AN ABSTRACT OF A THESIS

EVALUATING THE SPAWNING HABITAT AND CUMULATIVE EFFECT OF CATCH AND RELEASE FISHING MORTALITY OF SAUGER IN OLD HICKORY LAKE, TENNESSEE

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Master of Science in Biology

Humans can radically alter aquatic ecosystems directly and indirectly. Fragmentation of river systems via the construction of dams affects the ability of migratory fish to move throughout a system and can hamper their ability to spawn. Overexploitation of fish stocks, especially when they congregate below dams, can result in recruitment overfishing where harvest exceeds the ability of a stock to replenish its numbers. Restoration of fisheries should focus on the anthropogenic influences that preceded their decline. Sauger *Sander canadensis* in the tailwaters of several Tennessee impoundments represent the largest percid fisheries in the southeast USA. However, declining Sauger populations have been evident since historical spawning migrations were blocked by dams; and little is known about current spawning areas in the Cumberland River. Additionally, Sauger were seasonally vulnerable to anglers in tailwaters; and it is important to evaluate the population-level effects of catch-and-release (CR) mortality. The objectives of this research were to (1) describe the spawning migration of Saugers in the Cumberland River, and (2) estimate the instantaneous rate of CR and harvest mortality. To assess spawning movements, Saugers were implanted with radio transmitters in January 2014 and tracked weekly throughout the spawning season. To estimate the instantaneous mortality rate associated with CR fishing, Saugers implanted with radio transmitters were also tagged with an external high-reward Floy ($100) tag, and the reporting rate was assumed to be 100%. Telemetry relocations in conjunction with tag-return data allowed for the estimation of catch rates, release rates, and CR mortality for released fish. The monthly instantaneous mortality rate was 0.11, which represented one natural mortality, one harvest mortality, and two fish that died of CR mortality. Therefore, the instantaneous monthly natural mortality rate was 0.031, fishing harvest mortality rate was 0.035, and CR fishing mortality rate was 0.041. The weekly instantaneous emigration rate was 0.02, and their movements downstream and out of the tailwater began after water reached 10°C.

EVALUATING THE SPAWNING MIGRATION AND CUMULATIVE EFFECT OF CATCH AND RELEASE FISHING MORTALITY OF SAUGER IN OLD HICKORY LAKE, TENNESSEE

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CHAPTER 1

INTRODUCTION

Humans can radically alter aquatic ecosystems directly and indirectly. Fragmentation of river systems via the construction of dams affects the ability of migratory fish to move throughout a system (Pracheil et al. 2012) and can hamper their ability to spawn. Overexploitation of fish stocks, especially when they congregate below dams, can result in recruitment overfishing where harvest exceeds the ability of a stock to replenish its numbers (Coggins et al. 2007). Restoration of fisheries should focus on the anthropogenic influences (e.g., habitat degradation and loss; overfishing) that caused their decline (Raabe and Hightower 2014). Therefore, it is important to understand to what extent (if any) these influences are affecting fish populations in order to manage fisheries appropriately.

Saugers *Sander canadensis* in the tailwaters of Tennessee impoundments represent the largest percid fisheries in the southeast USA (Hackney and Holbrook 1978). However, declining Sauger populations have been evident since the mid-1980s (Pegg et al. 1996). As a result, the Tennessee Wildlife Resources Agency (TWRA) annually stocks Sauger in mainstem reservoirs to augment recruitment which fluctuates widely from year to year (Fischbach 1998). Variable recruitment by Saugers in Tennessee has been linked to February-April discharge and the number of fingerlings stocked (Fischbach 1998). Because discharge varies among reservoirs, mainstem reservoirs in the same river systems will not necessarily experience similar recruitment in the same years. Therefore, increasing recruitment via supplemental stocking makes fishable stocks less sensitive to missing year classes (Chevalier 1977). Although hatchery-reared fish may augment natural recruitment, they may negatively affect genetic diversity (Vidargas 2009).

Sauger often travel hundreds of km to reach their spawning grounds and they are the most migratory of all percids (Scott and Crossman 1973; Collette et al. 1977; Pegg et al. 1997; Kuhn et al. 2008; Bozek et al. 2011). Unfortunately, spawning habitats and migrations have been severely altered by dams (Bozek et al. 2011) and each winter and spring Saugers congregate below dams where their migration paths are blocked (Pegg et al. 1997). At water temperatures of about 10 °C, Sauger attempt to find suitable spawning habitat in the tailwaters (e.g., rocky shoals and cobble substrate; Priegel 1969; Walburg 1972; Hackney and Holbrook 1978; Pitlo 2002). After spawning, Saugers return to the main basin of the reservoir (Walburg 1972; Pegg et al. 1997). Although Saugers are capable of spawning in tailwaters (Priegel 1969; Walburg 1972; Pitlo 2002), exactly where spawning takes place in some Tennessee reservoirs, such as Old Hickory Lake, is unknown. Spawning migrations of Saugers in Tennessee were last researched by Pegg et al. (1997) in Kentucky Lake on the lower Tennessee River. That research revealed that some Saugers passed upstream through the navigation locks at Pickwick Dam but most remained in the tailwater throughout the spawning season. Those authors used radio-telemetry to identify three areas as possible spawning grounds in the tailwaters of Pickwick Dam.

Estimating mortality is an important aspect of fisheries management. Total instantaneous mortality (Z) of a population is the sum of natural mortality (M) and fishing mortality (F). There are several fisheries-based approaches for estimating total mortality (e.g., catch-curve analysis, mark-recapture studies), but differentiating between natural and fishing mortality is difficult. Given that Z=F+M, researchers often measure Z and F and assume the difference to be M. Unfortunately, this approach results in a biased estimate of M given its dependence on F (Miranda and Bettoli 2007), prompting methods that independently estimate natural and fishing mortality (Thompson et al. 2007; Pollock et al. 2011; Topping and Szedlmayer 2013).

Since the late 1990s the use of telemetry to monitor the long-term fate of fish in terms of natural mortality and discard mortality has become common (Donaldson et al. 2008). Studies typically involve externally tagging or implanting fish with transmitters and manually tracking them over long periods of time (6–24 months). Using telemetry in aquatic systems is more difficult than in terrestrial systems because the telemetered individual cannot be directly observed once it is located. Consequently, its status (i.e., alive; dead; tag loss) has to be inferred by their movement, or lack thereof (Hightower et al. 2001; Kitterman and Bettoli 2011). Modern telemetry equipment and advanced analytical techniques have permitted researchers to distinguish natural mortality from fishing mortality in some instances (Thompson et al. 2007).

Fishing mortality is perhaps the most critical aspect of the population dynamics of exploited stocks. Fishing mortality includes fish that are harvested (F_H) and fish that die following catch-and-release (CR) fishing (i.e., discard mortality or hooking mortality). There are three types of CR mortality (Pollock and Pine 2007). Immediate mortality occurs when the individual dies after being landed and prior to release. Short-term mortality refers to fish that die within 24–72 h post release. Delayed or cryptic mortality occurs when a fish dies more than 72 h post release. Immediate and short-term mortality have received much attention in the past due to the relative ease by which they can be measured. Such research typically involves holding fish in captivity post-capture to monitor their fate over a short period of time (e.g., Meerbeek and Hoxmeier 2011). However, this type of study design can bias estimates of CR mortality for free-ranging fish because it does not consider indirect effects such as increased predation following CR, nor the confounding effect of confining fish to cages, which can increase mortality (Udomkusonsri and Noga 2005; Pollock and Pine 2007). Delayed mortality has received less attention until recently due to the difficulty and expense of this type of research, but advances in telemetry receivers and transmitter tags have made this area of research more commonplace in recent years. Yet, the use of telemetry to monitor fate has its short comings. Determining mortality relies on repeated observations of the lack of movement of an individual and its fate is often unknown until multiple relocations are observed after death, demanding the use of decision rules to define life or death (Hightower et al. 2001). Additionally, mortality estimates rely on the assumption that a given death was not influenced by the presence of the transmitter. As a result, advanced surgical techniques and aseptic tools are used to avoid compromising the health of individuals (Burger et al. 1994; Mulcahy 2003; Wagner and Cooke 2005). Despite some caveats, telemetry methods are rapidly gaining acceptance as the best method of estimating CR mortality (Coggins et al. 2007; Pollock and Pine 2007; Thompson et al. 2007; Donaldson et al. 2008; Kerns et al. 2012).

Many studies have estimated F_H and CR mortality (e.g., Muoneke and Childress 1994; Bartholomew and Bohnsack 2005), but few studies have estimated instantaneous CR mortality rates (F_{CR}). Kerns et al. (2012) highlighted the importance of assessing the population-level effect of CR mortality by recognizing the distinction between F_{CR} and CR mortality. Catch-and-release mortality is the proportion of fish that die after being caught and released; whereas F_{CR} is the instantaneous fishing mortality *rate* associated with CR fishing (Kerns et al. 2012). Estimating F_{CR} incorporates immediate (prior to release), short-term (24–72 h), and delayed mortality (>72 h) as one estimate of CR mortality. For some fisheries, F_{CR} can be a large component of F if: 1) CR mortality is high; 2) the fishery is especially vulnerable on a seasonal basis; or 3) regulations protect a large portion of the stock and force anglers to release many of the fish they catch. Catch-and-release fishing can still be problematic even if CR mortality is low. For example, a reduced creel limit and a high size limit caused release rates of Common Snook C*entropomus undecimalis* in Florida to triple in less than a decade and even though CR mortality was only 3%, the cumulative effect on F_{CR} was high (Muller and Taylor 2006). Measuring F_{CR} for Sauger stocks in Tennessee reservoirs will aid in understanding stock status, evaluating current harvest regulations, and managing fisheries exposed to high release rates such as Sauger (Kerns et al. 2012).

The objectives of this research were to: 1) describe the spawning migration of Sauger in the Cumberland River using radio telemetry; and 2) estimate the instantaneous catch-and-release mortality rate of Sauger using high reward tags in conjunction with radio telemetry.

CHAPTER 2

STUDY AREA

Old Hickory Lake (OHL) is a mainstem reservoir located on the Cumberland River in middle Tennessee (Figure 1). Old Hickory Dam is managed by the U.S. Army Corps of Engineers and is located at Cumberland River km (CRkm) 347.9. At full pool (135.6 msl) Old Hickory Lake has a surface area of 9,105 ha. Cordell Hull Dam (CRkm 504.5) represents the upper boundary of OHL and is also managed by the U.S. Army Corps of Engineers. This dam was completed in 1973 to provide navigation, hydropower, and recreational benefits. Cordell Hull Dam has three turbines producing 350 million kW annually and at maximum generation they discharge approximately 900 cms. The Caney Fork River, a major tributary of the Cumberland River, enters the Cumberland River 6 km below Cordell Hull dam.

CHAPTER 3

METHODS

Fish Collection and Tag Implantation

Thirty Saugers were implanted with radio transmitters on January 14 and16, 2014. Saugers were collected from the upper reaches of OHL directly below Cordell Hull dam where they congregate in the winter months (Churchill 1992). Sinking monofilament experimental gillnets were fished for approximately 30 min at dusk when Sauger movement is thought to be highest (Cobb 1960). Experimental gillnets measured 1.8 x 45.5 m with five 9.1-m panels of 19, 25, 38, 51, and 64-mm (bar measure) mesh sizes.

Saugers were implanted with Advanced Telemetry System (ATS) transmitters; each had a 200-mm whip antenna and broadcast at a frequency between 30.000 and 31.999 MHz. Surgical tools were autoclaved before first-use and soaked in chlorhexidine for 10 min before they were used again. Tag identification, total length (TL), weight, sex (identified through the incision), and surgery duration were recorded for each individual. Because some of the fish were legal to harvest (i.e., longer than the minimum size limit of 381 mm TL), electrical anesthesia (rather than a chemical sedative such as MS-222 requiring a 21-d withdrawal period) was used to sedate all fish. Electrical current was applied to a cradle powered by a low-voltage DC control box. Electrical anesthesia is similar to chemical anesthetics in that fish are sedated physically and physiologically (Madden and Houston 1976; Robb and Roth 2003). Electrical anesthesia has been used to successfully sedate a variety of fish species (Curry and Kynard 1978; Jennings and Looney 1998; Henyey and Kynard 2002; Holbrook et al. 2012). Untreated water was irrigated over the gills of sedated fish. A 20-mm incision was made on the ventral midline anterior of the urogenital pore and posterior to the pelvic girdle. Through this incision, the radio transmitter was inserted. To create an opening for the whip antenna, a hypodermic spinal needle (150; 13-gauge) was used to puncture a hole approximately 10 mm posterior to the incision through which the whip antenna was guided. The wound was closed with three surgeon's knots using size-2 Monocryl Plus (Ethicon) suture. Saugers were held onboard in a live-well 2 h post-surgery to insure that there was no immediate mortality and then released. Seven Saugers netted from OHL in fall 2013 were implanted with dummy tags following the procedures described above and held for 30 d in a hatchery to ensure mortality associated with surgeries was negligible. All seven fish survived the holding period.

Spawning Habitat

Tagged Saugers were tracked weekly from January 30, 2014 to May 11, 2014 in the headwaters of OLH. Each tracking event consisted of traversing 40 km downstream from Cordell Hull Dam, which was the maximum distance that could be traversed by boat in one day. Consequently, when fish were missing it was assumed that they had swum downstream out of the tracking area. Tracking was conducted from a motorboat using an ATS Model R4500 digital scanning receiver and a hand-held directional loop antenna. Fish identity, water depth, water temperature, and GPS location were recorded for each observation.

Mortality

To estimate F_{CR}, Saugers implanted with radio transmitters were also tagged with an external high-reward Floy tag following the methods proposed by Kerns et al. (2012).

Offering a high reward on tags increases the likelihood that a tag is reported once recovered (Pine et al. 2003). Too low of a reward can result in non-reporting or reporting accumulated tags all at once (Pollock et al. 2001). High-reward tagging methods have long been used to achieve high tag-return rates in exploitation studies (Henry and Burnham 1976; Conroy and Blandin 1984; Pollock et al. 1991; Pollock et al. 2002; Meyer et al. 2012). Most research indicated that $100 rewards were needed to maximize return rates (Nichols et al. 1991; Taylor et al. 2006; Meyer et al. 2012). Therefore, in the present study 30 individuals were tagged with $100 (USD) external high-reward Floy tags. Tag-return data on telemetered individuals allowed documentation of catch rates, release rates, and post-release survival rates assuming: 1) 100% tag-reporting rates, 2) 100% tag-retention rates, 3) the sample is representative of the entire Sauger stock, and 4) survival is not affected by the tags. Implanted transmitters offered a $50 reward in the event that a tagged fish was harvested. Floy tags specified "$100 Reward," to ensure that anglers were aware of the high reward amount and reduce the likelihood of a tag not being reported. Furthermore, signs educating anglers of the tagging study were posted at boat ramps and fishing areas near Carthage, Tennessee. Exploitation rates for Saugers in Tennessee reservoirs can be very high (Bettoli 1998) and any Saugers caught over the size limit are invariably harvested (Bettoli 1998), but those fish would not provide any information on F_{cr}.

Data Analysis

Kernel density estimates were used to evaluate Sauger occupancy and were based on weighted residence time. Kernel density estimation (KDE) is a non-parametric approach to estimate the probability density function (pdf) of observed data across space and time. A non-parametric approach is commonly used for biological data because it avoids the constraints of assumptions about the distribution (Seaman and Powell 1996; Vokoun 2003; Cole 2011). I used a Gaussian kernel density estimator:

$$\hat{f}(x) = \frac{1}{nh}\sum_{i=1}^{n} K(\frac{x-X_i}{h}),$$

where *K(x)* is the kernel function which contributes the shape and *h* is the smoothing parameter (or bandwidth) which determines the width of the smooth kernel estimate (Vokoun 2003).

Analyses of telemetry data were restricted to individuals that were still alive two weeks post-surgery to avoid any changes in behavior associated with the capture, surgery, and recovery (Winter 1996; Paukert et al. 2001). Winter samples were defined as December 21-March 20 and spring samples were March 21-June 20 (astronomical seasons). A pooled sample and four composite samples were used to ensure that sample sizes were greater than 30 and trends were portrayed appropriately. Although some research draws inferences on populations based on estimates derived from telemetry relocations, the actual "sampling units" in telemetry studies are the number of fish telemetered (Aebischer et al. 1993; Winter 1996; Otis and White 1999). Therefore, estimates of kernel density in the present study were dependent on preceding and subsequent relocations using least cost-path distance. Although the exact path followed to get from origin to destination is unknown, fish do not move in a straight line (Guy et al.1994), nor do they expend energy for swimming unless necessary. In light of these considerations, Laffan and Taylor (2013) developed a software tool called FishTracker for estimating the geographic areas occupied by animals (i.e., home range), especially for populations restricted by physical boundaries such as cliffs, streams, or unfavorable areas that have high costs (e.g., metabolic, predation, stressful habitat) associated with them such as roads, open fields, or poor water quality.

FishTracker software was used to calculate the least-cost path distance between the origin and destination of telemetered individuals and assigned per-segment occupation times that constrained Sauger movements to the Cumberland River, rather than straight line paths that do not consider boundaries. Some studies estimated the kernel density of composite samples with relocations that are assumed to be independent and do not take into account boundaries (Cole 2011). However, this can result in biased KDEs, especially where data points are close geographically but separated by land in reservoirs with complex shorelines and river systems where meander length is small (Laffan and Taylor 2013). For each Sauger relocation, least-cost path distance from observation *i* to *i*-1 was derived from the Cumberland River raster (2-m cells) and occupation time was assigned to each transit raster cell based on the time elapsed between tracking events and the distance traveled. Overlapping transit rasters were summed and transformed to point data weighted by the total residence time of that location. Kernel density estimates were then calculated from the weighted point data to create maps. Analyses were conducted in ArcGIS 10.1.

In R, the Cumberland River channel line was fit to the OHL polygon and distance from the Cordell Hull Dam (DFD) was measured by spatially joining fish location with the channel line. Geometric mean DFD with 95% confidence intervals were then plotted in SigmaPlot 10.0. Seasonal and weekly variations in Sauger movement, depths occupied, and distribution were evaluated using mixed-model analysis of variance (ANOVA) in the Statistical Analysis System version 9.3 (SAS Institute, Cary, North Carolina). Fixed effects were week and season (winter or spring) and individual fish and the fish*week and fish*season interactions were treated as random effects. Minimum displacement per week (MDPW) and DFD were $\log_e$-transformed to stabilize the increasing variance observed with increased movement and DFD. The Bonferroni multiple-comparisons procedure (α=0.05) was used to evaluate pairwise differences in DFD and MDPW between weeks and season. Linear regression models were used to define the relationship between surface water temperature where Sauger were relocated and date.

A staggered entry Kaplan-Meier approach estimated sources of mortality (harvest, natural mortality and CR mortality), catch rate, and emigration rate using the survival function,

$$\bar{S}(t) = \prod_{tj \leq t}\left(1 - \frac{d_j}{r_j}\right),$$

where *t* is the time interval in which the probability of survival is estimated from the conditional probabilities of each event (*j*), d_j represents the number of individuals that "fail" (e.g., die, are harvested, are caught, or emigrate), and r_j is the number of individuals at risk (the number located at event *j*). Failure to locate a fish on any given search could have been due to 1) transmitter failure; 2) the transmitter signal was missed; 3) the fish moved out of the study area; or 4) the fish was harvested (Hightower et al. 2001). I assumed fish to be alive when they changed locations between tracking events and deemed them dead when they remained in the same location over four consecutive tracking events, or only moved with the river's current until out of the sampled area (Hightower et al. 2001; Thompson et al. 2007). Patterns in movement were qualitatively assessed based on preceding and subsequent locations, distance traveled, and directional movement (e.g., upstream, downstream, stationary). Patterns in movement were quantitatively assessed using MDPW as a baseline to dismiss movements that were too large to be natural and likely the result of a dead fish displaced downstream. Gaps in relocation histories were assumed to be missed observations and were used to estimate relocation probability. Missed observations were defined as the failure to relocate an individual that was found within two weeks prior to and after the missed event. The return of internal transmitters ($50) by anglers provided an estimate of harvest. The return of external high-reward Floy tags ($100) in the absence of a transmitter provided an estimate of the number of fish that experienced CR fishing. Emigration could not be directly measured and when fish were missing it was assumed that they moved down and out of the tracking area.

CHAPTER 4

RESULTS

Tag-implantation surgery duration averaged 4:35 min ± 6.6 s (SE; Table 1). Eighteen fish were under the minimum size limit (381 mm TL) and 12 fish were over the limit. Five Sauger were females and the sex of the remainder could not be determined with certainty without prolonging the invasive tag implantation procedure. Tagged Sauger ranged in length from 340 to 472 mm TL with a mean of 381 ± 5.9 mm (SE); they weighed between 323 and 1,036 g with a mean of 523 ± 32 g. All Sauger survived the two-week data quarantine period and all tagged fish contributed some data during the 110-d sample period that began January 21, 2014 and ended May 11, 2014. Thirteen tracking events accumulated 272 observations; the number of fish locations per tracking event ranged from 11 to 27 fish and averaged 20.8 ± 1.03 fish. There were 21 instances when fish were likely in the sampling area based on previous and subsequent locations but were not located; thus, the estimated relocation probability was 0.90. Ten of those 21 missed observations occurred on February 12, 2014 when only half of the sampling area was traversed due to inclement weather; thus, that relocation probability is likely underestimated.

Spawning Habitat

Surface water temperatures in the tailwater increased steadily from 3.4ºC on January 30, 2014 to 10.0ºC on April 2, 2014 (Figure 2). Temperatures rose abruptly to 13.3ºC on April 11, 2014 and then increased steadily to 14.4 ºC through the end of the study. Over the entire study the water warmed at a rate of 0.88 ºC per week.

Most Sauger moved downstream after being tagged and then commenced upstream movements from January to late March (presumably the beginning of the spawning season) and returned to the main basin in mid-April after water temperatures exceeded 13.0 ºC. Many Sauger took refuge in the still waters near the lock chamber of the Cordell Hull Lock and Dam. Some of those fish did not provide information regarding spawning shoals because they stayed near the lock chamber for the entire spawning season. However, the number of tagged fish in this area began to decrease after the water temperature reached 10.0 ºC.

Tagged fish displayed a clustered distribution (Figure 3) and some reaches were frequented by radio-tagged Sauger throughout the entire spawning season. Water temperatures at which Saugers are known to spawn (9–13 C) occurred between March 24 and April 18, 2014. There were fourteen areas identified as potential spawning shoals and ten pre-spawn staging areas that may have been important components of their spawning migrations (Figure 4). The most heavily used potential spawning areas were between Goodall Island and the Cordell Hull Lock and Dam. The areas identified as pre-spawn staging areas appeared to be used for refuge because Sauger migrated from them upstream to spawning shoals from January to March and were also used by some individuals as they returned to the main basin beginning in late April.

Distance from the dam (DFD) locations ranged from 0.17 rkm to 33.6 rkm and had a geometric mean of 4.5 ± 2.14 rkm (SE). Geometric mean DFD varied from 3.3 to 5.2 rkm from January 30 to March 14, 2014. Afterwards, it decreased to 3.0 rkm between March 24 and April 11, 2014 (when fish were presumably spawning) and then increased progressively as Sauger returned to the main basin beginning April 18, 2014 (Figure 5).

Although DFD was similar in the winter and spring tracking seasons (df=28; F=0.10; P=0.7525), it was significantly higher on May 11, 2014 than during the three subsequent tracking events (March 24 to April 11, 2014) when Sauger were presumably spawning (df=28; F=2.56; P=0.0036). Minimum displacement per week (MDPW) ranged from 6 m to 25,442 m and the geometric mean was 899 ± 123 m. The MDPW was significantly higher in spring than in winter (df=28; F=5.44; P<0.0001) and MDPW on May 5, 2014, when fish were emigrating downstream, was significantly higher than MDPW on February 12, March 7, and March 14 (df=28; F=3.24; P=0.0004). Geometric mean MDPW was consistently less than 2,000 m except when one of the spillgates on Cordell Hull Dam had to be opened on May 5, 2014, which may have displaced Sauger downstream (Figure 6).

Depths where radio-tagged Sauger were located ranged from 3.2 to 17.6 m with a mean depth of 8.4 ± 0.17 m. Mean depth was lowest during April 2014 when surface water temperatures were suitable for spawning (10–13.3ºC; Figures 7 and 8). In winter, Sauger occupied significantly deeper water compared to spring (df=28; F=5.86; P=0.0231).

The kernel density estimates (KDE) for January 30 to February 28, 2014 showed seven areas where occupancy was high and there was little residence near the dam (Figure 9). Outside of those seven high-occupancy areas the KDE displayed a uniformly gray color, indicating that Sauger moved through these areas but did not take residence. Most of the observations were at or just downstream of the first bend 4 rkm downstream of Cordell Hull Dam.

The KDE for February 28 to March 24, 2014 was much different and showed a general upstream shift of occupancy (Figure 10). There was high occupancy near the dam with less occupancy (i.e., more white reaches) below Peyton Creek even though that area contained more observations than the previous composite sample. Fish moving into the sampling area that had not been previously relocated were responsible for that pattern; they had little influence on occupancy because the time they spent in the area was unknown as a result of not knowing their preceding location.

The KDE for the period of March 24 to April 18, 2014 showed many kernels between Goodall Island and Cordell Hull Dam with less occupancy downstream (Figure 11). The kernels were smaller than in the earlier composite samples, indicating that Sauger were congregating in those areas and did not stray very much from those selected habitats. Relative to the previous composite sample, fish were more dispersed below and more clustered above Goodall Island and fewer fish were near the dam.

The KDE for April 18 to May 11, 2014 was similar to the previous composite sample. Darker kernels were in the same locations but darker shading below Goodall Island indicated that some fish had started to emigrate from the tailwater (Figure 12). Furthermore, there were fewer observations in the upper 4 km of the tailwater. To conclude, it appeared that KDE maps displayed evidence of the following: immigration (Figure 9), pre-spawn staging (Figure 10), spawning (Figure 11), and spawning and emigration (Figure 12).

Mortality

Four fish died during the study and nine emigrated from the study area after the spawning season (Figure 13). Fish #21 was harvested on day 9 (January 30, 2014) and both tags (internal and external) were returned for rewards. Fish #3 was deemed a natural mortality (or unreported CR mortality) on day 52 (March 14, 2014) after it was tracked to the same location on four subsequent tracking events. Six fish were caught-and-released (i.e., their external reward tags were returned) and based on movement patterns, two of those fish (#11 and #31) died after being released. Fish #11 was caught at the dam on day 61 (April 11, 2014), released, and was observed on two subsequent tracking events moving slowly downstream and was presumed to have died and floated ~36 km out of the sampling area (Figure 14). This fish was presumed dead because the distance it had to travel (>36 km) to exit the sampling area between tracking events was too far for it to be consistent with movements observed for other tagged fish. Fish #31 was relocated for eight consecutive weeks less than 3 km from the dam and on day 57 (April 7, 2014), it was caught, released, and never located again (Figure 15). This fish was deemed dead because of the distance it had to travel (>40 km) in order to exit the sampling area and its previous relocation history. It is not likely that these two fish (#11 and #31) were in the sampling area and missed given their consistent relocation history up to their respective dates of capture. Furthermore, individuals that emigrated (both CR fish and control fish) showed gradual downstream moments after water reached 10°C and were able to be relocated before exiting the sampling area. This held true for even the most active fish that made extensive movements upstream and downstream during the study. At the end of the study on May 11, 2014, an additional 16-km downstream reach was traversed in an effort to locate additional fish but none were found.

The monthly instantaneous mortality rate (Z) was 0.106 and represented one natural mortality, one harvest mortality, and two fish that died of CR mortality. Therefore, monthly M = 0.031, F_h= 0.035, and F_{cr}= 0.041 with a 10% exploitation rate (including CR; u). Twenty-three percent of the tagged fish were caught and handled and the release rate for fish over the harvest size limit was 50%; the pooled release rate for all sizes was 86%. The weekly instantaneous emigration rate was 0.02 and began after water reached 10°C.

CHAPTER 5

DISCUSSION

Spawning Habitat

Identifying spawning habitats used by Sauger will allow hatchery personnel to target those areas in years when capturing a sufficient number of brood stock immediately below the dam is difficult. Biologists with the Tennessee Wildlife Resources Agency have had difficulty in recent years collecting enough broodstock from the Cumberland River to maintain their hatchery operations and using too few brood fish can adversely affect genetic diversity (Vidargas 2009). Sauger spawning habitat and genetic mixing in the Cumberland River drainage has been reduced due to habitat fragmentation and flow management; therefore, protecting the remaining stock and their spawning habitats from dredging and other environmental perturbations is critical for the sustainability of this sensitive river species.

Sauger spawning migrations in OHL were similar to patterns displayed in other impounded systems (St John 1990; Hesse 1994; Pegg et al. 1997). Movement patterns in the present study reflected a two-stage migration: Sauger moved upstream to overwinter in the tailwater below the dam, then moved to nearby spawning shoals in early spring before returning to the main basin in late spring. Sauger congregated in shallower water on shoals when the water temperature reached 10ºC on April 2, 2014. Presumed spawning behavior was observed in some areas when fish made rapid movements (over the course of only a few minutes) to the opposite bank while staying in the same general vicinity for the day. The habitats selected presumably for spawning in the Cumberland River in the present study were similar to those reported by Jaeger et al. (2005) in the Yellowstone River. Spawning in that study occurred in areas with large boulder, riprap, and cobble substrate associated with bluffs, bends, narrow valleys, and resistant banks. In the present study during the presumed spawning season, Sauger avoided areas of low velocity and wide valleys with river banks that tended to slope back as they sloughed off. Based on Sauger distribution during the spawning season, spawning shoals in the Cumberland River were plentiful upstream of Goodall Island but scarcer downstream. It is also noteworthy that many of those presumed spawning shoals were located in the middle of the stream channel where current was faster. It makes sense ecologically to conserve energy during pre-spawn and only expend energy in higher-velocity habitats when spawning.

Sauger movements in the Cumberland River were much lower during winter than spring and did not increase until surface water temperatures increased to preferred spawning temperatures. Pegg et al. (1997) reported similar findings on the lower Tennessee River when they assessed pre- and post-spawning movements of Sauger. However, in that study fish moved much further (1.1 km/day; range: 1–276 km) and had the ability to pass through dams more freely, although most fish stayed within 30 km of Pickwick Dam for most of their study. Similarly, Sauger in the Cumberland River remained within 30 km of Cordell Hull Dam for most of winter and spring. Sauger movements were also much higher (1.0 km/day) in the Yellowstone River which is considered a more pristine system with a natural flow regime (Jaeger et al. 2005). Because of the natural flow regime, Sauger in the Yellowstone River had more than 100 km of suitable spawning habitat available to them, which may explain greater movement in that system. Based on distribution data, Sauger in

OHL have perhaps only ~35 km of suitable riverine spawning habitat that likely declines in quality moving downriver of the dam.

Lastly, the FishTracker software tool is based on the ecological concept that fish do not expend energy unless they need to; therefore, quantifying their movements (or lack thereof) is meaningful. Specifically, FishTracker is useful in complex systems where there are many physical boundaries. Estimating MDPW was more accurate using FishTracker because distance was measured by the minimum number of raster cells necessary to connect consecutive observations and not river kilometers, an approach that does not account for islands or lateral movement within a system. This approach is especially useful when observations are not independent (i.e., the current location of an individual is influenced by its preceding location). It follows that short intervals between tracking events yield data that are more dependent than data from tracking events with longer intervals. A misguided practice in telemetry studies has been to strive for uncorrelated relocations even though telemetry research can more clearly portray what an individual is doing with serially correlated relocations (dependent data), as long as the relocations are representative (Aebischer et al. 1993; Rogers and White 2007). Caution should be taken when designing movement studies in meandering systems similar to the Cumberland River or systems with complex shorelines. Least-cost paths tended to overestimate the probability of occurrence on the inside bends, especially when the distance between relocations was large. Hence, the closer observations are in space (i.e., time) the less error the predicted least-cost path will have because there is less distance to approximate. Ideally, daily relocations would be best with highly migratory species in riverine environments such as Sauger.

Mortality

Estimating sources of mortality provides insight into how populations should be managed to maximize benefits from a fishery while sustaining fishable stocks. Catch-and-release fishing is encouraged as a way to expand the sport fishing industry in the United States. Even though encouraging CR fishing is not a realistic management option in harvest-dominated fisheries such as Sauger in Tennessee, the need to assess CR mortality was still appropriate because a large proportion (~60% in the present study) of the fishable stock could not be legally harvested.

Many studies have used telemetry techniques to estimate mortality of highly mobile species such as Striped Bass *Morone saxatilis* and Blacktip Sharks *Carcharhinus limbatus* (Hightower et al. 2001; Heupel and Simpfendorfer 2002; Young and Isely 2004). However, applying these techniques to open systems is much more difficult and is restricted to species that demonstrate high site fidelity and moderate residence times (Star et al. 2005). In the present study I took an open-system approach that is common in the marine realm because only a portion of Old Hickory Lake was monitored and fish could enter and leave the sampling area. Because Sauger have high site fidelity (i.e., they typically stay in Tennessee tailwaters throughout winter and spring), an open-system approach was appropriate.

Exploitation (10%) was much lower below Cordell Hull Dam than in other Tennessee tailwaters. Pegg et al. (1996) estimated that annual exploitation in Kentucky Lake, Tennessee was as high as 36% (not adjusted for non-reporting). Furthermore, in a pilot study in the fishing season that preceded the present study 15 Sauger implanted with transmitters were exploited at a rate near 30% (excluding CR mortality). The weather during the fishing season in the present study was characterized by several long bouts of below-average winter temperatures, which may have suppressed fishing effort and reduced exploitation.

Previous research has estimated CR mortality of Sauger, but presenting CR mortality as an instantaneous rate that contributes to Z has not been estimated for Sauger until now. Bettoli et al. (2000) caught 93 Sauger, held 74 in net pens to determine short-term (16–22 h) mortality, and tagged the remaining 19 with external radio transmitters to monitor long-term (12 d) mortality. Short-term mortality was 4% and long-term mortality was 12% and the pooled mortality rate was 6%. In a similar study, Kitterman and Bettoli (2011) tagged 81 angled Sauger with ultrasonic tags to monitor their fate over four weeks and reported 22 to 32% CR mortality (depending on the criterion used to define death). In the upper Mississippi River, Meerbeek and Hoxmeier (2011) angled 105 Sauger and held them in nets pens; short-term mortality (72 h) was 26% and individuals captured at depths greater than 9 m were more likely to die. Most of the Sauger habitat in OHL is shallower than 9 m, which suggests that CR mortality should be less in this system than in the upper Mississippi River where Meerbeek and Hoxmeier (2011) conducted their study. However, that is not what I found; CR mortality in the present study (33%) was higher and had a cumulative effect based on high release rates (86% in this case). Therefore, high F_{cr} should be expected in years when the weather allows for a long fishing season and catch rates are higher.

Although CR mortality in the Cumberland River below Cordell Hull Dam may be problematic, Bettoli et al. (2000) suggested that catch-and-release regulations will benefit Sauger fisheries in Tennessee because anglers invariably harvested fish under the size limit when regulations permitted one or two sublegal fish to be kept. Furthermore, Bettoli (1998) reported that 60% of anglers ranked “Catching fish to eat” as the primary reason they targeted Sauger, which suggests that liberal limits would reduce Sauger stocks. Sauger are currently managed with a 381-mm minimum length size limit and a 10 fish creel limit in OHL, and results from this research suggest that those limits should remain in effect. Although some Sauger will die from CR mortality and provide no benefits to consumption-oriented anglers, the high size limit will help ensure that the population persists and reduce the likelihood of recruitment overfishing.

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Table 1.—Summary information for 30 radio tagged Sauger released into the Cumberland River on January 15-16, 2014 in the Cumberland River, Tennessee, indicating FLOY tag number, radio frequency, total length (TL), weight, sex, and surgery duration.

FLOY #	Frequency	TL (mm)	Weight (g)	Sex	Surgery Duration
2	30.030	433	831	-	6:23
3	30.010	362	481	F	5:44
4	30.130	402	657	F	5:01
5	30.140	382	513	-	5:10
6	30.110	456	894	-	4:52
7	30.080	380	482	-	5:17
8	30.090	368	415	-	4:03
9	30.070	405	625	-	4:01
10	30.150	361	394	-	4:11
11	30.100	362	426	-	4:35
12	30.270	371	469	F	3:52
13	30.280	472	1036	F	4:31
14	31.662	378	512	-	4:31
15	30.190	340	380	-	4:26
16	30.260	368	406	-	4:17
17	30.020	372	442	-	4:24
18	30.050	375	475	-	5:00
19	30.040	355	406	-	4:17
20	30.120	381	543	-	4:33
21	30.060	385	470	-	3:39
23	30.180	361	401	-	3:35
25	31.012	353	405	-	3:53
26	30.792	366	456	-	4:33
27	30.160	442	933	F	4:16
28	30.250	375	502	-	4:21
29	31.692	390	458	-	4:49
30	30.300	345	429	-	4:29
31	31.652	381	503	-	5:08
33	31.682	357	426	-	5:09
34	30.290	343	323	-	4:30

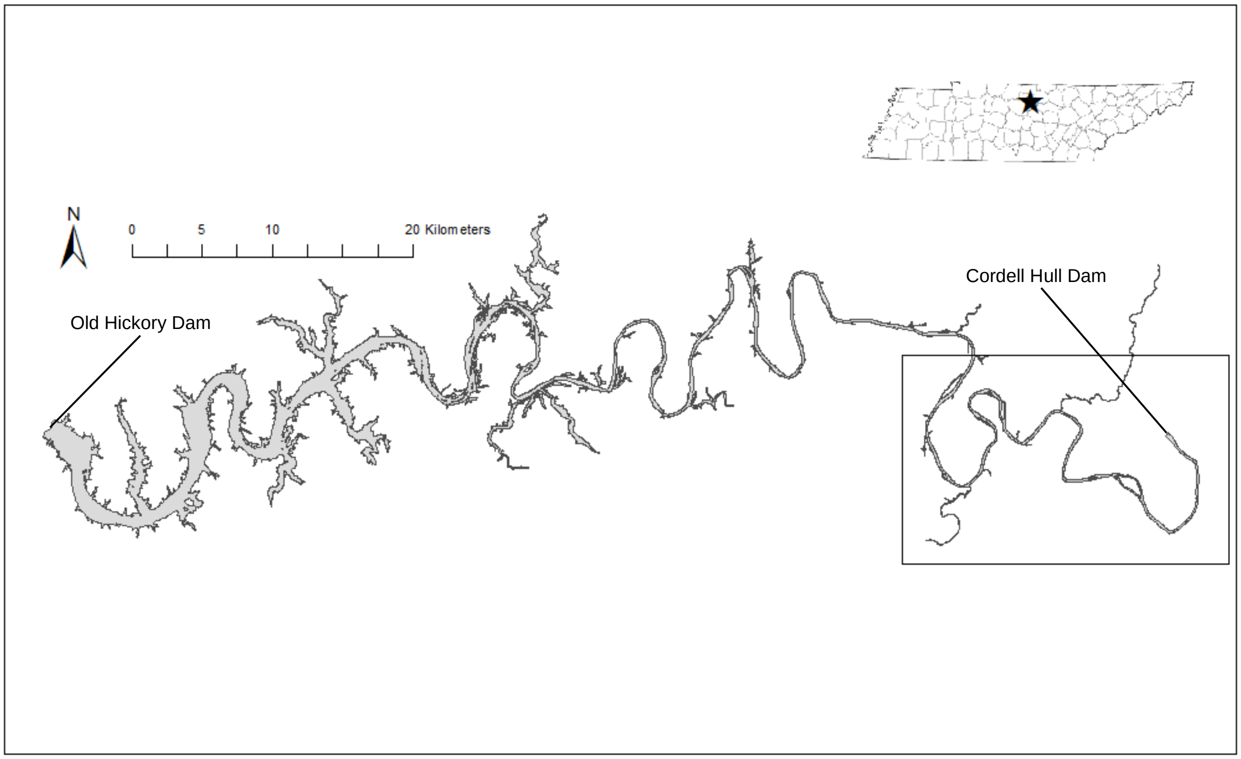


Figure 1. Map of Old Hickory Lake on the Cumberland River, Tennessee with a box indicating the Cordell Hull Dam tailwater where this study was conducted.

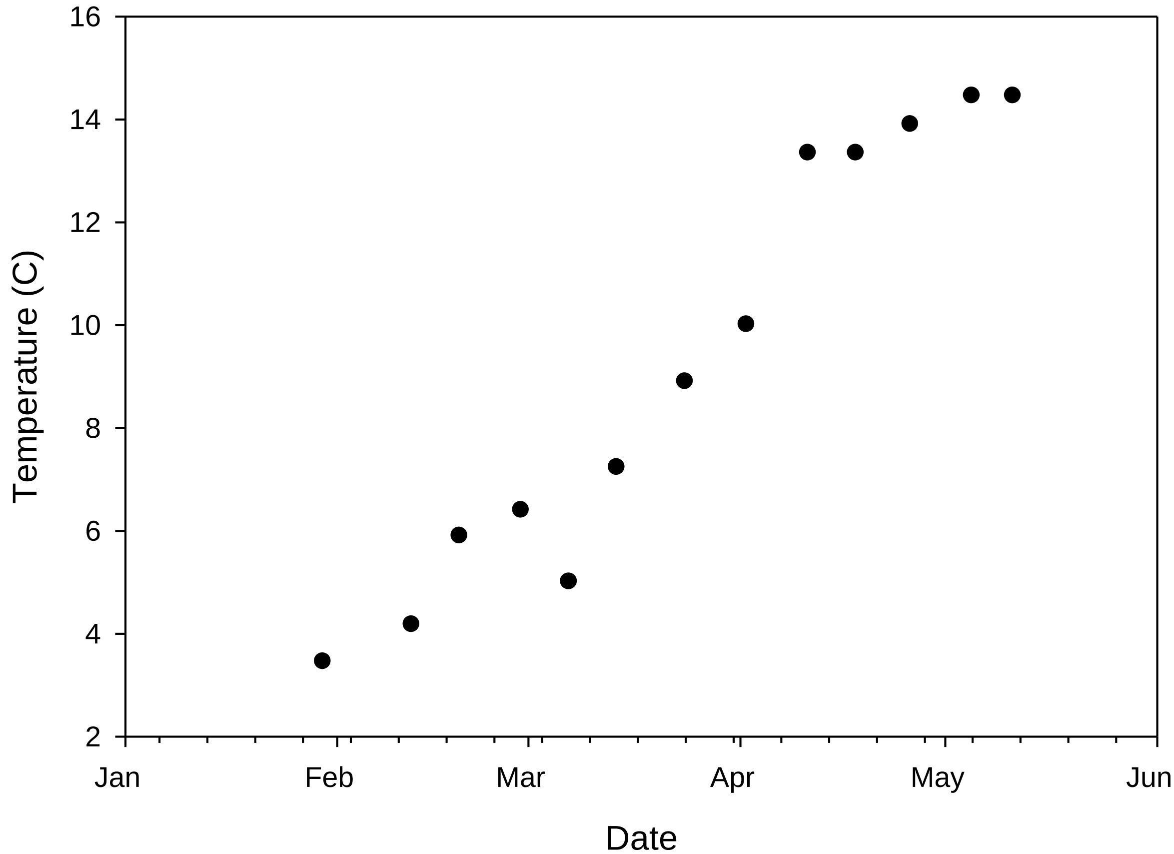


Figure 2. Surface water temperatures immediately downstream of Cordell Hull Dam on the Cumberland River, Tennessee, from January through May, 2014.

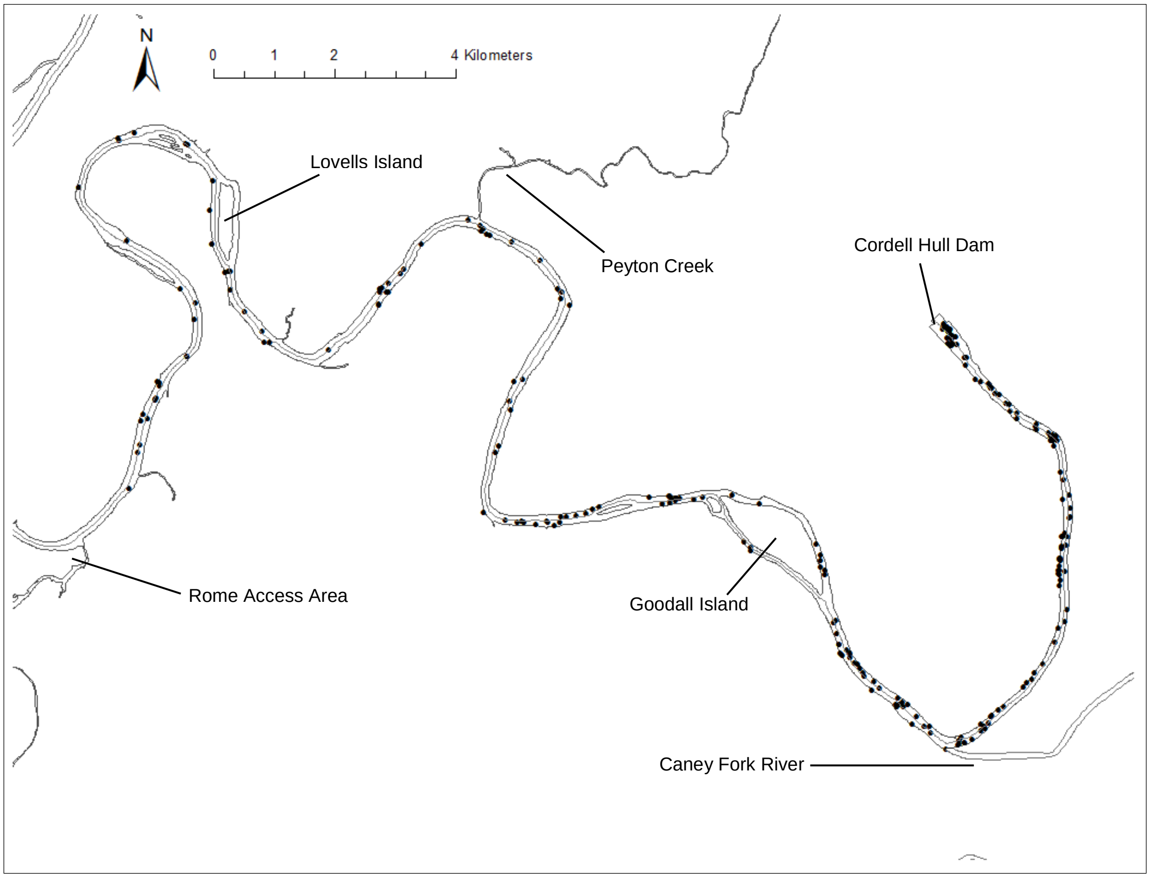


Figure 3. The 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam where radio-tagged Sauger were located (black dots) from January through May, 2014.

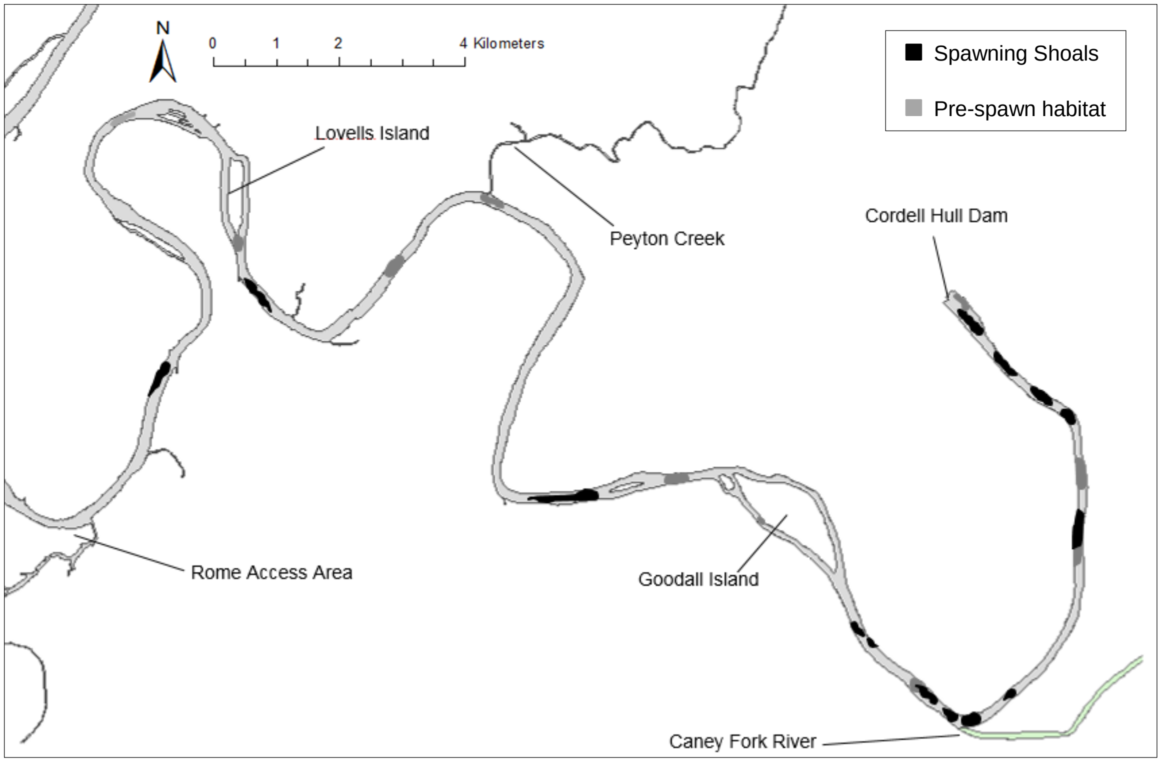


Figure 4. Presumed spawning and pre-spawning areas based on residence time of 30 radio-tagged Sauger in the 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam from January 30 to May 11, 2014.

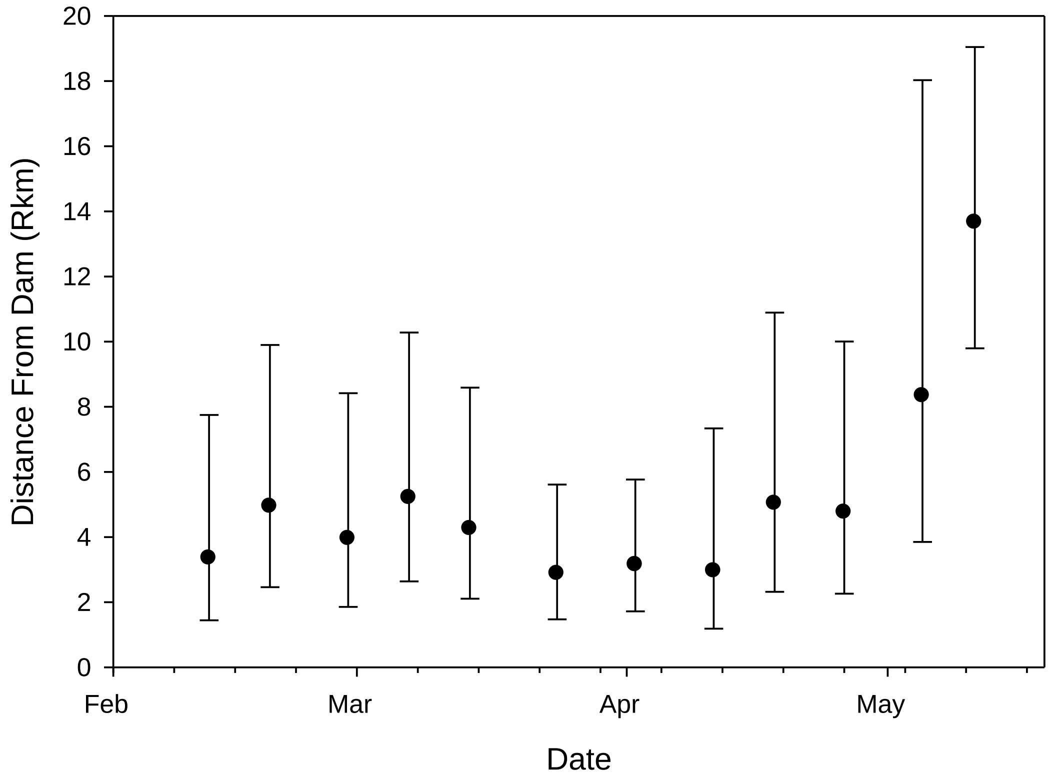


Figure 5. Geometric mean distance from the Cordell Hull Dam where Sauger were located from January to May, 2014. Error bars represent 95% confidence intervals.

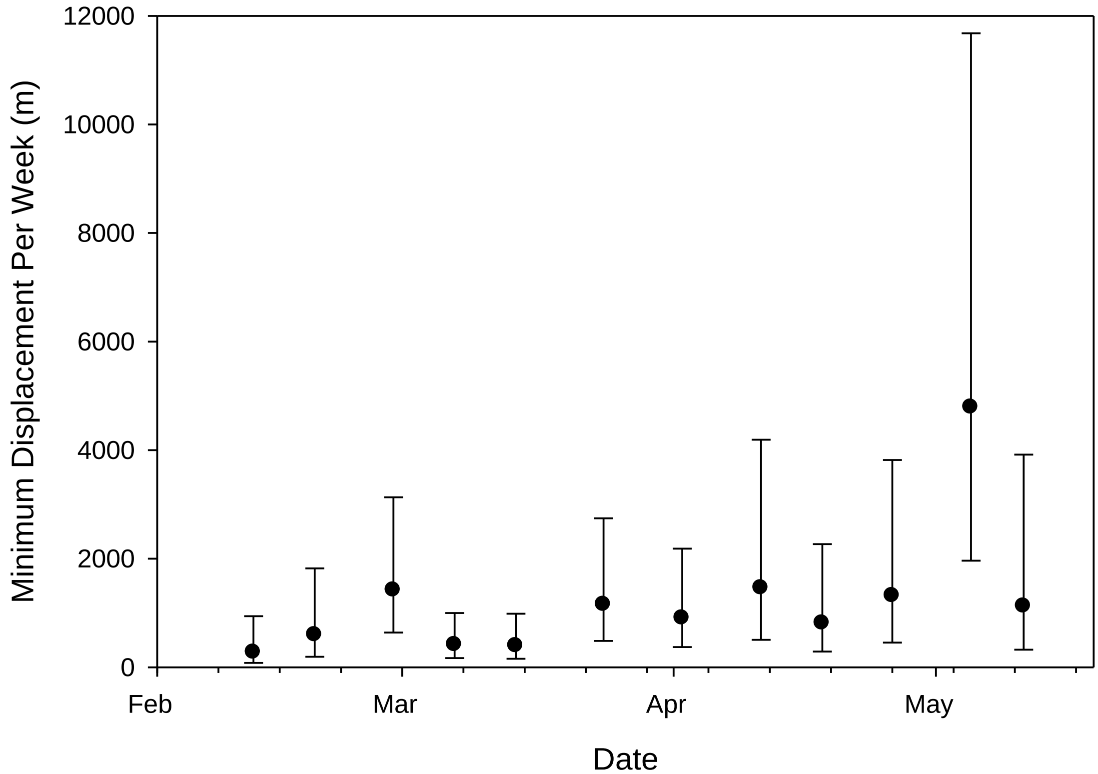


Figure 6. Geometric mean minimum displacement per week for radio-tagged Sauger in the Cumberland River from January through May, 2014. Error bars represent 95% confidence intervals.

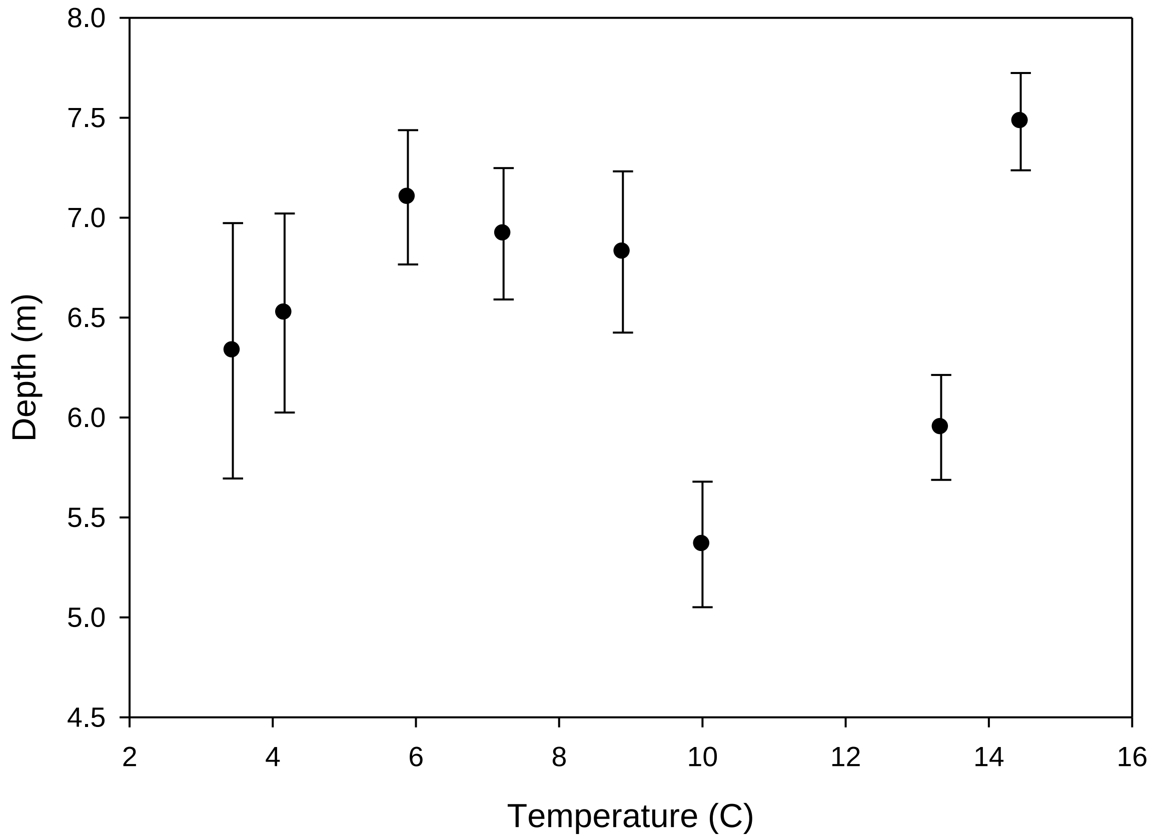


Figure 7. Weekly mean depth of habitats where radio-tagged Sauger were located versus surface water temperature in the Cordell Hull Dam tailwater on the Cumberland River, Tennessee, from January–May, 2014. Error bars represent one standard error.

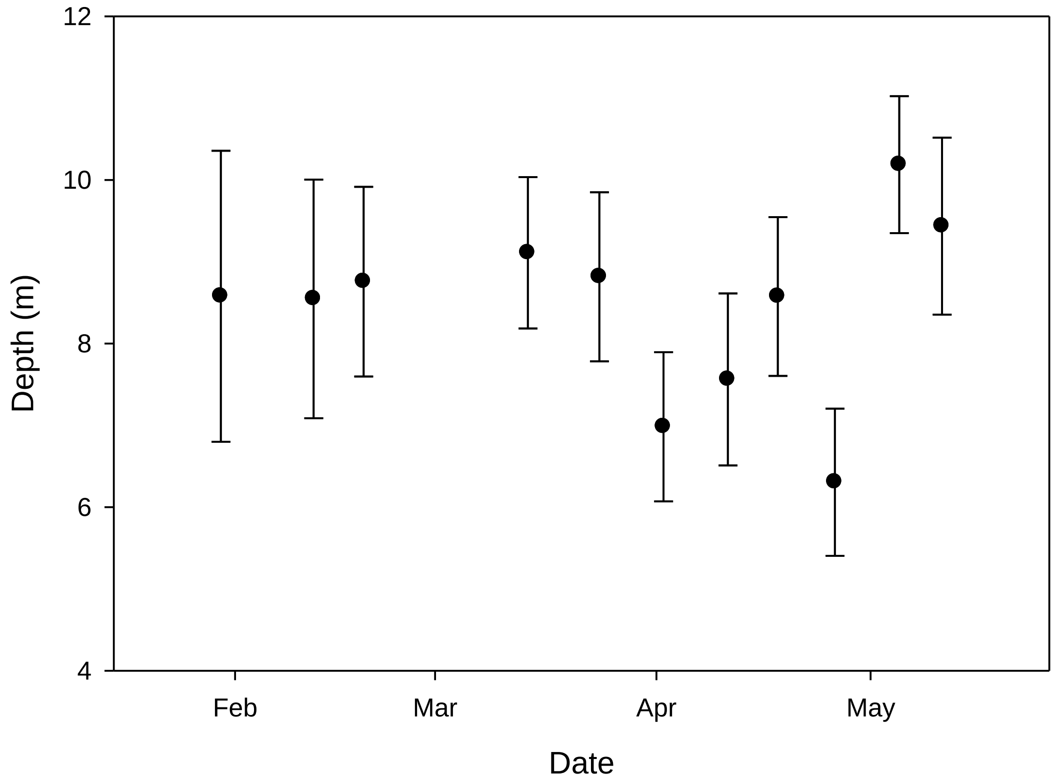


Figure 8. Mean depth (m) of habitats where radio-tagged Sauger were located in the Cumberland River, Tennessee, from January 30 through May 11, 2014. Error bars represent one standard error.

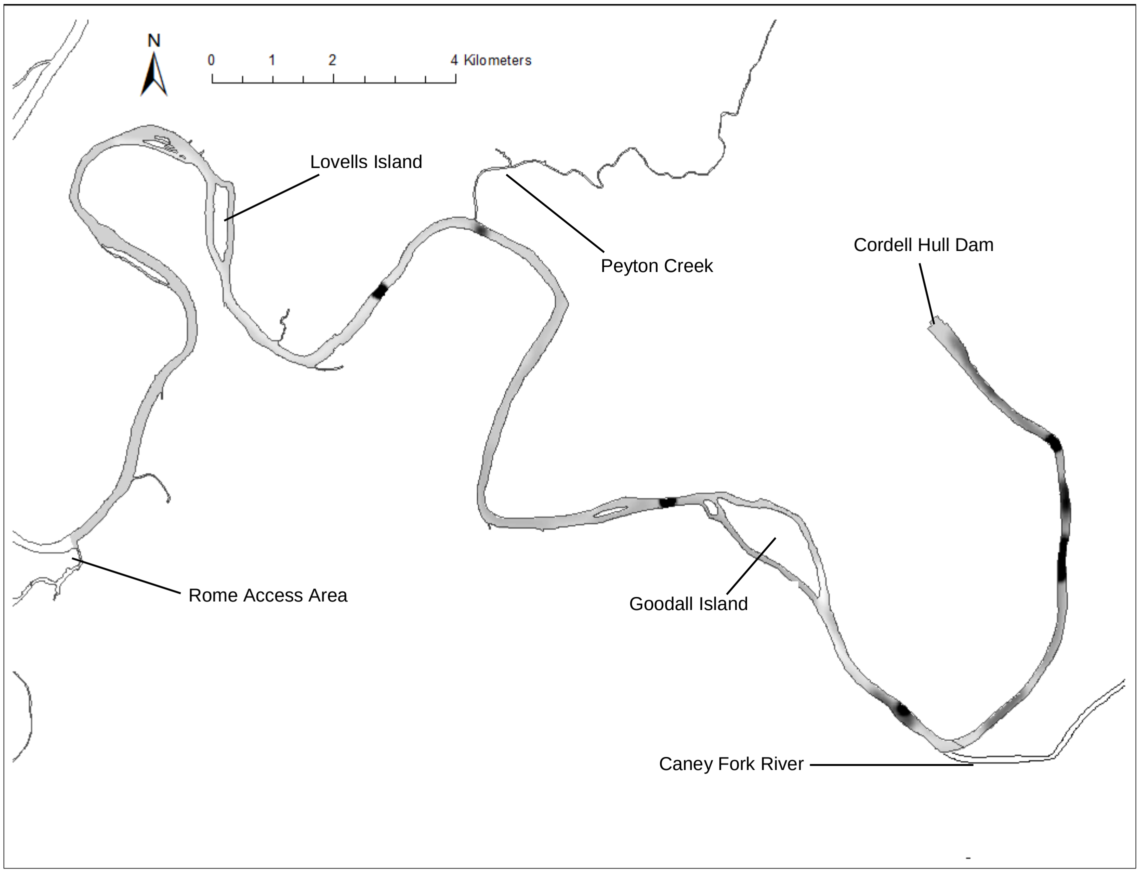


Figure 9. Kernel density estimates weighted by residence time of 30 radio-tagged Sauger in the 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam from January 30 to February 28, 2014.

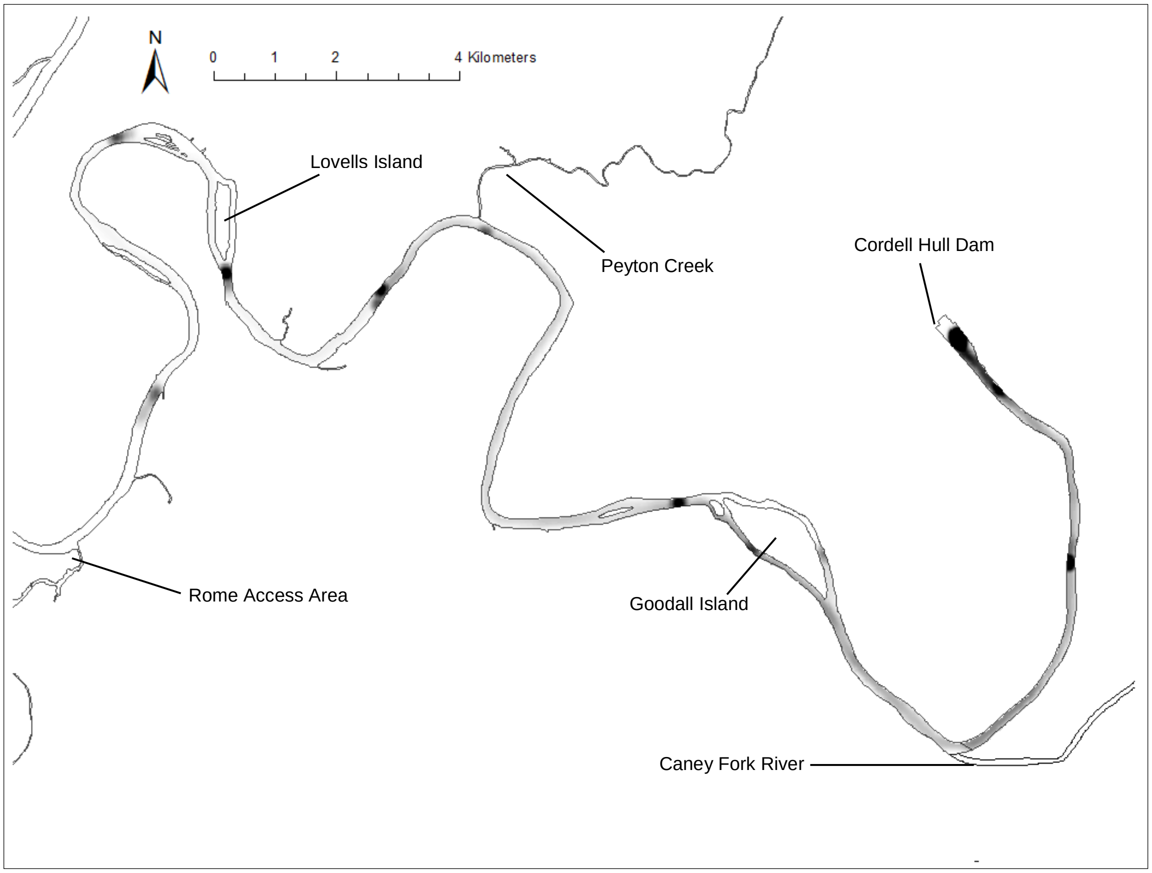


Figure 10. Kernel density estimates weighted by residence time of 30 radio-tagged Sauger in the 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam from February 28 to March 24, 2014.

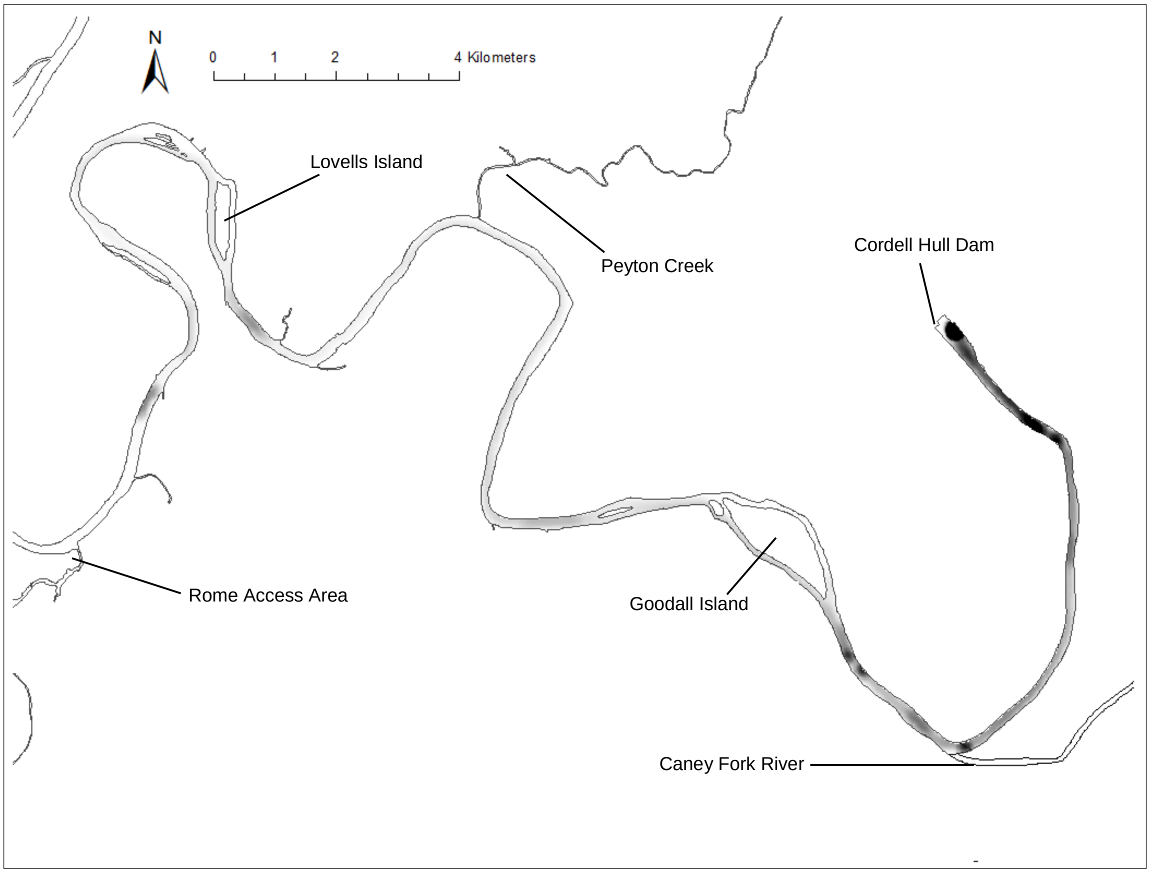


Figure 11. Kernel density estimates weighted by residence time of 30 radio-tagged Sauger in the 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam from March 24 to April 18, 2014.

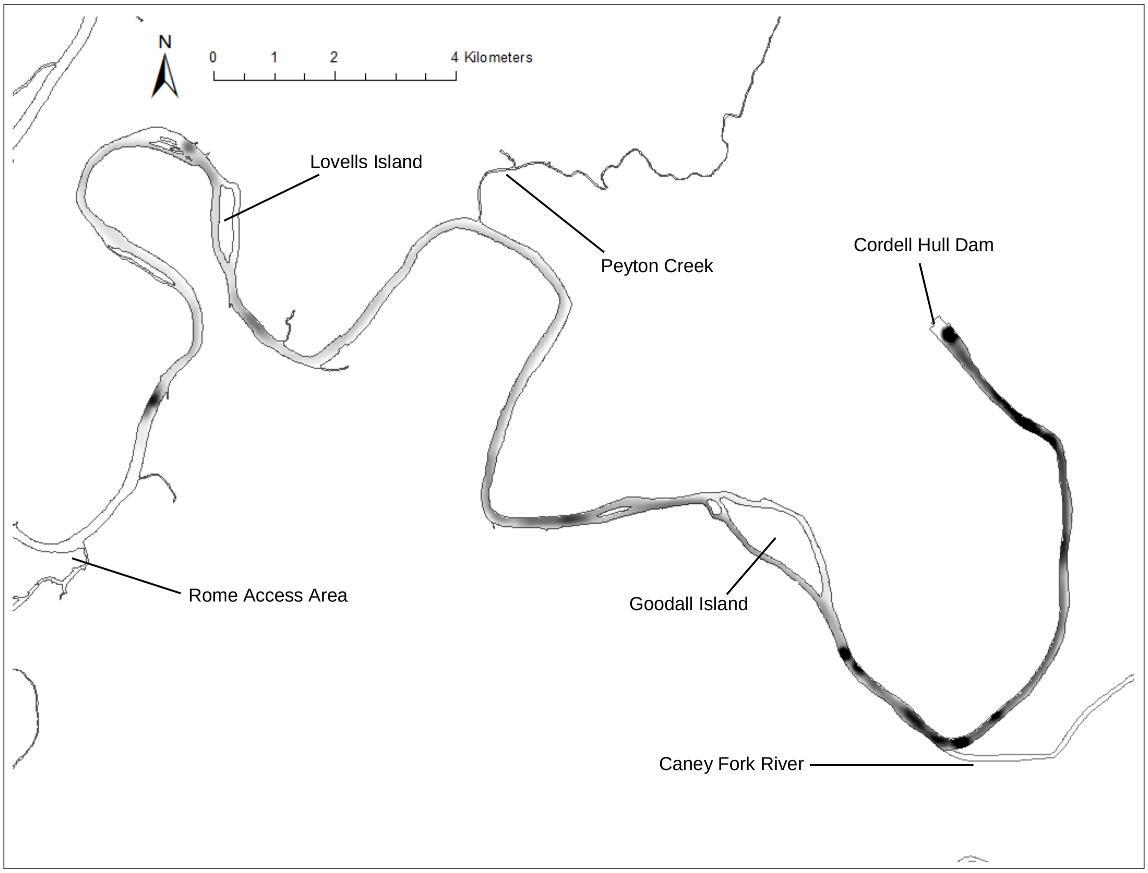


Figure 12. Kernel density estimates weighted by residence time of 30 radio-tagged Sauger in the 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam from April 18 to May 11, 2014.

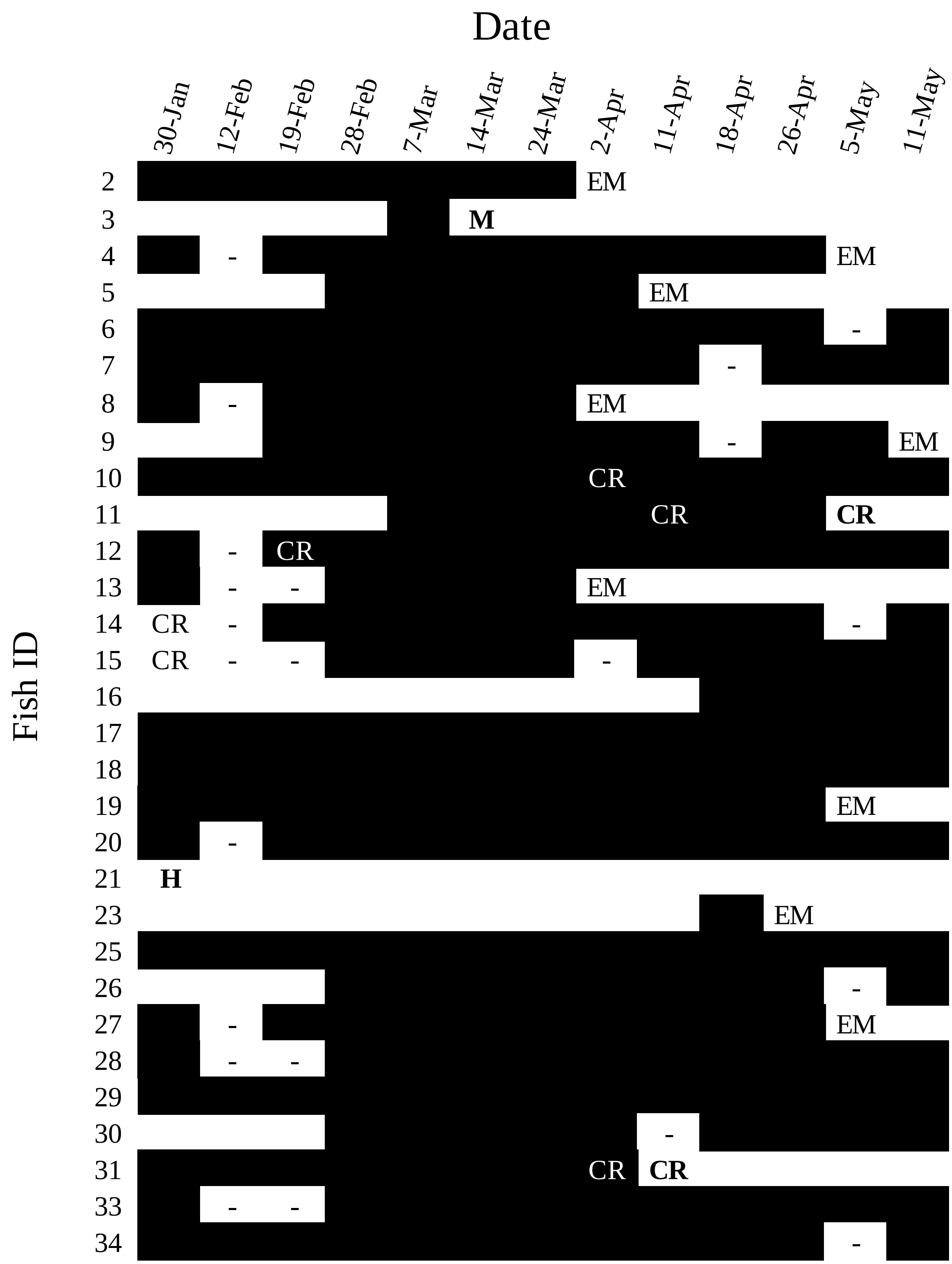


Figure 13. Relocation history of 30 radio-tagged Sauger in Old Hickory Lake, Tennessee, from January–May, 2014. Black boxes represent relocations and dashes (-) represent missed observations. Letters denote their fates, indicating when fish were harvested (H), caught and released (CR), emigrated from the sampling area (EM), or died of natural mortality (M). Bold text denotes sources of mortality.

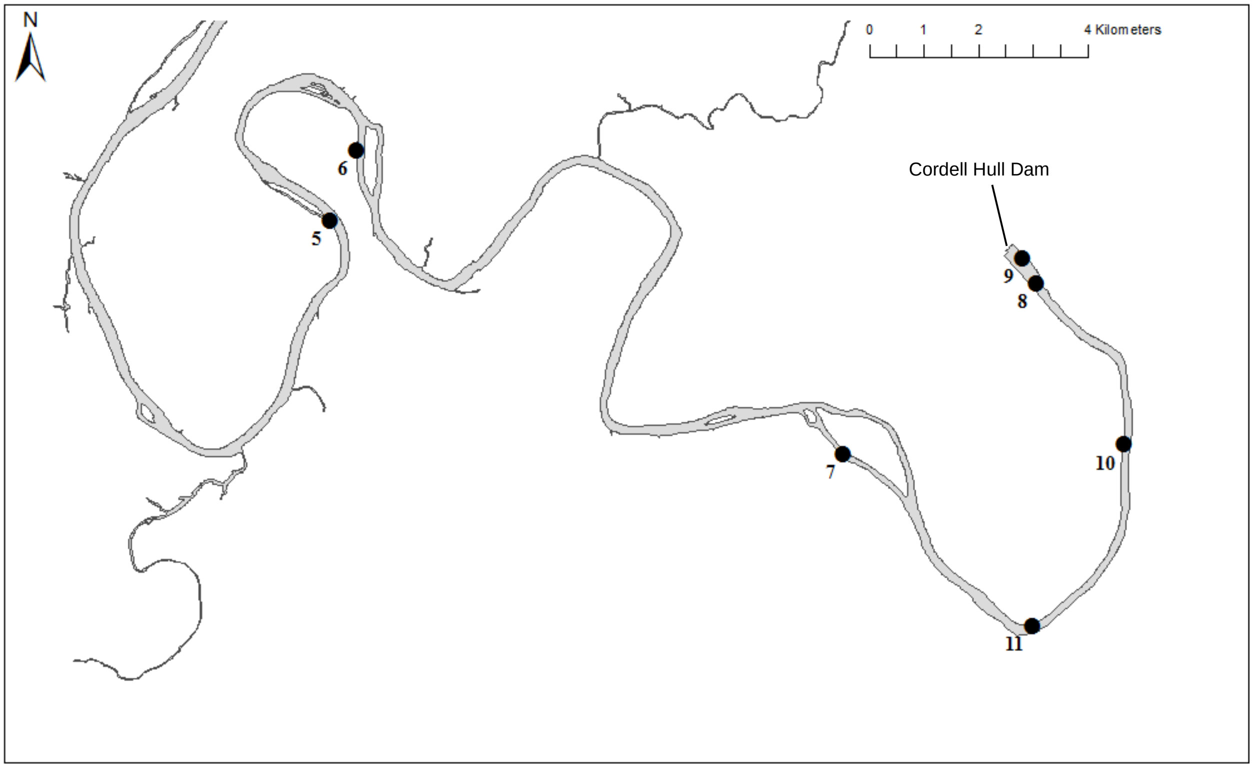


Figure 14. The 40-km reach of the Cumberland River, Tennessee below the Cordell Hull Dam where radio-tagged Sauger were tracked January–May, 2014. Fish #11 relocations are shown with black dots and the numbers denote weekly tracking events. Fish #11 was caught and released the day after its week 9 location was recorded and was assumed to have died from CR mortality.

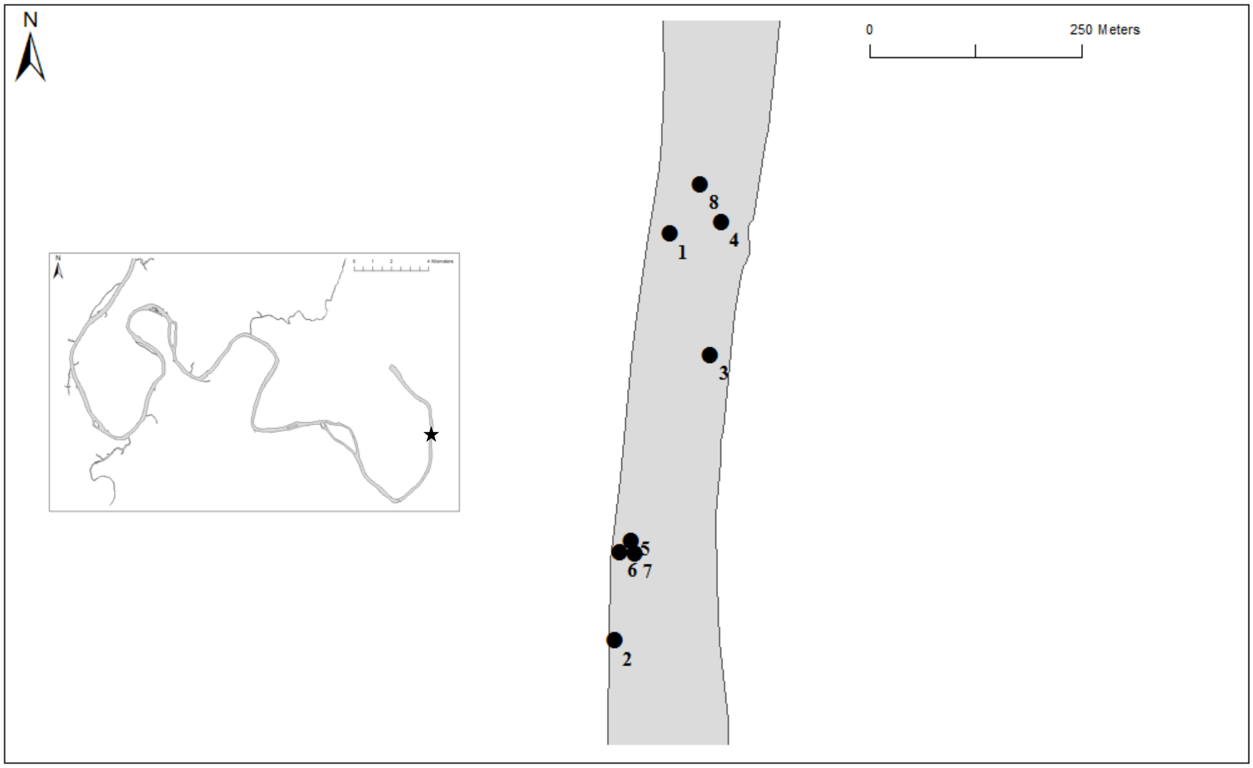
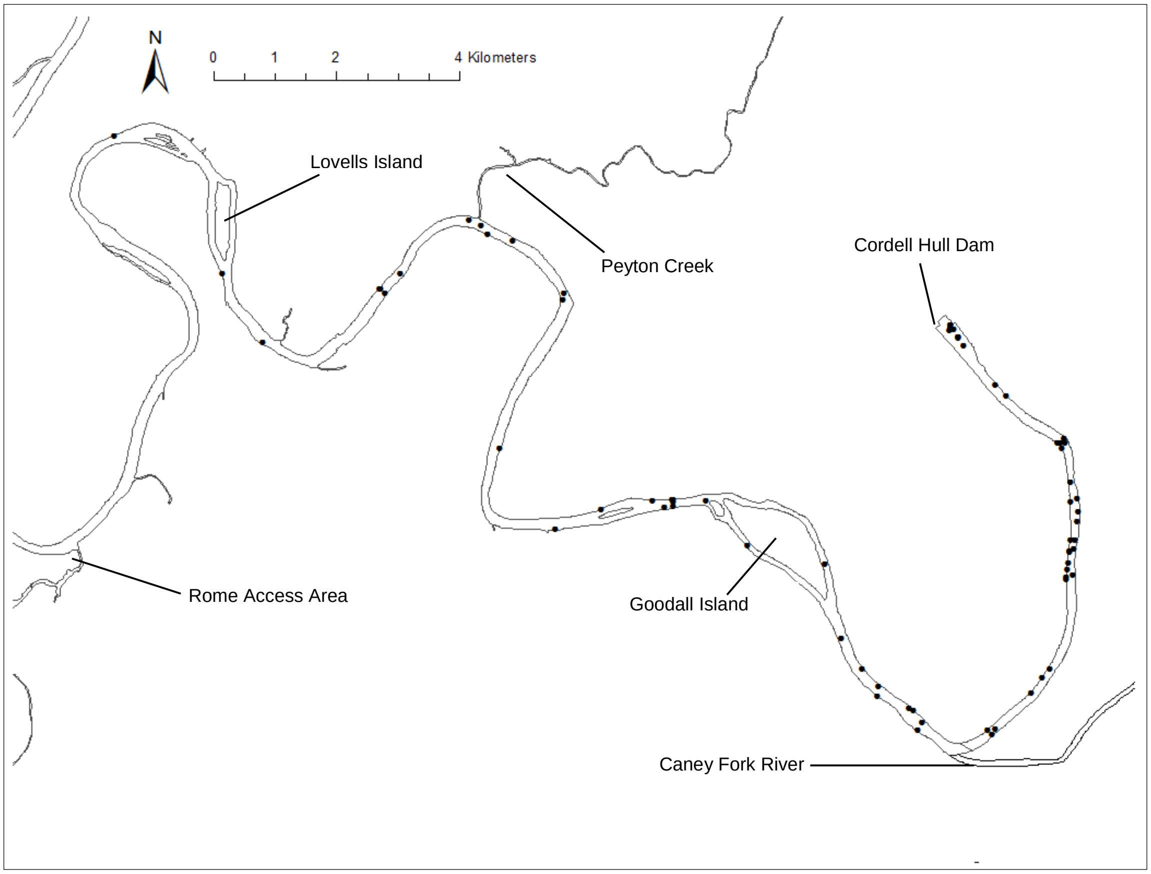


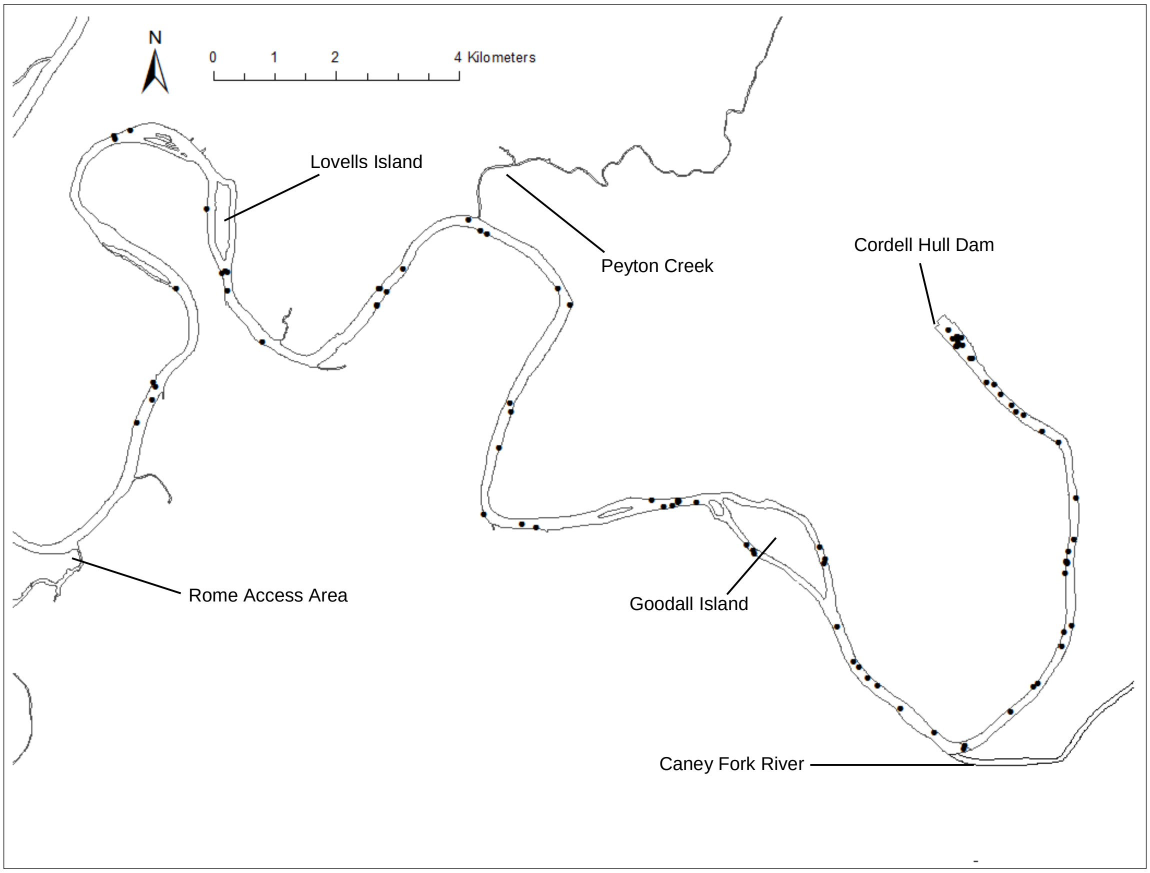
Figure 15. The 40-km reach of the Cumberland River, Tennessee below the Cordell Hull Dam (insert) where radio tagged Sauger were tracked January–May, 2014. Fish #31 relocations are shown with black dots and numbers denote weekly tracking events. Fish #31 was caught and released the day after its week 8-location was recorded and never located again. This fish was assumed to have died from CR mortality.

APPENDIX

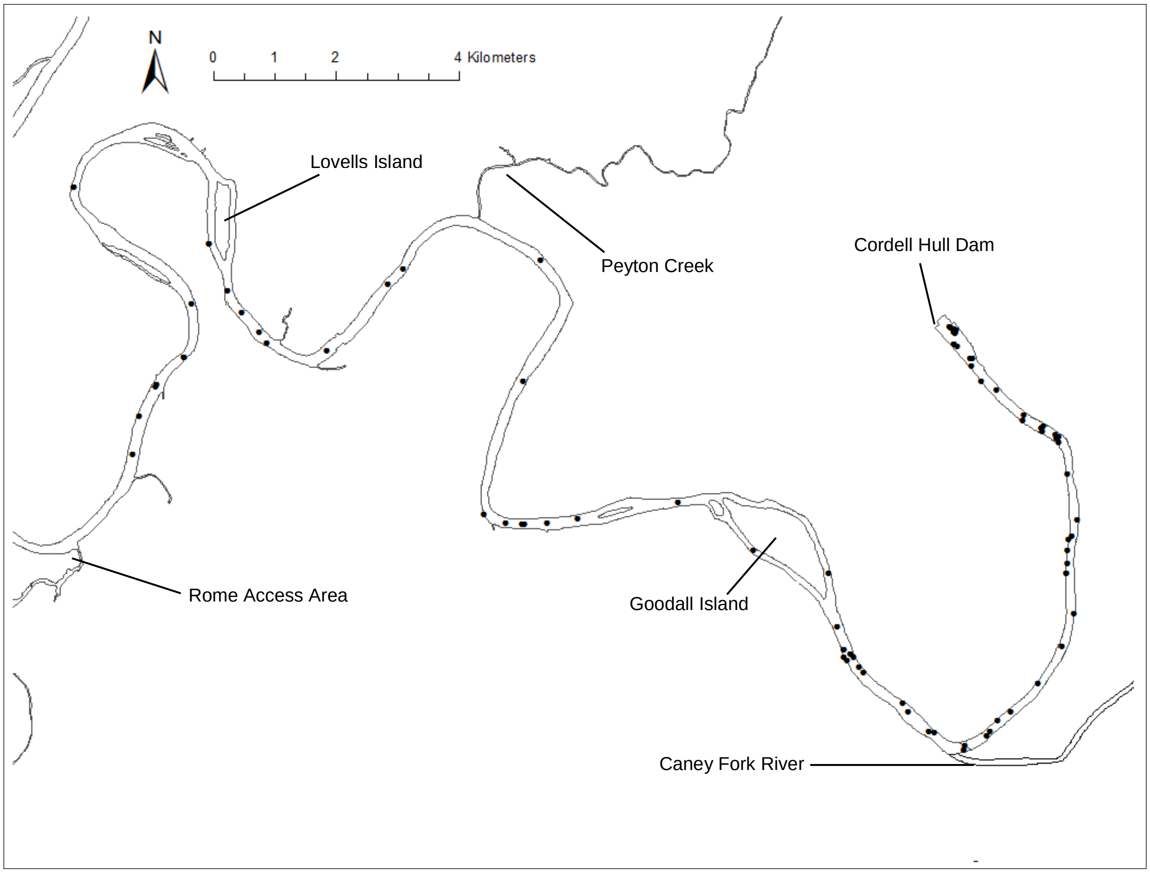
COMPOSITE SAMPLE RELOCATION MAPS



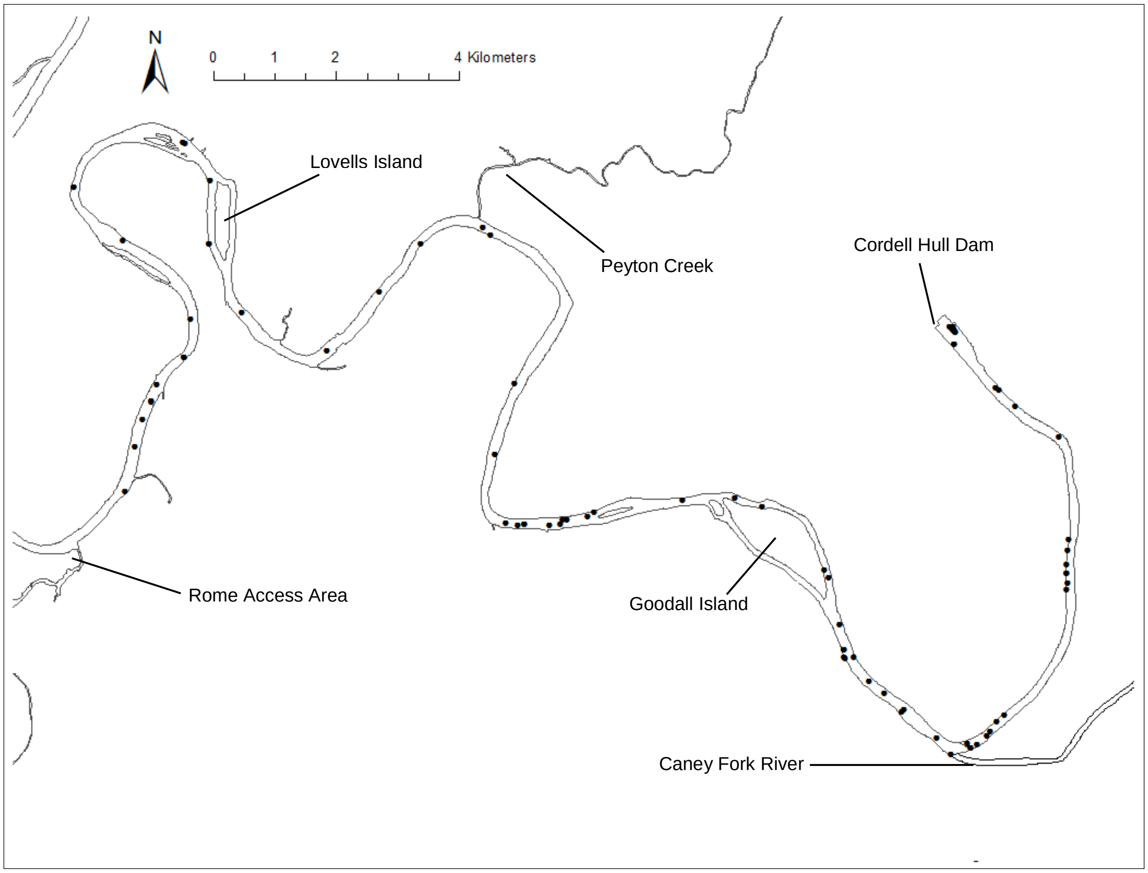
Map 1. The 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam where radio-tagged Sauger were located from January 30 to February 28, 2014. Sauger are represented by the black dots.



Map 2. The 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam where radio-tagged Sauger were located from February 28 to March 24, 2014. Sauger are represented by the black dots.



Map 3. The 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam where radio-tagged Sauger were located from March 24 to April 18, 2014. Sauger are represented by the black dots.



Map 4. The 40-km reach of the Cumberland River, Tennessee, below Cordell Hull Dam where radio-tagged Sauger were located from April 18 to May11, 2014. Sauger are represented by the black dots.

VITA

Grant Marvin Scholten was born on October 17, 1989 and grew up in Rock Valley, Iowa. He Graduated from Rock Valley Public High School in 2008. He went on to receive his Associate of Science degree in Environmental Studies from Iowa Lakes Community College in 2010 and his Bachelor of Science degree in Animal Ecology with the Fisheries and Aquatic Sciences option and a minor in Statistics from Iowa State University in 2012. He entered Tennessee Technological University in August 2012 and is a candidate for the Master of Science degree in Biology.