018). These researchers have outlined methods to track the movement of individuals at large and small scales, and they have observed movement of individuals across multiple habitat types within a stream.

The Sickle Darter *Percina williamsi* (Page & Near, 2007) is one rare fish species that has been understudied until recently (Jett 2010; Tennessee Wildlife Resources Agency [TWRA], 2015 Virginia Department of Wildlife Resources [VDWR], 2015; Hecke & Alford, 2021). Historically, its distribution included the upper Tennessee River basin (UTRB) in the states of North Carolina (NC), Tennessee (TN), and Virginia (VA; Etnier & Starnes, 1993; Jenkins & Burkhead, 1994; Page & Near, 2007; Jett, 2010; Burns et al., 2007; TWRA, 2015; VDWR, 2015; Tracy et al., 2020; Hecke & Alford, 2021). Without a more complete understanding of this species, including its movement and habitat usage, it is hard to prescribe suitable conservation measures to preserve it. At the microhabitat scale, the Sickle Darter occupies flow-adjacent pools over a mix of substrate types (e.g., cobble, boulder, sand, gravel, silt), and it is strongly associated with small woody debris or macrophyte cover. This species is thought to remain in the same reach for most of the year, and individuals are captured in the same microhabitats year after year (same range of depths, velocities, etc.). However, there have been cases where it moves to deeper pools in the winter season (Etnier & Starnes, 1993). There is anecdotal evidence that suggests they migrate short distances from pools to gravel areas of riffles for spawning, however no study has documented this (Etnier & Starnes, 1993; J.R. Shute, personal communication). Studies on darter movement, in general, show that movement tends to be species-specific and location dependent (Roberts & Angermeier, 2007; Roberts et al., 2008; Baxter, 2015). For example, Baxter (2015) found that Kentucky Arrow Darters *Etheostoma spilotum* (Gilbert, 1887) in tributaries of the Red Bird River (Kentucky, USA) will move both upstream and downstream and cover distances from 40 m – 4,000 m.

The goal of our study was to assess how the Sickle Darter moves spatially within a stream and to determine temporal variation in its movement. We achieved this goal with the following objectives: 1) determine the movement extent of the Sickle Darter in the upper Emory River system and the potential environmental drivers of this movement, 2) assess the spatiotemporal variation in movement, and 3) determine the species' home range . This study will further our knowledge of Sickle Darters by documenting how this species moves within its range, and it will help inform future conservation measures to preserve this species.

Methods

Study Area

The Emory River is a spring-fed tributary system of the upper Tennessee River watershed in east Tennessee (Etnier & Starnes, 1993; TDEC, 2002; Fig. 1). This river originates in Morgan County, and it flows southeasterly until it meets its confluence with the Clinch River in Roane County, Tennessee (Tennessee Department of Environmental Conservation [TDEC], 2002). The Emory River main stem is 74 km long and its basin drains an area of ~2,300 km^2 (TDEC, 2002). This basin flows through two different Level III ecoregions: the Southwestern Appalachian Mountains and the Ridge and Valley (Omernik, 1997).

Fish Collection and Tagging

Sickle Darters were captured from known occurrence locations within the Emory River drainages on two different dates (09/27/2019 and 11/16/2019; Page & Near, 2007; Jett, 2010). This river was chosen because it supports one of only two robust populations remaining in its fragmented distribution (Page & Near, 2007; Hecke & Alford 2021). Backpack electrofishing and minnow seines (Bonar et al., 2009) were used to capture individuals. A total of eight Sickle Darters varying in size from 56 to 88 mm total length were collected, tagged, and released at their point of capture in the Emory River system (two sites), which included (1) Rock Creek (width of ~12 m, depth of ~1 m), a small tributary to the Emory River in Morgan County, Tennessee, and (2) the main stem upper Emory River (width of ~10 m, depth of ~1 m) in Morgan County, Tennessee.

PIT tags were used to track individual Sickle Darter movement (Smyth & Nebel, 2013). The model of PIT tags deployed were Biomark® HPT8 minichipTM (8.4mm X 1.4mm, 134.2KHz). These PIT tags are not known to hinder growth, movement, or behavior of small benthic fishes (Ruetz et al., 2006; Knaepkens et al., 2007). Tagging methods closely followed Baxter (2015). Sickle Darters were tagged on the ventral side and on the posterior end between the gular area and the vent. This area is the standard PIT-tagging location for small-bodied freshwater fishes (Kuechle & Kuechle, 2012; Baxter, 2015). A scalpel was used to make a small insertion at this location, then the PIT tag was inserted by hand following the mid-ventral line at an approximate 45° angle. After insertion of the PIT tag, the location was treated with a petroleum jelly made of an antiseptic betadine solution. All materials used were sterilized with 75% ethanol, and the individuals assisting with the PIT tagging of a fish wore nitrile gloves to avoid potential infection of the PIT-tagging location. After insertion, each fish was checked for a unique PIT-tag number. Fish were placed in a container of ambient river water with aeration and allowed to recover for 45 min. After the recovery period, the tagged fish were released back to its capture location. Each individually tagged fish was checked once again in the river for a corresponding PIT-tag number. PIT-tagging mortality and retention were assessed for tagged individuals throughout the study

Fish Tracking

The movement of PIT-tagged individuals was tracked biweekly after the original tagging date (09/27/2019; n=4) for 6 months (September-March). A second tagging date took place on 11/16/2019 (n=4). These PIT tags can remain active for up to 70 years. Tagged fish were tracked using a Biomark® HPR Plus reader and a BP Plus portable antenna. The antenna allows the PIT-tag reader to detect the tags under water, even if the fish is hiding under cover (e.g., a rock or vegetation) simply by holding the reader approximately 30 cm from the animal. The antenna has been found to sufficiently detect a benthic PIT-tagged species, the Mottled Sculpin *Cottus bairdii* (Cope, 1872), which is strongly associated with rock cover (Kelly et al., 2017). Cross-channel paths (i.e., left bank to right bank) were conducted in a zig-zag motion across the wetted width of the stream at each tagging site to track the PIT-tagged individuals. These paths were done continuously until all fish were accounted for, or the detection reach was covered (≈500 m) at each tagging site. The paths did not overlap and there was <0.15 m between each of the individual paths. Each time a PIT-tagged fish was located a weighted fluorescent marker was placed to identify the point of detection. To determine if the "detection" was from a live fish, we used visual confirmation to determine that the PIT-tagged fish was still alive (i.e., gill or body movement observed) and that the PIT tag had not been lost. The corresponding geolocation of the "detected" Sickle Darter was recorded. The detection locations were marked so that microhabitat and environmental data could be collected for each detected individual.

Environmental and Habitat Variables

Microhabitat characteristics were measured within a 2-m^2 area around the weighted marker (Table 1). These data included canopy cover (%), dissolved oxygen (mg/L), pH, stream depth (m), stream wetted width (m), water temperature (°C), water velocity (cm/sec), and percentage of substrate types (e.g., gravel, sand). Dissolved oxygen and water temperature data were collected with a Pro20 Dissolved Oxygen Meter. The pH data were collected with an Oakton PCSTestr 35 pH tester. Stream depth data were collected with a Keson 50-m field-measuring tape. Water velocity data (cm/sec) were collected using the neutrally-buoyant object method, whereby a floating perforated plastic ball was timed as it drifted the 2-m distance at the area of detection (distance traveled/time). This was done three times total to get an estimate of mean water velocity for the area of detection. Substrate data were collected by visually determining the percentage of each substrate (sand/silt, gravel, cobble, and boulder) at each detection location within the 2-m^2 detection area. Other environmental data were collected daily throughout the study for the Emory River watershed, and these data included discharge (m^3/sec) from the U.S. Geological Survey (USGS) gauge # 03540500 at Oakdale, TN, precipitation (cm), and photoperiod (hours) from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (2020) climate station GHCND: USW00053868 at Oak Ridge, TN. Water temperature (°C) data were collected every hour using two Onset HOBO temperature loggers, with one deployed at the Rock Creek site and another deployed at the upper Emory River site.

Data Analyses

Sickle Darter movement data were analyzed in multiple ways. Movement was characterized by estimating detection (0-1; Hubert and Fabrizo, 2007). Logistic regressions were run to assess the temporal relationship of detection throughout the study. To determine the spatial movement of Sickle Darters, geolocations were plotted in ArcMap (ESRI, 2020), and the point-distance function was used to get an estimate of distance (m) between detection points from tracking events. This was done for every tracking point for each tagged fish, such that distance moved was determined by calculating distanced moved from the most previous tracking event. Mean movement distance (±SD) was calculated for each tracking event. Furthermore, we determined the frequency of upstream and downstream movement throughout this study. A two-tailed Kolmogorov-Smirnov test was used to assess if frequency of Sickle Darter movement upstream or downstream was distributed equally. We estimated a total frequency of substrate use during each tracking event. We assessed the relationship of time on total frequency of substrate with a simple linear regression. An ANOVA was run followed by a post-hoc Tukey test to determine if significant differences of darter substrate-type use existed between tracking events. Statistical significance for all analyses were evaluated at an alpha = 0.05, and all analyses were completed in R (R Core Team, 2020; Zar, 1999).

We modeled the mean movement distance of Sickle Darters against the various temporal environmental and microhabitat variables. We did this by using best-subsets regression modelling, a form of multiple regression (Zar, 1999). We chose best-subsets regression modelling because the data were structured in a quantitative manner, that is, response and predictor variables were continuous. We also chose to use best-subsets regression modeling because it is an efficient method to test all possible combinations of the predictor variables (MacNally, 2000). Mallow's Cp and Adjusted R^2 were used to assess model fit at each temporal scale (7-day, 3-day, 1-day). We chose these temporal scales to capture delayed effects on Sickle Darter movement. Further, we used corrected Akaike information criterion (AIC_c) to determine the number of models to interpret at each spatial scale and the best model in each model group. Corrected Akaike information criterion was used to account for the small samples size used in our analyses. At each spatial scale, all models with ΔAIC_c value ≤5 were interpreted further (Akaike, 1973; Burnham & Anderson, 2004; Symonds & Moussalli, 2011; Liao et al., 2018). We further interpreted our best models at each spatial scale by assessing model fit with Analysis of Variance. To minimize effects of multicollinearity, variables with VIF <4 were interpreted further in the analysis of variance.

To estimate the home range (90% of contour) and the core range (50% of contour) for each PIT-tagged Sickle Darter, the kernel density tool was used in ArcMap (ESRI, 2020). The Fish Tracker tool in ArcMap was used to smooth out the home range estimates and make them fit the actual riverine system where this study took place (upper Emory River watershed; Laffan & Taylor, 2013). This tool applies the home range estimate to a more fish-like habitat (rivers), by making the estimate fit the aquatic environment more, compared to estimates of home range for terrestrial species (Laffan & Taylor, 2013). Total and median home range size (m^2) for each PIT-tagged Sickle Darter was estimated. Area of home rage was estimated rather than the linear home range because the estimates of home range were on such a small scale. We assessed the relationship of size (total length in mm) of PIT-tagged fish on home range with simple linear regression modeling.

Results

A total of eight Sickle Darters were tagged on two different dates. At the Rock Creek site, six individuals were tagged, and two individuals were tagged at the upper Emory River site. On the first tagging date (09/27/2019) there was an initial tagging mortality rate of 25% (1 of 4 fish). One fish died after being tagged, but this fish was small in comparison to other PIT-tagged fish (56 mm) and showed signs of stress immediately after capture and prior to tagging. On the second date (11/16/2019), there was an initial tagging mortality rate of 0%. The mean (±SE) size of all PIT-tagged fish was 70 (±4.1) mm and 3.1 (±0.5) g.

A total of 10 tracking events were conducted. Our study was cut short due extreme water flows that seemed to displace Sickle Darters outside of our detectable range or cause mortality. In February of 2020 the Emory River experienced a record flood event (2089 m^3/sec at the USGS Gauge at Oakdale, TN on 02/06/2020). Sickle Darter movement declined throughout out the study (linear regression, F=2.08, df=8, P-value = 0.03, R^2=0.21; Fig. 2). Our detection of Sickle Darters also declined significantly throughout the study (logistic regression, β=-31.92, odds ratio=<0.01 P-value=<0.01). Like detection, this was likely caused by the high flow event. The frequency of Sickle Darter movement downstream or upstream from its capture site was not significantly different (D= 0.19, P-value= 0.88; Fig. 3). There was no significant relationship between time and the four substrate types utilized at each detection location during each tracking event (sand: 1.28, df=7, P-value= 0.30, R^2= 0.18; cobble: 2.02, df= 7, P-value= 0.21, R^2= 0.25; boulder: 0.11, df=7, P-value= 0.76, R^2= 0.02; gravel: 1.11, df=7, P-value= 0.33, R^2= 0.16). An ANOVA with post-hoc tukey test was not utilized because there were no significant relationships. Nevertheless, sand and cobble were utilized the most throughout the study (Fig. 4).

There was little variation in the relationship between environmental variables and Sickle Darter movement across the three temporal scales. At the 1-day temporal scale, the top 5 best-subsets models associated with movement included median daily discharge, precipitation, and daily temperature change, with the model including median daily discharge being the best model (6.14 AIC_c; Table 1). However, models that included median daily discharge and precipitation (7.80 AIC_c), daily temperature change (7.83 AIC_c), and precipitation (7.90 AIC_c) fit the data well. At the 3-day temporal scale, the top 5 best-subsets models included median daily discharge, daily temperature change, mean daily temperature, and precipitation, with the model including median daily discharge being the best model (6.14 AIC_c; Table 1). However, models that included daily temperature change (5.95 AIC_c), mean water temperature (6.11 AIC_c), and precipitation (6.16 AIC_c) also fit the data well. At the 7-day temporal scale, the top 5 best-subsets models included median daily discharge, daily temperature change, mean daily temperature, and precipitation, with the model including median daily discharge being the best model (8.39 AIC_c Table 2). However, models that included median daily discharge and precipitation (8.44 AIC_c), and mean daily temperature change, mean daily discharge, and precipitation (9.41 AIC_c) also fit the data well. The top models from each scale and predictor variables were retained for interpretation because they met criteria for further interpretation analyses (Table 2). At the 1-day temporal scale, the median daily discharge was negatively associated with Sickle Darter movement, but this relationship was not statistically significant ($t = -1.88$; P-value = 0.16). At the 3-day temporal scale, the median daily discharge was negatively associated with Sickle Darter movement, but this relationship was not statistically significant ($t = -1.82$; P-value = 0.14). At the 7-day temporal scale, the median daily discharge was negatively associated with Sickle Darter movement and was statistically significant ($t = -6.51$; P-value =<0.01). No other model variables aside from median daily discharge had a VIF <4, so they were not considered further in the analysis of variance.

Sickle Darter home range size varied individually (Fig. 5). Only PIT-tagged fish from Rock Creek were considered for the home range analyses. The median (min.-max.) size of home ranges was 157.5 (86.0-312.5) m^2. There was no significant relationship between PIT-tagged fish size and home range size (5.05, df=5, P-value = 0.09, R^2=0.56; Fig. 6).

Discussion

Sickle Darter movement varied temporally during our study, but overall, they moved very little from a spatial context. Thus, it is likely that Sickle Darters exhibit high site fidelity in this river system, especially during average to low discharge. Prior to this study, there was anecdotal evidence suggesting that Sickle Darters in Little River (Tennessee, USA) move to deep pools during the winter months and to shallow gravel riffles to spawn in the spring (Etnier & Starnes, 1993; J.R. Shute, personal communication). However, the movement of Sickle Darters in the Emory River system may be different compared to that in the Little River. The Little River is considered a small to medium-sized river, and it has a mosaic of heterogenous riverine features, such as riffles, runs, and pools with highly variable depths and substrates. The upper Emory River system, on the other hand, consists of short and few riffles with shallow pools and runs (<1 m deep) and a relatively homogeneous mix of sand, silt, and cobble substrates. The riverine features of these two systems, and amount of available habitat may influence the extent to which individuals from these two fragmented populations move. Other studies on darter movement have found different results pertaining to the distance moved by darters (Roberts & Angermeier, 2007; Roberts et al., 2008; Holt et al., 2013; Baxter, 2015; Hicks & Servos, 2017). Roberts et al. (2008) found that the Roanoke Logperch, *P. Rex,* exhibited high site fidelity throughout their tagging study. Holt et al. (2013) and Hicks & Servos (2017) found that the Brown Darter *E. edwini* (Hubbs & Cannon, 1935) and Rainbow Darter *E. caeruleum* (Storer, 1845), respectively, exhibited high site fidelity throughout their tagging studies. In contrast, the Blackbanded Darter, *P. nigrofasciata* (Agassiz, 1854), a species more ecologically and phylogenetically like the Sickle Darter, was found to move farther distances (max distance moved of 420 m) than what we report for the Sickle Darter (Freeman, 1995). These differences may be due to the shifting sandy bottom streams that Blackbanded Darters occupy in coastal plain ecoregions, compared to Sickle Darters which are found in more interior mountain streams. Baxter (2015) found that Kentucky Arrow Darters can move a large distance as well, with some individuals moving up to 4 km. Thus, differences in movement of darters are probably due to a multitude of factors, dependent on species and location (i.e., stream type). Unfortunately, our study was cut short due record flooding in the Emory River, which resulted in displacement of PIT-tagged individuals outside of our detectable range or caused mortality due to the high flow event. This prevented us from observing Sickle Darter movement during the spawning season of this species (late February to early April; Etnier & Starnes, 1993). A new movement study should be completed to observe how this species moves on an annual basis to encompass the spawning season and summer months which we failed to observe in our study. Further studies should also consider how the movement of this species potentially varies in other rivers within its range. There are three remaining viable populations of Sickle Darters (Hecke & Alford, 2021) in the upper Emory River sub-basin, Little River sub-basin, and Middle Fork Holston River sub-basin. It is possible that Sickle Darters move differently in these sub-basins due to each sub-basin's unique riverine features, size, and amount of available habitat (Ward, 1998). These populations are separated by dams and their impoundments. Because we found that Sickle Darters exhibit high site fidelity, it may be unlikely that these populations would mix because of dispersal.

Sickle Darter movement can be linked to changes in discharge. We found that discharge, no matter the temporal scale, had a negative influence on Sickle Darter movement. However, we did observe that discharge over 7 days prior to tracking appears to be more important than discharge for 3 days and 1 day prior to tracking. In response to changes in discharge, Sickle Darters appeared to move less when there is increased variation in discharge. Albanese et al. (2004) found that flood events can strongly affect the movement of small-bodied stream fishes, which further supports our findings that Sickle Darter movement is linked to discharge. Other studies have found that darter movement is related more to the amount of available habitat and multiple environmental characteristics within a specific river. (Roberts & Angermeier, 2007; Roberts et al.2008). Mundahl & Ingersoll (1983) found that the Johnny Darter *E. nigrum* (Rafinesque, 1820) and Fantail Darter *E. flabellare* (Rafinesque, 1819) movement during fall months was driven by population density and quality of habitat. Baxter (2015) found that there was very little seasonal effect on the movement of Kentucky Arrow Darters. We observed a significant change in water temperature in our study, but this variable was not a significant driver of Sickle Darter movement. If tracking could have been conducted for a full year, then water temperature may have been identified as an influential variable on Sickle Darter movement. We were only able to track Sickle Darters during fall and winter, when water temperature may not be as important as during the spring spawning season. Future studies should look at the potential relationship of Sickle Darter movement throughout a complete seasonal cycle to determine if water temperature plays a significant role in the movement of this species.

Microhabitat utilized by Sickle Darters throughout this study remained constant. Sickle Darters were found to inhabit the same substrate frequency at each detection site during each tracking event (i.e., sand and cobble). Other studies on darter movement have found varying results. Skyfield et al. (2008) found sex-linked differences in microhabitat use by the Gilt Darter *P. evides* (Jordan & Copeland, 1877). We did not distinguish between male and female individuals in our study. Future studies should consider this component when looking at the movement of the Sickle Darter, but males do not exhibit sexual dimorphism like most darter species, thus a sex-specific study would be challenging. Holt et al. (2013) found that Brown Darters did not move to different microhabitats, but rather moved to different areas of the river that had the same available microhabitats. Baxter (2015) also found that Kentucky Darters did not move between microhabitats, but rather moved to different areas where the preferred microhabitat was available. Freeman (1995) found that the Blackbanded Darter moved across different habitats to reach a desired microhabitat. The section of Rock Creek where we observed Sickle Darter movement is not comprised of a mosaic of habitats, and habitat is homogenous, consisting primarily of cobble and sand substrates and shallow pools.

Sickle Darter (adult) home ranges are relatively small compared to many other freshwater fish species (Minns, 1995). There have been very few home range studies on darters, but home range of small-bodied stream fishes appears to be small (Gerking, 1953; Winn, 1958; Hill & Grossman, 1987; Rakocinski, 1988; Freeman, 1995; Minns, 1995; Hicks & Servos, 2017). Hicks & Servos (2017) found the Rainbow Darter *E. caeruleum* had a very small home range (median = 5 m) and remained in the same riffle in which they were tagged. This is similar to our results, where Sickle Darters had a small home range and were found in the same habitat type over time. Winn (1958) estimated the food, reproductive, and escape range (all of which comprise the home range) for 10 species of darters in rivers and reservoirs, finding that home range was very small (< 5 m) for each species. However, these estimates of home range were based off visual observations, and no tagging or mark-recapture study was conducted to quantitatively determine home range. Scalet (1973) found that Orangebelly Darters *E. radiosum* (Moore &

Rigney, 1952) appear to have a small range but did not estimate actual size of this species' home range. Compared to other benthic species, like the European Sculpin (45-m^2 home range) and the Banded Sculpin *C. carolinae* (Gill, 1861; 47 m^2), the home range of the Sickle Darter is substantially bigger (Greenberg & Holtzman, 1987; Downhower et al., 1990; Minns, 1995). This study outlines a method to estimate the home range of darters and other rare, benthic, and small-bodied fish species and it may also facilitate/inspire future tagging studies on imperiled small-bodied fishes. Future research should consider how Sickle Darter home ranges vary from sub-basin to sub-basin.

Our study suggests that an interesting relationship exists between hydrology and Sickle Darter movement. Future research should explore this relationship by assessing this species' critical swimming speed in the presence and absence of refugia (habitat complexity; Scott & Magoulick, 2008). This will help biologists and researchers understand what happens to the Sickle Darter during high flow events. Further, this will also help shed light on the functional organization of this species within the fish assemblage (Poff & Allan, 1995). With a more variable environment (more frequent high flow events) being a likely result of climate change, understanding the hydrologic and climatic factors that negatively affect populations of Sickle Darters will be key to the preservation of this rare fish (Ficke et al., 2007; Hecke & Alford, 2021). Future research should consider the movement of Sickle Darters on a smaller temporal scale. We only assessed Sickle Darter movement every ~2 weeks between tracking events, this may have caused us to underestimate how much Sickle Darters move. Future movement studies based on PIT tagging, should consider using flatbed (streambed) arrays to detect PIT-tagged fish, this would allow for fine scale (daily) and more estimates of Sickle Darter movement, rather than the portable antenna that we used in this present study (Johnston et al., 2009).

PIT tagging of rare, small-bodied fish like darters, is possible and yields a high PIT-tag retention and tagging-survival rate. This study outlines a way to conduct movement studies on similar small-bodied imperiled fishes. We experienced a low tagging-mortality (~14%), and tag loss (0%) throughout this study, which is supported by other PIT-tagging studies on other small benthic fish species (Baxter, 2015; Knaepkens et al. 2017). Baxter (2015) observed similar results with tagging-mortality (none reported) and tag loss (0%) on the Kentucky Arrow Darter. Ideally, we would have retained individuals outside of our actual study and monitored PIT-tag retention and mortality through a pilot study, but due to the rareness (proposed for federal listing; USFWS, 2011) of the Sickle Darter, we were unable to collect a large number of fish to support such a study. Nonetheless, we did find that Sickle Darters ≥ 55 mm can support PIT tags. This is supported by Baxter (2015), who suggest that larger individuals of a darter species should be able to support PIT tags. This leads to higher tag survival and retention rates. Knaepkens et al. (2017) PIT-tagged European Bullheads (50-94 mm) and found relatively low tagging mortality (~10%), which further supports the premise that larger specimens of small-bodied fish can be PIT-tagged.

Our study provides further knowledge to the understanding of Sickle Darters. Adding to our knowledge base of Sickle Darters will be important for the future of this species as it was proposed federal listing under the U.S. Endangered Species Act (US, 1973; TWRA, 2015; VDWR, 2015; USFWS, 2011). This species is considered an imperiled species due to anthropogenic factors in the upper Tennessee River basin, particularly habitat fragmentation from dams and other environmental disturbances (Hampson et al., 2002; Jelks et al,.2008; Angermeier & Pinder, 2015; Hecke and Alford, 2021) This study developed further research questions for this species which should be addressed when considering how to preserve the Sickle Darter. However, our study found that Sickle Darters exhibit high site fidelity. This is likely to prevent them from recolonizing habitat that become reconnected due to dam removal and improved/mitigated river operations.

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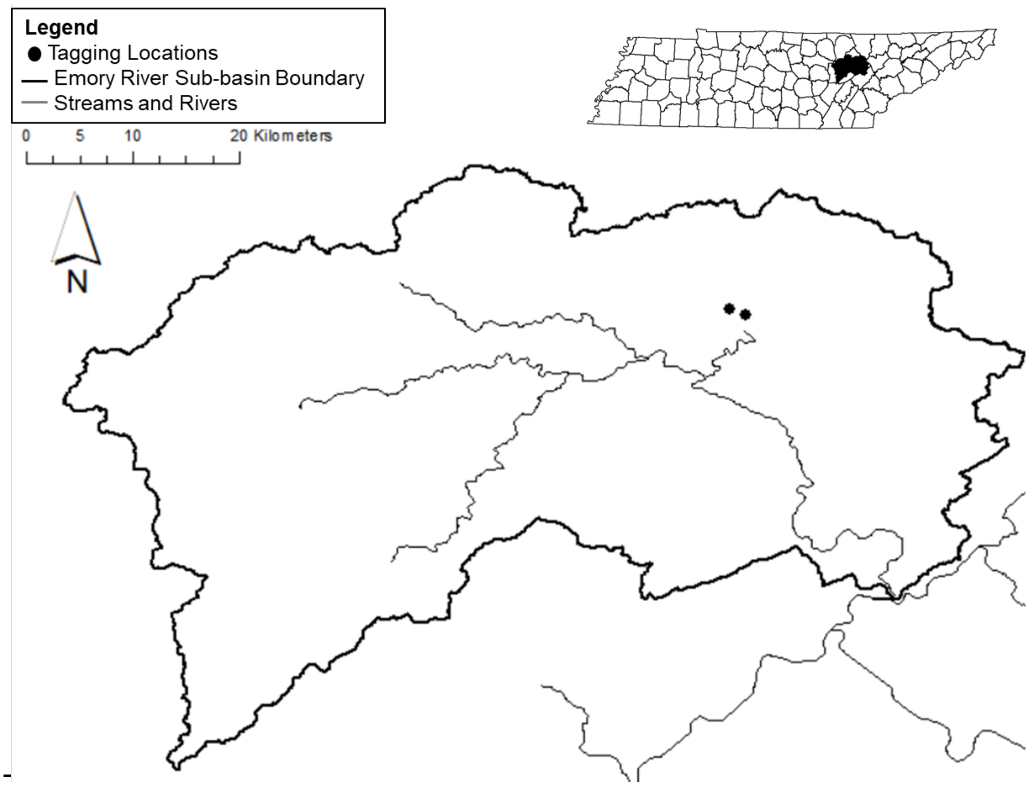

Fig. 1 The Emory River sub-basin. The black circles signify the two tagging locations used in this study.

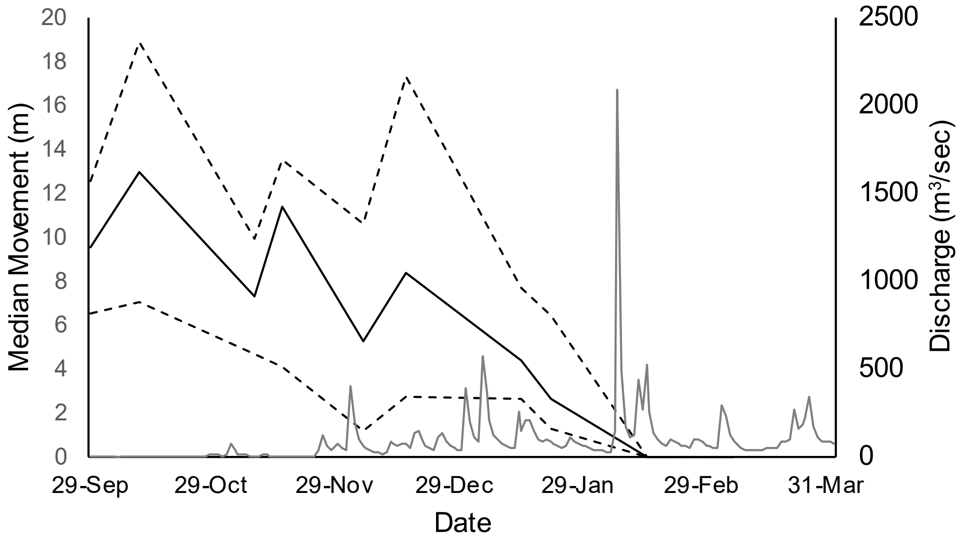

Fig. 2 The median (solid black line) movement (m), minimum and maximum movement (dotted black line) of PIT-tagged Sickle Darters in relation to discharge (observed throughout the study.

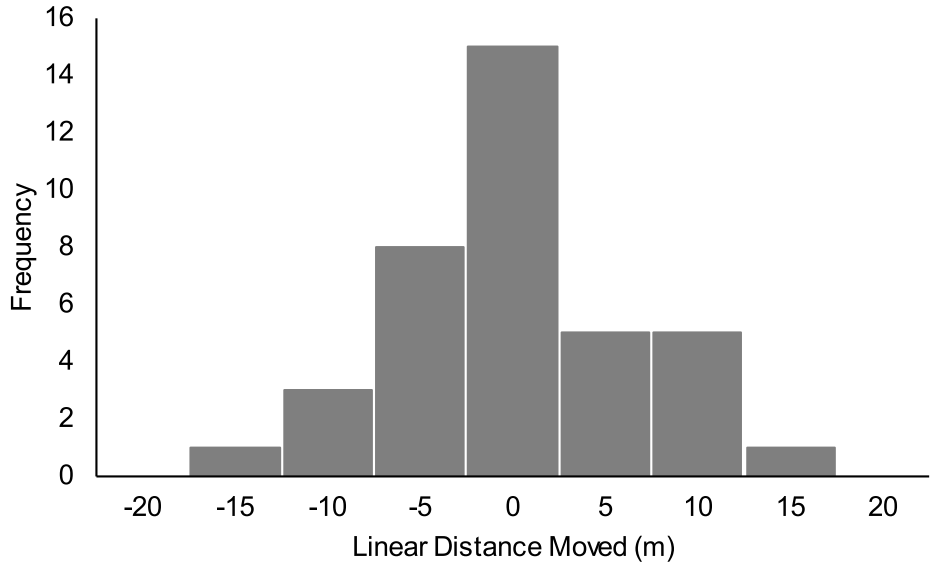

Fig. 3 The frequency of movement upstream (positive) and downstream (negative) by PIT-tagged Sickle Darters throughout the study.

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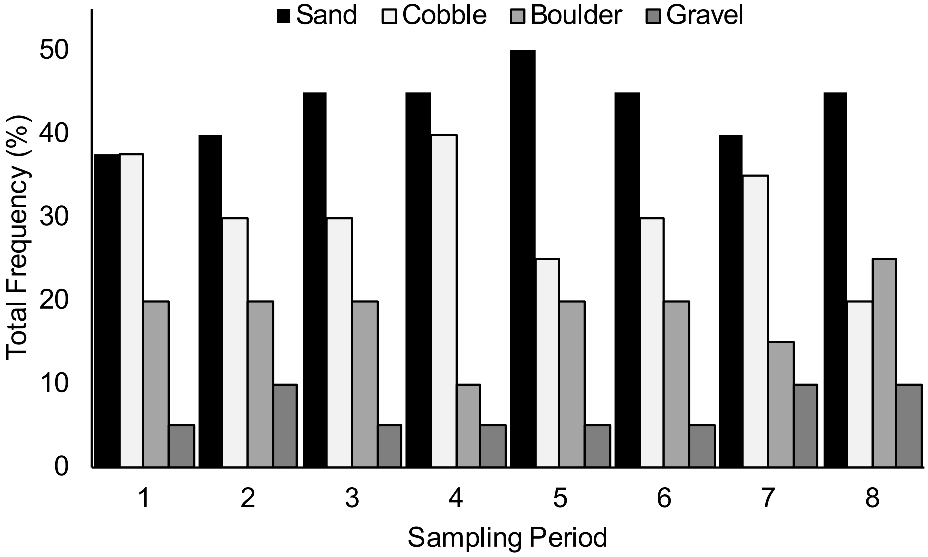

Fig. 4 Estimates of the total frequency of substrates during each of the 8-tracking periods.

Table 1 Results of best subsets multiple linear regression modeling as a variable selection procedure for movement (response variable) by the Sickle Darter in the upper Emory River sub-basin at three temporal scales (1-day, 3-day, 7-day). The top 5 models are shown that achieved the lowest AIC$_c$, lowest Mallow's C*p* statistic, and highest adjusted R^2. Variables retained for interpretation had variance inflation factors (VIF) < 4.0. Assumptions of regression analysis were met by the top model. Discharge = median discharge, Precip = total precipitation, DailyTempChange = daily temperature change, MeanWaterTemp = mean water temperature

Variables included in Model	AIC$_C$	ΔAIC$_C$	Mallows' C(*p*)	Adj. R^2	Number of Model Parameters
1-day					
Discharge	6.14	0.00	1.92	0.39	1
Discharge, Precip	7.80	1.66	2.13	0.58	2
DailyTempChange	7.83	1.69	5.04	0.07	1
Precip	7.90	1.76	5.19	0.05	1
DailyTempChange, Discharge	8.73	2.59	2.65	0.52	2
3-day					
Discharge	4.76	0.00	0.00	0.38	1
DailyTempChange	5.95	1.20	2.59	-0.03	1
MeanWaterTemp	6.11	1.35	2.99	-0.09	1
Precip	6.16	1.40	3.13	-0.11	1
Discharge, Precip	7.00	2.24	1.35	0.37	2
7-day					
Discharge	8.39	0.00	11.88	0.69	1
Discharge, Precip	8.44	0.05	3.42	0.89	2
DailyTempChange, Discharge, Precip	9.41	1.03	3.03	0.94	3
DailyTempChange, Discharge	11.10	2.72	11.17	0.74	2
Discharge, MeanWaterTemp	11.24	2.85	11.79	0.73	2

Table 2 Analysis of variance results for best subsets MLR for movement (response variable) by the Sickle Darter across 3 temporal scales (1-day, 3-day, 7-day). Results shown are for the best model from Table 2. Root MSE= root mean square error, Stand. B_i = standardized beta coefficient, VIF = variance inflation factor. The +/- sign for t-value indicates the direction of the association between the environmental covariate and distance of stream occupied. Discharge =median discharge.

Models: Temporal Scale	Variable	t-value	P-value	Stand. Bi.	VIF
1-day					
Root MSE=2.36					
	Intercept	2.72	0.05	0.00	0.00
	Discharge	-1.82	0.14	-1.08	3.44
3-day					
Root MSE=7.21					
	Intercept	0.66	0.56	0.00	0.00
	Discharge	-1.88	0.16	-1.11	2.65
7-day					
Root MSE=1.09					
	Intercept	2.01	0.140	0.00	0.00
	Discharge	-6.51	<0.01	-1.44	2.51

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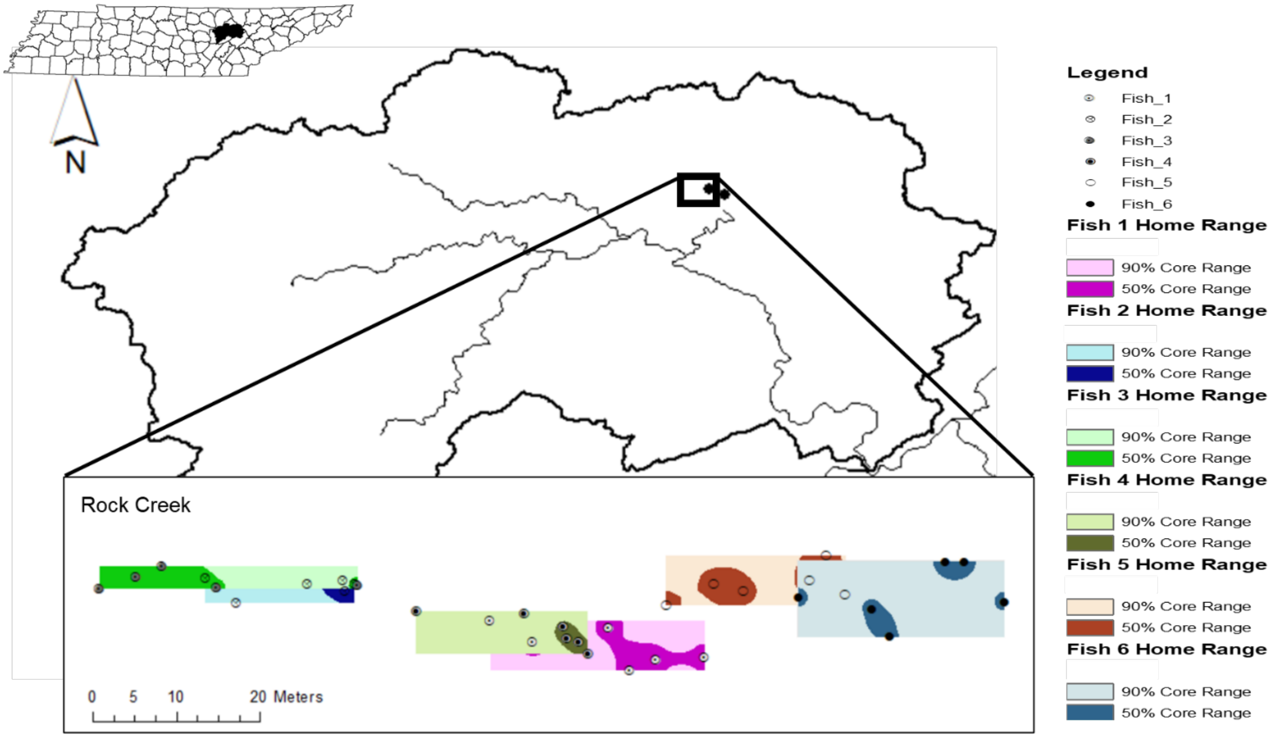

Fig. 5 The home range estimates for the 6 PIT-tagged fish from the Rock Creek site. Each fish's home range displays the 90% core range and 50% core range.

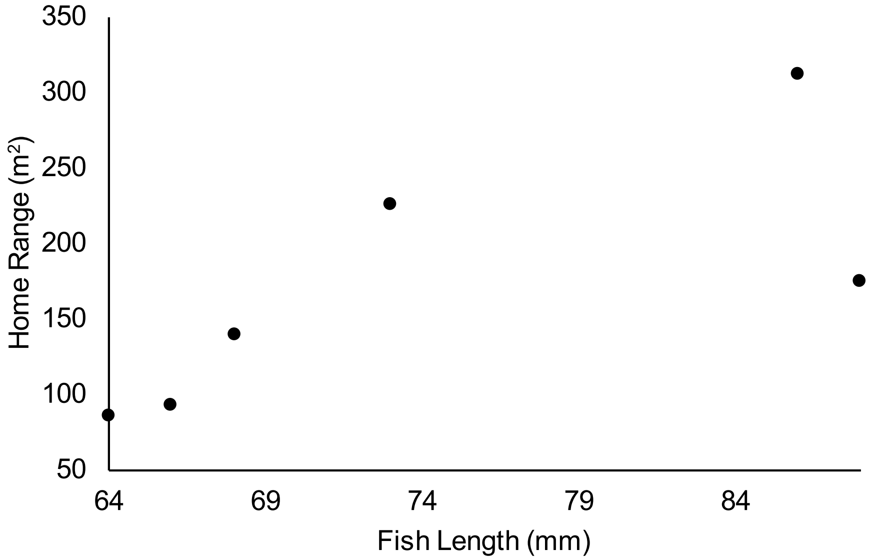

Fig. 6 Plot of estimated home range (m^2) and PIT-tagged fish size (mm).