POPULATION DYNAMICS OF APALACHICOLA RIVER GULF STURGEON: MODELING JUVENILE SURVIVAL AND THE CPUE-ABUNDANCE RELATIONSHIP

by

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(Under the Direction of Adam G. Fox and Marty J. Hamel)

ABSTRACT

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*), an anadromous sturgeon native to the northern Gulf of Mexico, was listed as threatened under the ESA in 1991 due to population declines from commercial harvest and habitat loss. The Gulf Sturgeon Recovery Plan recommended using catch-per-unit-effort (CPUE) to monitor abundance, but the relationship between CPUE and total abundance (estimated through mark-recapture methods) remained untested. Additionally, little is known about juvenile survival trends; increased mortality during overwinter periods in coastal waters has been identified as a potential bottleneck. In this thesis, we found a significant positive correlation between CPUE and total abundance, suggesting CPUE could be useful for tracking abundance. We also evaluated juvenile survival, and found high juvenile survival across all seasons, refuting the hypothesis of a winter mortality bottleneck. These results can help managers identify species population trends and refute the hypothesized seasonal survival bottleneck for juveniles.

INDEX WORDS: Apalachicola River, Mark-recapture, Survival, CPUE, *Acipenser oxyrinchus desotoi*

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## DEDICATION

I would like to dedicate this work to my best friend and wife, Jamie, for all the ways she has supported me throughout this process. Being with you puts life in perspective and helps make life less stressful. I would also like dedicate this to my parents, who always value learning, whether academic or in my different interests and hobbies. Lastly, I would like to dedicate this to Khala, for always reminding me that there is something more important than staring at a screen.

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TABLE OF CONTENTS

CHAPTER 1

Introduction and Literature Review

**The Apalachicola River**

The Apalachicola-Chattahoochee-Flint River system (ACF) drains approximately 48,500 $km^2$ in Georgia, Alabama, and Florida (Livingston 2008). The ACF is impounded by 14 dams operated by the U.S. Army Corps of Engineers and Georgia Power; two additional dams were removed in 2013 (ACOE 2016). The Jim Woodruff Lock and Dam (JWLD) is the southernmost of these, creating Lake Seminole at the confluence of the Chattahoochee and Flint rivers near the Georgia-Florida border. The ACF provides hydro-electric power, public water supply, agricultural water supply, recreational opportunities, and habitat for commercially important and ESA protected species (Corn et al. 2007, Lawrence 2016).

The Apalachicola River is the largest river in Florida by discharge with an average of 736 $m^3/s$ (Morey and Dukhovskoy 2012). It is formed by the confluence of the Chattahoochee and Flint rivers and flows approximately 171 km from the JWLD through six counties in the Florida panhandle before draining to the Gulf of Mexico (Livingston 2008). The river's watershed below JWLD covers some 6,100 $km^2$ and is home to over 1,500 species of native plants and animals, several of which are endemic to the watershed. It hosts an estimated 131 species of freshwater and estuarine fishes, more than any other river basin in Florida (Light et al. 1998, ANERR 2008). The lower portions of the Apalachicola River fall mostly within approximately 3,600 $km^2$ of protected lands comprised of Tate's Hell State Forest, Apalachicola National Forest, Apalachicola Wilderness and Environmental Area, and the Apalachicola River Water

Management Area. The Brothers River is a coastal plain tributary that flows into the Apalachicola River near river kilometer (kilometers from the mouth of the river) 19 and supports summer aggregation areas for Gulf Sturgeon (Wooley and Crateau 1985).

**Gulf Sturgeon Description**

Gulf Sturgeon, *Acipenser oxyrinchus desotoi*, are a long lived, anadromous, ray-finned fish native to the Northern Gulf of Mexico. They are a subspecies of Atlantic Sturgeon, *A. o. oxyrinchus*, differentiated genetically (King et al. 2001), as well as by their relative spleen and relative head size, pectoral fin length, and geographic distribution (Vladykov 1955). They are identifiable by their rows of bony scutes, heterocercal caudal fin, and large size – adults can reach > 2m in length (Huff 1975, Sulak et al. 2016). Gulf Sturgeon are benthic-feeding fish with protrusible mouths; they rely on specialized receptor pores and barbels to locate prey in the soft substrates of the coastal seafloor (Miller 2004). Gulf Sturgeon have a maximum lifespan of 20–40 years and take a long time to reach sexual maturity: males take 7–10 years and females take 8–12 years (Huff 1975). Individuals show strong fidelity to their natal river, but some adults will occasionally visit nearby systems (Rudd et al. 2014).

**Range**

Gulf Sturgeon utilize both marine and freshwater habitats. Their historic range spanned the northern Gulf of Mexico including major coastal river systems from southeast Texas to Tampa Bay, Florida (Sulak et al. 2016). Currently only seven rivers from Louisiana to Florida support spawning populations – the Pearl, Pascagoula, Escambia, Yellow, Choctawhatchee, Apalachicola, and Suwannee Rivers. During winter months Gulf Sturgeon are found in marine and estuarine habitat. Adults prefer shallow, sandy, nearshore habitat often associated with barrier islands (Fox et al. 2002, Ross et al. 2009). Juveniles are typically strongly associated with the mouth of their natal river but will visit open water in the Gulf of Mexico (Sulak and Clungston 1999, Sulak et al. 2009). During spring and summer months, adult and juvenile Gulf Sturgeon inhabit aggregation areas typically within their natal river (Foster and Clungston 1997, Heise et al. 2005).

**Migratory Life History**

Gulf Sturgeon were historically believed to spawn only in the spring, however recent evidence indicates that some fish spawn in the fall instead. Multiple captures of ripe adults during fall months, as well as telemetered adults making upriver migrations to spawning grounds during September–November, suggested a subset of fish in the Suwannee River spawn in the fall (Randall and Sulak 2012). Recent genetic evidence has confirmed the presence of a distinct fall-spawning population in several rivers, including the Suwannee (B. Kreiser, University of Southern Mississippi, pers. comm.) and Apalachicola rivers (B. Kreiser, pers. comm.). Because fall spawning has only recently been confirmed, previous research and literature has generally described a life history as it pertains to the spring spawning population.

Spring spawning occurs once water temperatures reach 17–21 ºC (Sulak and Clugston 1999). The primary drivers for egg-hatching success are thought to be current, temperature, and substrate (Chapman and Carr 1995); little is known about the triggers and drivers of the fall spawn. After hatching, age-0 (young-of-year [YOY]) Gulf Sturgeon are thought to disperse widely downstream to drift feed over sandy open areas of the river, although little information is available on this life stage (Kynard and Parker 2004, Sulak et al. 2016). These YOY remain in their natal river until January or February of the year after hatch when – as age-1 fish – they may migrate into the estuary (Huff et al. 1975, Sulak and Clungston 1999). During this first year, they face mass mortality (Pine et al. 2001). Individuals that survive to age-1 are considered recruited to the juvenile population (Fox et al. 2021).

Juvenile Gulf Sturgeon (ages 1–6) with total lengths (TL) between 340–890 mm (Sulak et al. 2016) have not reached sexual maturity, but these fish annually migrate between the estuary and up-stream habitats of their natal river (Sulak et al. 2009, Sulak et al. 2016). Juvenile individuals occupy habitat close to their natal river mouth in the estuary transition zone during winter months, with some fish moving into open marine waters for short periods (Sulak et al. 2009, Hancock 2019). While in the estuary, they feed heavily on the benthic infauna (Brooks and Sulak 2005). Prey items of juvenile Gulf Sturgeon include crustaceans such as amphipods, grass shrimp, and isopods, as well as oligochaetes, polychaetes, and larval insects (Mason and Clugston 1993, Brooks and Sulak 2005). Juvenile individuals will move upriver into their natal river in March–May (Sulak et al 2016, Hancock 2019). In the river, sturgeon seek deep holes and channels and avoid high-current areas – this is hypothesized to preserve energy and avoid high temperatures during summer and early fall (Wooley and Crateau 1985, Sulak and Clugston 1999, Sulak et al. 2007). Little is known about the summer feeding habits of juvenile Gulf Sturgeon (Mason and Clugston 1993, Sulak et al. 2012). Juvenile sturgeon will remain in the river until September–November when, as water temperatures decline and photoperiod shortens, they migrate to the estuary where they remain until spring.

Sub-adult Gulf Sturgeon (ages 6 through 12; FL 891–1250 mm) are not fully sexually mature although they demonstrate some signs of gonadal development. Sub-adults conduct yearly migrations between their natal river and the Gulf of Mexico, where they occupy nearshore marine habitat in the winter (Parauka et al. 2001). During this time, they feed heavily on benthic invertebrates including polychaetes, lancelets, annelids, ghost shrimp, brachiopods and mollusks

(Mason and Clugston 1993, Carr et al. 1996, Fox et al. 2000). Most sub-adults return to upriver habitats between March–May (Fox et al. 2000). While in freshwater, sub-adults occupy similar areas as juveniles, but they cease feeding due to decreased foraging efficiency (Mason and Clugston 1993, Gu et al. 2001, Cohuo 2021). Like the juveniles, sub-adults leave the river between September–November where they will move into marine feeding habitats.

Sexually mature adult Gulf Sturgeon (typically >1250 mm FL) also conduct annual migrations between marine habitat in the Gulf of Mexico and their natal river. They also make upriver migrations to spawning sites, which are characterized as reaches of the river with relatively high flow and hard substrate composed of coarse gravel, limestone, or bedrock (Fox et al. 2000, Heise et al. 2004). Spring spawning migrations occur from March to early May (Fox et al. 2000, Pine et al. 2006), but the timing of fall spawning migrations is not well understood. Water temperature and high river discharge are thought to be a cue for this upriver migration (Chapman and Carr 1995, Foster and Clugston 1997), although this relationship with flow is not definitive as other research showed arrival of spawning adults to occur at a similar time each year independent of high flow events (Fox et al. 2000). Other possible cues for this migration include lunar cycle and photoperiod (Sulak and Clungston 1998, Ross et al 2004, Sulak et al. 2016). Due to the high energetic cost of spawning and the associated migration, especially for females, adults may wait several years between spawning events (Fox et al. 2000, Parauka et al. 2011, Sulak et al. 2016, USFWS and NMFS 2022). After spawning is completed, adults typically fall back to aggregation areas in lower stretches of the river.

Non-spawning adults show similar movement patterns to sub-adults. They will typically enter the river several weeks later than spawning individuals, although some individuals have been documented to enter the river much later in the summer or not entering the river at all (Fox et al. 2000). Adult Gulf Sturgeon do not feed while they are in the river (Mason and Clugston 1993, Gu et al. 2001, Sulak et al. 2012, Cohuo et al. 2021). Adults will migrate from the river between September–November into marine habitat (Heise et al. 2005, Dula et al. 2022). During winter months, adults will feed heavily in nearshore habitat (Fox et al. 2002, Sulak et al. 2012). They share the same prey items as sub-adults (Mason and Clugston 1993, Carr et al. 1996, Fox et al. 2000).

**Threats and Status**

Due to a robust commercial fishery that began in the 1890s, Gulf Sturgeon populations declined range wide, leading to the subspecies being listed as threatened under the Endangered Species Act (ESA) in 1991(Huff 1975, USOFR 1991). According to the Gulf Sturgeon Recovery/Management Plan, one criterion for determining species recovery is that each Gulf Sturgeon population must be stable or growing (USFWS and GSMFC 1995). This metric can be tracked through the use of standardized sampling techniques to monitor abundance in each population. Although the species has been protected from harvest and monitored for decades, this criterion has not been satisfied for many populations - including the Apalachicola River USFWS and NMFS 2022).

Multiple impediments to Gulf Sturgeon recovery persist, including dam construction and other anthropogenic river modifications that limit upriver habitat availability in multiple river systems. In the Apalachicola River (Figure 1.1), the construction of the JWLD in 1957 blocked Gulf Sturgeon from accessing approximately 78% of their historic riverine habitat, much of which was used in their spawning migrations (USFWS and NMFS 2022). Construction of dams not only acts as a physical barrier to upper river reaches but can also result in unnatural flow conditions due to regulated water release. These modifications to flow regime may affect Gulf

Sturgeon cues for upriver spawning migration, spawning success of adults, and survival of YOY (Flowers et al. 2009, USFWS and NMFS 2022, D'Ercole 2023). In addition, altered flow regime from the JWLD affects the variability of salinity in Apalachicola Bay and the surrounding estuary (Livingston 2008, Morey and Dukhovskoy 2012). The salinity of the estuary during winter may be a critical factor in the ability for juvenile sturgeon to forage, as their salinity tolerance is likely lower than that of sub-adults or adults (Allen and Cech 2007, Niklitschek and Secor 2009, Allen et al. 2014).

Other potential threats to the Apalachicola River population include bycatch in trawling and entanglement fisheries, dredging and channelization, vessel strikes, hurricanes, and anthropogenic contamination releases such as the Deepwater Horizon oil spill (Wooly and Crateau 1985, Sulak et al. 2016, Dula et al. 2022, USFWS and NMFS 2022). These threats can cause direct mortality of individuals or degradation of habitat that can result in decreased fitness. These factors, as well as their protracted life cycle (Walters and Kitchell 2001), likely have prevented or slowed recovery of most Gulf Sturgeon populations.

**Abundance and Recruitment**

Prior to commercial harvest, the Apalachicola River was thought to have the largest population of Gulf Sturgeon with an estimated abundance of 18,000 adult individuals (Ahrens and Pine 2014). Since the species' ESA listing, adult abundance in this population has been estimated by various studies. Several have used mark-recapture models to produce point estimates of 260–886 adult individuals (Table 1.1). The most recent adult abundance estimate available was 406 individuals (95% confidence interval [CI]: 195–854) in 2021 (Dula et al. 2022). Abundance of Gulf Sturgeon in the Apalachicola River and other systems has also been monitored using a sonar count index (Dula et al. 2022, USFWS and NMFS 2022). Side-scan sonar imaging has recently been employed to estimate abundance for multiple sturgeon species (Thomas and Haas 2002, Flowers and Hightower 2015, Andrews et al. 2020, Kazyak et al. 2020). For Gulf Sturgeon, side-scan sonar has been used to count adult and subadult (>900 mm FL) sturgeon during summer months when they aggregate in certain reaches of the river. These counts have been conducted on an annual basis in set reaches of the Apalachicola River system since 2012. Annual sonar count index values are a primary way to track population stability. In the Apalachicola River, index counts were consistently above 500 individuals for the period of 2012-2018. However, index counts declined dramatically (by >50%) between the 2018 and 2019 counts, likely as a result of Hurricane Michael, a category 5 hurricane that hit the lower Apalachicola River shortly after the 2018 count (USFWS and NMFS 2022, Dula et al 2022). This observed decrease in sonar index counts appears to reflect a decline in adult abundance in the Apalachicola River (Dula et al. 2022), suggesting that the population is not meeting the recovery criteria of stability or growth. Although sonar count index can be used to gain abundance information for larger-bodied sub-adult and adult sturgeon, this approach cannot currently enumerate juvenile fish.

Understanding annual recruitment is another research priority for Gulf Sturgeon (USFWS and NMFS 2022). Quantified data on annual recruitment (i.e., the abundance of age-1 juveniles) can provide useful information on species recovery. This method focuses on age-1 fish instead of YOY for two reasons: YOY Gulf Sturgeon disperse widely, making targeted capture difficult (Sulak and Clungston 1999, Kirk et al. 2010), and YOY are thought to face mass mortality with less than 1% of total spawned eggs surviving to age-1 (Pine et al. 2001). Because of this very low age-0 survival, the number of age-1 fish each year is a better measure of recruitment. Mark-recapture models have been used to estimate age-1 juvenile abundance for multiple sturgeon species, including Atlantic Sturgeon and Shortnose Sturgeon (e.g., Farrae et al. 2009, Schueller and Peterson 2010, Kleinhans and Fox 2024, Bahr and Peterson 2016, Hale et al. 2016, Bahr and Peterson 2017, Baker et al. 2023). In the Apalachicola River, estimates of annual recruitment vary from 28–218 age-1 Gulf Sturgeon per year (Fox et al. 2021, Dula et al. 2022, D'Ercole 2023).

Because the precision of any mark-recapture estimate relies on suitable recapture rates (Conroy and Carroll 2009), this method requires substantial effort on a yearly basis. The precision of these estimates can be reduced when capturing animals is difficult because they are rare or elusive (Pine et al. 2001, Dudgeon et al. 2015, Withers et al. 2019, Lees et al. 2021). Additionally, environmental factors –such as temperatures in excess of permit restrictions or high river flows – can also reduce capture probability (Fox et al. 2021).

The Gulf Sturgeon Recovery/Management Plan lists a short-term objective of no decline in CPUE (catch-per-unit-effort) from a baseline level over a period of 3–5 years (USFWS and GSMFC 1995). However, CPUE is not always a good index of true abundance. Under the assumption that the number of fish captured is proportional to sampling effort, CPUE can be a useful index of abundance. However, changes in catchability which can result from a number of factors including behavioral responses to density or environmental conditions, can violate this assumption and render CPUE a poor index of abundance (Hubert et al. 2012). The relationship between CPUE and juvenile abundance needs to be addressed before implementing CPUE as a means to track yearly recruitment of age-1 fish to the population.

**Survival**

Understanding the survival of both adult and juvenile Gulf Sturgeon is also key to assessing population recovery. Several studies have used acoustic telemetry data to model survival in the Apalachicola. Using a simple method that looked only at the percentage of acoustically tagged fish that returned the subsequent year, Dula et al. (2022) calculated adult survival rates of 64–97% annually between 2016–2019. Mark-recapture estimates using a combination of acoustic detection and physical recapture data have recently been used to estimate adult survival in all seven natal river populations of adults, including the Apalachicola River (Parker 2023). Survival rates over five-year periods between 1990–2019 and a single two-year period showed adult survival to range between a low of 0.81 (0.77–0.85) in 2015–2019 and a high of 0.97 (0.60–1.00) in 2000–2004.

One proposed hypothesis for the lack of Gulf Sturgeon recovery is that elevated overwinter mortality of juvenile sturgeon (while they are in the estuary) acts as a bottleneck to adult recruitment (USFWS and NMFS 2022). In the Apalachicola River, previous studies have attempted to quantify overwinter survival by comparing mark-recapture-derived estimates of age-2 juvenile abundance to the abundance of that same cohort (as age-1 juveniles) the previous year. This approach has not been successful, perhaps because of the confounding effects of the presence of both spring- and fall-spawned populations in the river (Fox Lab unpublished data). Because detection of acoustically tagged sturgeon is more likely than physical recaptures of a fish, juvenile survival has also been calculated using percentages of acoustically tagged fish that returned the following year – the same kind of simple model used on the adults. Using this method, juvenile survival estimates from 2014–2017 varied from a low of 33.3% to a high of 90.0% with a study-wide mean of 62% of age-1 fish surviving to age-2. These survival estimates assumed 100% detection probability, making them very conservative. In addition, these models are not able to estimate survival on a finer temporal scale than annually, making them impractical for addressing the hypothesis of elevated mortality during winter.

Cormack-Jolly-Seber (CJS) models have recently been suggested as a better way to estimate the survival of Gulf Sturgeon (Colbourne et al. 2021). The CJS model estimates apparent survival($\Phi$) in an open population by considering recapture at time $i$+1 and the probability of recapture($p$) (Figure 1.2). Recaptures can include other methods of resighting or detection of individuals, such as acoustic telemetry.

Because these models cannot distinguish mortality from permanent emigration, the estimates they produce are of “apparent survival,” a combination of both. In the case of juvenile Gulf Sturgeon, emigration from one river system to another should be a non-issue, due to their strong fidelity to their natal river and inability to traverse open marine waters for extended periods, which is necessary to transition to other river systems (Altinok et al. 1998, Sulak et al. 2009, Rudd et al. 2014). Since CJS models can vary the period for both detection probability and apparent survival, mortality can be addressed on multiple temporal scales, including seasonally (Kahn et al. 2023).

For these reasons, the objectives of this study were to:

1. Investigate the relationship between age-1 abundance estimates and gillnet CPUE using mark-recapture data.
2. Test the hypothesis of elevated overwinter mortality for juvenile Gulf Sturgeon in the Apalachicola River.

The results of this study will fill knowledge gaps and assist managers in making decisions related to the future recovery plans for Gulf Sturgeon in this river system. The current method used to estimate juvenile abundance requires an intense annual sampling schedule, but if the results from objective 1 indicate a strong positive relationship between juvenile abundance and CPUE, researchers and managers may be able to reduce sampling effort while continuing to collect information on recruitment trends. For instance, recruitment can be evaluated with current intensive mark-recapture techniques in some years, supplemented with less intensive sampling and CPUE monitoring in others, reducing the total sampling effort. The lack of a strong relationship between abundance estimates and CPUE would support current recruitment evaluation methods and would highlight that the CPUE-based recovery criteria are not useful in accurately tracking species abundance (short-term recovery objective; USFWS and GSMFC 1995).

In order for managers to make impactful changes to safeguard Gulf Sturgeon, information on when they are vulnerable to threats can identify areas to focus on mitigating actions. If our results from objective 2 indicate that survival is in fact lowest during the winter when juveniles are in the estuary – steps can be taken to identify and mitigate specific threats during that time. In addition, having accurate survival estimates will help future studies calculate the growth rate of the population, which is necessary in addressing the recovery criteria of a stable or increasing population (USFWS and GSMFC 1995).

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## Tables and Figures

**Table 1.1:** Recruitment estimates from mark-recapture studies done on adult and subadult Gulf Sturgeon in the Apalachicola River. For each study we have shown, the year the estimate is derived from, the length cutoff used for each study (in mm), the point estimate of abundance, 95% confidence intervals (CI) of the estimate, and the publication they came from.

| Study Year | Size cutoff (mm) | Estimate | 95% CI | Publication source |
|---|---|---|---|---|
| 1999 | >700 TL | 260 | 230-310 | Pine and Allen 2005 |
| 2003 | >660 TL | 350 | 221-648 | USFWS 2004 |
| 2004 | >700 TL | 350 | 260-440 | Pine and Allen 2005 |
| 2014 | >900 FL | 886 | 674-1211 | Dula et al. 2022 |
| 2021 | >900 FL | 406 | 195-854 | Dula et al. 2022 |

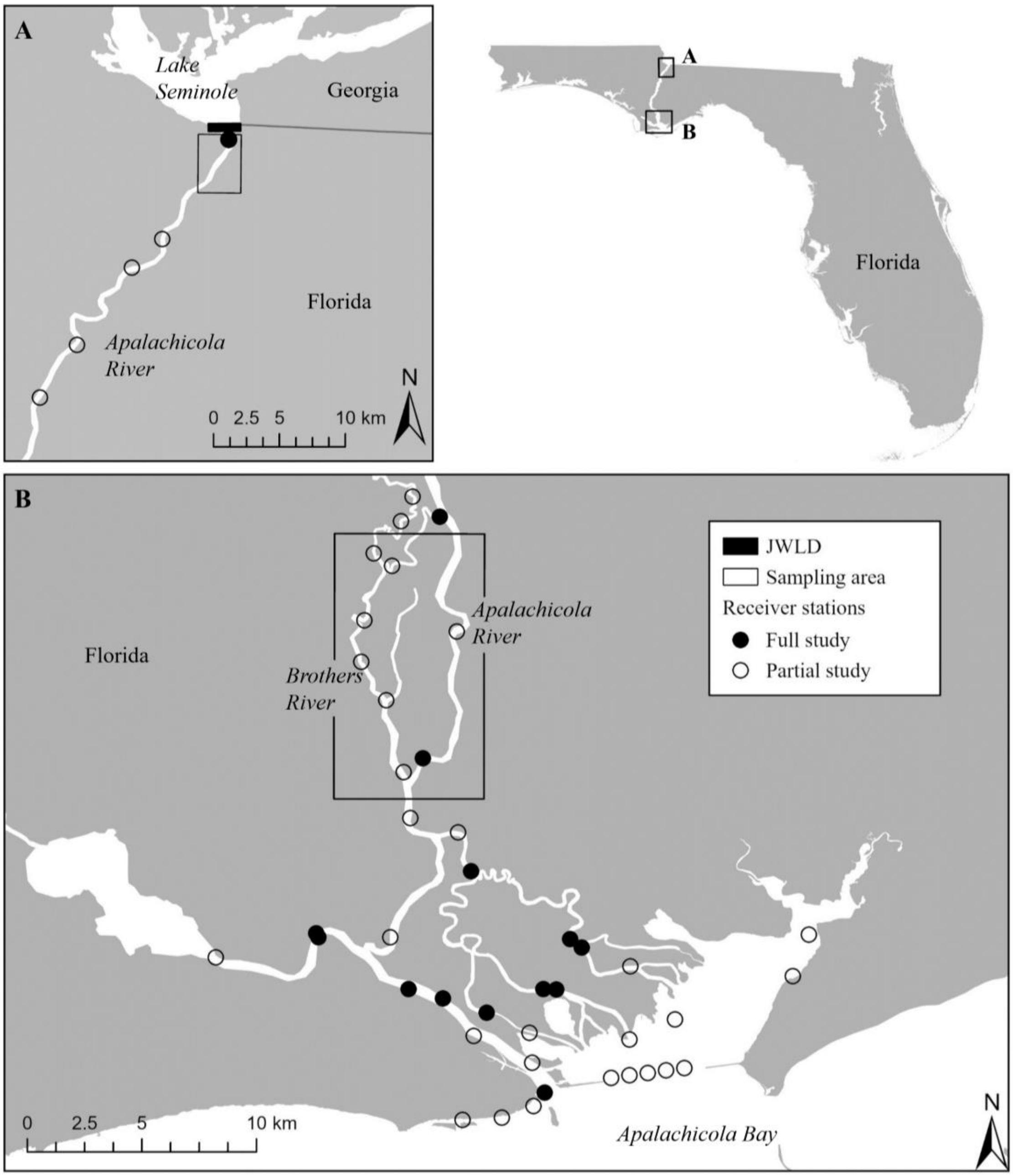


**Figure 1.1:** Map of the study site in the Apalachicola River in Florida: (**A**) map of the upper Apalachicola River downstream of the Jim Woodruff Lock and Dam (JWLD), indicated by a black rectangle) and (**B**) the lower Apalachicola River and Brothers River. Acoustic receiver station locations are indicated by circles (full black circles indicate receiver stations that were active for the full study period from 2014–2023 and open circles indicate those that were active for a portion of the study period. Sampling for juvenile Gulf Sturgeon between 2014–2022 occurred within the boxes outlined in black.

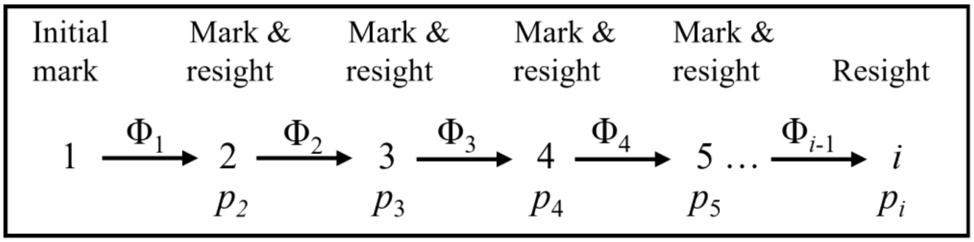


**Figure 1.2:** Structure of Cormack-Jolly-Seber models. Apparent survival (Φ), the probability that an animal will survive and not permanently emigrate from the study area, and detection probability (*p*), the probability that an animal with be detected between study periods, are parameters estimated by the model.

# CHAPTER 2

# ASSESSING THE CPUE-RECRUITMENT RELATIONSHIP OF AGE-1 GULF STURGEON IN THE APALACHICOLA RIVER, FLORIDA[1]

[1]R.T. Wilson, A.J. Kaeser, B.J. Irwin, M.J. Hamel, and A.G. Fox. To be submitted to *North American Journal of Fisheries Management*.

**Abstract**

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is an anadromous fish that historically occupied the northern Gulf of Mexico from southeast Texas to Tampa Bay, Florida. During the 20th century, commercial harvest and habitat fragmentation led to major population declines and a listing as threatened under the Endangered Species Act in 1991. The Gulf Sturgeon management plan lists catch-per-unit-effort (CPUE) as the metric to track changes in population size, recent estimates of annual recruitment (i.e., age-1 abundance) have relied on more time- and effort- intensive mark-recapture methods, because the relationship between CPUE and abundance has not been tested for Gulf Sturgeon. The objective of this study was to assess the CPUE-abundance relationship for age-1 Gulf Sturgeon in the Apalachicola River, Florida. Previous studies have used mark-recapture methods to estimate age-1 abundance in this population from 2014–2022. We calculated CPUE based on several reduced-effort sampling scenarios and used linear regressions to compare CPUE to the published abundance estimates. We found a significant ($\alpha < 0.05$) positive linear relationship between CPUE and abundance for age-1 Gulf Sturgeon during the whole summer, and during two of the shortened sampling scenarios (June and partial May-June sampling). Although CPUE in this population does closely tracks the estimated total abundance, we recommend the continued use of mark-recapture to estimate recruitment due to small samples sizes and large confidence intervals in predicted abundances based on CPUE.

**Introduction**

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is a threatened anadromous fish native to the northern Gulf of Mexico. The species is identifiable by its large size, reaching >2 m in length, rows of bony scutes, and heterocercal tail. Gulf Sturgeon share many morphological features with their sister subspecies, the Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), but are differentiated genetically as well as by their geographic distribution (Vladykov 1955, Huff 1975, King et al. 2001). Throughout their range, Gulf Sturgeon population declined sharply in the 20th century due mainly to commercial harvest for their meat and roe, as well as habitat loss from dam construction, dredging, and other anthropogenic river modifications (Huff 1975, Wooly and Crateau 1985, Sulak et al. 2016, USFWS and NMFS 2022). These declines in populations led to moratoriums on harvest of the species on a state by state basis between 1974 and 1990 (Odenkirk 1989, Sulak et al. 2016), followed by their listing as threatened under the Endangered Species Act (ESA) in 1991. According to the Gulf Sturgeon Recovery/Management Plan, a criterion for recovery would be a self-sustaining population with a stable or positive growth rate (USFWS and GSMFC 1995). This recovery objective was written to be applied on a river-specific basis, due to the strong fidelity Gulf Sturgeon have to their natal river (Rudd et al. 2014). In order to assess this criterion, one recovery task was to implement standardized population sampling and monitoring techniques in order to assess population growth rate.

The Apalachicola River is thought to have had the largest historic population of Gulf Sturgeon, with an estimated population of 18,000 adults prior to 1900 (Ahrens and Pine 2014). The Apalachicola River is the final drainage of the Apalachicola-Chattahoochee-Flint river basin (ACF) which drains approximately 48,500 $km^2$ across Georgia, Alabama, and Florida (Livingston 2008). With the construction of the Jim Woodruff Lock and Dam (JWLD) in the 1950s, the riverine range of Gulf Sturgeon in the ACF was reduced by approximately 78% (USFWS and NMFS 2022). The Apalachicola River population of Gulf Sturgeon was also heavily affected by commercial fishing (Flowers 2008). Since the ESA listing, adult population abundance in the Apalachicola River has been estimated multiple times using mark-recapture methods; point estimates of abundance vary from 260–886 adult individuals (USFWS 2004, Pine and Allen 2005, Dula et al. 2022). Since 2012, adult Gulf Sturgeon population abundance in the Apalachicola River has also been monitored through annual side-scan sonar index counts (Dula et al. 2022, USFWS and NMFS 2022). Side-scan sonar imaging has recently been used to enumerate adult and subadult sturgeons in various other rivers as well (Thomas and Haas 2002, Flowers and Hightower 2015, Andrews et al. 2020, Kazyak et al. 2020). Sonar-based index counts in the Apalachicola River between 2012–2018 consistently observed over 500 individuals, but there was a sharp decline between 2018 and 2019 due to Hurricane Michael, a category 5 hurricane that hit the lower Apalachicola River between the 2018 and 2019 index counts (Dula et al. 2022). Although these sonar index counts provide timely information on abundance of adult and sub-adult Gulf Sturgeon, this approach cannot currently be used for smaller-bodied juveniles.

Age-1 Gulf Sturgeon abundance in the Apalachicola River has been estimated annually using mark-recapture techniques since 2013 (Fox et al. 2021, Dula et al. 2022, D'Ercole 2023). These age-1 estimates are a quantified measure of annual recruitment, one of the research priorities for the species (USFWS and NMFS 2022). This focus on age-1 instead of age-0 (young-of-year [YOY]) to enumerate recruitment is done for two reasons: YOY disperse widely making targeted capture difficult (Sulak and Clugston 1999, Kirk et al. 2010), and YOY face high mortality, with less than 1% of spawned eggs estimated to reach age-1 (Pine et al. 2001). In the Apalachicola River, point estimates of abundance for age-1 fish are between 28–218 individuals per year (Fox et al. 2021, Dula et al. 2022. D'Ercole 2023).

The precision of any mark-recapture estimate relies on a suitable recapture rate (Conroy and Carroll 2009), so quantifying annual recruitment with this method requires substantial effort on a yearly basis; even more effort may be required when working with rare or elusive organisms (Dudgeon et al. 2015, Withers et al. 2019, Lees et al. 2021), or when environmental factors can reduce capture probability (Fox et al. 2021). Because of these issues, mark-recapture estimates take considerable time and resources to attain meaningful estimates. When managers are monitoring a population, they often employ standardized methods of repeatedly sampling the system during a season of each year to evaluate changes in that population. Change in catch-per-unit-effort (CPUE) during standardized sampling is a commonly used method to track relative changes in abundance of population in fisheries (Hubert and Fabrizio 2007). This method relies on the assumption that any changes in true population abundance are reflected as changes in CPUE. Calculating changes in CPUE typically requires less sampling effort than estimating abundance with mark-recapture methodology. The Gulf Sturgeon Management/Recovery Plan lists CPUE as a method to track abundance changes to assess if the population is meeting the criteria of stability or growth (USFWS and GSMFC 1995). If the number of fish captured is in fact proportional to abundance, CPUE can be a useful index of abundance. However, changes in catchability as a result of environmental conditions, fish behavioral responses (*e.g.*, to different population densities), or other factors can violate the assumption of constant catchability and render CPUE a poor metric for tracking trends in relative abundance (Hubert et al. 2012). For Gulf Sturgeon, the relationship between age-1 abundance and CPUE needs to be investigated before CPUE can be implemented as a means to track yearly recruitment of age-1 fish to the population. The primary utility in using CPUE instead of mark-recapture is the reduction in yearly effort required to produce recruitment trend information. Therefore, the objective of this study was to compare the relationship between age-1 cohort abundance (as estimated by mark-recapture methods) and CPUE.

## Methods

### *Study Site*

The Apalachicola flows approximately 171 km from the JWLD to Apalachicola Bay and the Gulf of Mexico. It is surrounded largely by federally and state protected lands including Tates's Hell State Forest, Apalachicola National Forest, Apalachicola Wilderness and Environmental Area, and the Apalachicola River Water Management Area. The Brothers River is a lower tributary to the Apalachicola River joining near river kilometer (kilometers from the mouth of the river) 19 (Figure 2.1). The Brothers River supports summer aggregation areas for Gulf Sturgeon of all life stages and has been the focus of sampling for the species in the system (Wooley and Crateau 1985, Fox et al. 2021, Dula et al. 2022).

### *Sturgeon Capture*

Capture of juvenile Gulf Sturgeon occurred between 2014–2022 in the Apalachicola and Brothers rivers. Sampling occurred in May through July for most years of the study, although sampling continued as late as October in some years. Sampling sites were chosen from previously determined aggregation areas, primarily within the Brothers River (Marbury 2016, Hancock 2019, Fox et al. 2021). The majority of sampling occurred each year at those set sites. Sampling sites were typically visited once per week but were occasionally visited multiple times within a week. Sturgeon were captured using anchored experimental gill nets composed of three 15-meter panels of 7.6-, 8.9-, and 10.2-cm stretch monofilament mesh. Two to five nets were deployed at a time, with soak times of 30–120 minutes depending on weather conditions, water temperature, and dissolved oxygen levels. All captured sturgeon were measured for fork and total length, weighed, and checked for external tags (*e.g.*, FLOY tags) or internal tags (*e.g.*, passive integrated transponders [PIT]). If no PIT tag was present, one was implanted near the base of the dorsal fin. All fish were then immediately released near their capture location.

*Analysis of Abundance*

Our analysis used previously published estimates of age-1 abundance (i.e., annual recruitment) for Gulf Sturgeon in the Apalachicola River (Fox et al. 2021, Dula et al. 2022, and D'Ercole 2023). In those studies, age was assigned by interpreting the modal distribution of length-frequency histogram of captured juvenile Gulf Sturgeon (Moran 2018, Fox et al. 2021). Ages of some individuals were also validated by consensus reads of pectoral fin spines. The abundance of each year's age-1 cohort was estimated using Huggins closed capture models (Huggins 1991). During our study period, age-1 abundance estimates varied from a low of 28 in 2017 to a high of 218 in 2014 (Table 2.1).

*Analysis of CPUE*

For 2014–2022, we calculated CPUE as age-1 captures per net hour; this accounted for variations in number of nets set per sampling occasion and varied soak times. We calculated CPUE at several time scales, including whole summer sampling and several scenarios of reduced sampling effort:

1. Sampling in May only
2. Sampling in June only
3. Partial sampling in May and June (the first 5 sampled days per month; 10 days total), and
4. Whole summer sampling.

For each study year, the number of age-1 Gulf Sturgeon captures and net hours of sampling were calculated for each of these sampling scenarios. In 2014 and 2021 sampling only occurred during four days in May so the partial sampling CPUE for those two years included four days of May sampling and five from June. In 2016, sampling did not begin until June, so CPUE was not available for May or the partial May and June intervals for that year.

In addition to calculating CPUE under these four sampling scenarios, CPUE was also calculated using two different methods. In the first method (total CPUE), the catch included in CPUE included all capture events, including initial captures and any recapture(s) of age-1 fish:

$$CPUE_{tot} = \frac{all\ \ age\text{-}1\ Gulf\ Sturgeon\ captures}{net\text{-}\ hours}$$

The second method (unique CPUE) only considered initial captures of age-1 fish, and any subsequent recapture events of a fish were removed from the calculation:

$$CPUE_{unq} = \frac{unique\ age\text{-}1\ Gulf\ Sturgeon\ captures}{net\text{-}\ hours}$$

*Assessing the CPUE-Abundance Relationship*

In order to address the primary assumption required to use CPUE as a means to track abundance – that the number of fish captured is proportional to the amount of effort – the relationship between estimated age-1 Gulf Sturgeon abundance and CPUE was investigated using a suite of linear regression models (Table 2.2). These models related $CPUE_{tot}$ and $CPUE_{unq}$ during the whole summer sampling scenario and $CPUE_{unq}$ during the three shortened sampling scenarios to the point estimates (derived through mark-recapture analysis) of age-1 abundance each year. Model results were assessed for significance ($\alpha = 0.05$), and any models with a significant relationship between CPUE and abundance were then compared using adjusted $r^2$ values.

## Results

*Sturgeon Capture*

Between 2014 and 2022, a total of 3,367 nets were set for 3,602 hours in the Brothers and Apalachicola rivers. Yearly effort varied from a low of 278 net-hours in 2016 to a high of 692 net-hours in 2019 (Table 2.3). There were a total of 707 captures of 535 unique individual age-1 Gulf Sturgeon during the study period. Yearly unique captures varied from 19 individuals in 2018 to 145 in 2014 (Table 2.3). Our study-wide CPUE of unique age-1 Gulf Sturgeon was 0.149 fish per net-hour meaning it took approximately 6.7 hours of effort per captured age-1 fish.

*Unique vs. Total CPUE*

When we investigated the relationship between both total CPUE and unique CPUE vs. abundance during the whole summer sampling scenario, we found a significant linear relationship with $p < 0.05$ for both CPUE metrics (Table 2.2). The unique CPUE model (adjusted $r^2 = 0.696$) better fit the data than the total CPUE model (adjusted $r^2 = 0.488$) (Table 2.2). The relationship between unique-capture CPUE and the estimated abundance was positive and linear; age-1 Gulf Sturgeon abundance was expected to increase by 54.2 individuals for every 0.1 increase in CPUE (Figure 2.2). Because the relationship was stronger, for the remainder of our analyses, we focused on unique CPUE.

*Shortened Sampling Season Scenarios*

There was a significant relationship ($p < 0.05$) between unique CPUE and abundance for the June and the Partial May-June sampling scenarios (Table 2.2). The relationship was not significant for the May sampling scenario. Both significant models had a positive linear relationship between CPUE and abundance. For the June sampling scenario, unique CPUE showed an adjusted $r^2 = 0.396$ (Table 2.2), with a predicted 36.1 increase in abundance for every

0.1 increase in CPUE (Figure 2.3). In the partial May-June sampling scenario, unique CPUE resulted in an adjusted $r^2 = 0.463$ (Table 2.2) with a predicted 39.6 increase in abundance for every 0.1 increase in CPUE (Figure 2.4).

**Discussion**

The primary assumptions of using CPUE as an index of abundance are that the number of fish captured is proportional to the amount of effort expended, and that the number of fish captured reflects true abundance (Hubert et al. 2012). Thus, if CPUE increases from one year to the next, it is because the fish abundance has increased. Because changes in fish behavior can change catchability (Hubert and Fabrizio 2007, Hubert et al. 2012), that primary assumption is often violated and renders CPUE a poor metric for tracking population abundance. For this reason, it has been suggested that long-term studies move away from CPUE and instead use measures of total abundance (Harley et al. 2001, de Moor et al. 2011, Erisman et al. 2011). However, in some cases CPUE can provide sufficient information with substantially lower effort and/or cost.

We found that there was a significant ($p < 0.05$) positive linear relationship between CPUE of age-1 Gulf Sturgeon from the entire sampling season and the estimated abundance of age-1 sturgeon for each year, for both unique individuals and for total age-1 catch. In short, whole-season standardized catch of age-1 Gulf Sturgeon was proportional to their estimated total abundance. However, using unique capture CPUE provided a better fit as indicated by adjusted $r^2$ value (Table 2.2).

Although we found a significant positive relationship between abundance and CPUE from whole summer sampling, there is little utility in using CPUE instead of mark-recapture estimates unless sampling effort can be reduced. Thus, we investigated unique CPUE at three simulated shortened time scales. We did not find a significant relationship between unique capture CPUE in May and estimated total abundance. This could be due to environmental factors, such as higher flows making gear less effective at capture, or other factors relating to migratory life history of the fish. During the spring, juvenile Gulf Sturgeon are moving from the estuary into the river, so sampling in May will not be able to capture individuals that have not yet returned to sampling sites, resulting in possible incomplete sampling of the population.

There was a significant ($p < 0.05$) relationship between abundance and both unique capture CPUE in June and unique capture CPUE from partial sampling in May and June. Both sampling scenarios require substantially lower effort than the whole-summer sampling currently required to derive mark-recapture based estimates of abundance. Either shortened sampling scenario would be more time effective solutions to long-term monitoring of the age-1 Gulf Sturgeon population, in terms of effort, time, and the associated sampling and personnel costs. Sampling for a shorter time period would also reduce stress or potential mortality of captured sturgeon. Although gill-netting for sturgeon does not pose a major risk of mortality to sturgeon when conditions are favorable (Baker et al. 2008, Kahn and Mohead 2010, Damon-Randall et al. 2010). Being able to obtain CPUE data that accurately reflect age-1 population changes over a relatively short period of time would be especially useful in years where environmental conditions shorten the available sampling season (*e.g.*, tropical storms or high temperatures).

*Management Implications*

Currently, sampling to estimate annual recruitment (i.e., age-1 abundance) of Gulf Sturgeon in the Apalachicola River requires sampling for the whole summer (May–July) to obtain enough capture and recapture data for Huggins closed capture models to run successfully.

However, environmental conditions that preclude sampling may result in an inability to quantify the age-1 cohort that year. However, we have demonstrated that there are two sampling scenarios that can collect CPUE data that accurately reflect changes in abundance. The collection of CPUE data instead of total abundance data can result in substantial reductions in effort, and therefore cost.

We suggest that the partial May-June sampling schedule would be preferable over the sampling period due to the shorter time frame of sampling (two weeks compared to a month) and the better model fit (Table 2.2). In addition, the partial May and June sampling gives a more realistic timeframe for sampling as it allows for effort to be divided in the case of adverse sampling conditions compared to the continuous sampling for one or more months. Environmental conditions such as high flows in spring, high temperatures in late summer, and severe storms during hurricane season (June–November) often dictate when sampling can occur. Allowing sampling to be broken up into two separate weeks during the typical sampling season helps avoid adverse gill-netting conditions. Sampling in May and June also would reduce the number of days sampling in elevated water temperatures, reducing stress of captured sturgeon (Kahn and Mohead 2010).

Although our results indicate the possibility of using CPUE as a metric to track the age-1 abundance of Gulf Sturgeon in the Apalachicola, there are still some caveats about using CPUE instead of estimated total abundance. This study assessed only 9 years for whole summer sampling and June sampling and 8 years for May sampling and partial May and June sampling. Changing conditions in future years may result in different relationships between abundance and CPUE during various time periods. Additionally, the estimated total abundances of age-1 sturgeon derived from Huggins mark-recapture models were low (28–218) with a relatively high degree of uncertainty in each year. When we compared the age-1 abundances predicted from our linear models based on CPUE models to abundances derived from Huggins mark-recapture models, the width of the 95% confidence intervals for the CPUE-based models were often wider than the Huggins models. This indicates higher uncertainty in the estimates (Figure 2.5). In addition, there are multiple years where the predicted estimate from the linear models falls outside of the range of the Huggins models confidence intervals (Figure 2.5). For these reasons, we would caution the use of CPUE as a metric to track abundance of age-1 Gulf Sturgeon in the Apalachicola River and continue using mark-recapture to enumerate recruitment. In years when whole summer sampling is not possible, unique CPUE may still be useful in getting relative abundance information for the population.

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**Tables and Figures**

**Table 2.1:** Gulf Sturgeon age-1 abundance estimates in the Apalachicola River from 2014–2022. The 95% confidence interval for each estimate as well as the source for each estimate is given.

| Year | Age-1 abundance | 95% Confidence interval | Source |
|---|---|---|---|
| 2014 | 218 | 190–241 | Fox et al. 2021 |
| 2015 | 54 | 34–119 | Fox et al. 2021 |
| 2016 | 51 | 35–67 | Fox et al. 2021 |
| 2017 | 28 | 24–36 | Fox et al. 2021 |
| 2018 | 31 | 21–48 | Fox et al. 2021 |
| 2019 | 103 | 87–132 | Dula et al. 2022 |
| 2020 | 122 | 88–189 | Dula et al. 2022 |
| 2021 | 139 | 100–209 | D'Ercole 2023 |
| 2022 | 161 | 136–197 | D'Ercole 2023 |

**Table 2.2:** Model description and results from linear regression analysis of abundance estimates and catch-per-unit-effort (CPUE) for age-1 Gulf Sturgeon in the Apalachicola River, Florida from 2014–2022. Included for each model are the range of years used in each regression, CPUE parameters including if total captures were used (including recaptures of individuals) or only unique captures (recaptures of individual fish excluded), and time scale of interest. Results shown included the *p*-value and adjusted $r^2$ value for each regression.

| | | CPUE parameters | | | |
|---|---|---|---|---|---|
| **Model** | **Years included** | **Captures** | **Time Scale** | ***p*-value** | **Adj. $r^2$** |
| $CPUE_{tot}$ | 2014–2022 | Total | Total | 0.022 | 0.488 |
| $CPUE_{unq}$ | 2014–2022 | Unique | Total | 0.003 | 0.696 |
| $CPUE_{may}$ | 2014, 2015, 2017-2022 | Unique | May | 0.367 | 0.000 |
| $CPUE_{jun}$ | 2014-2022 | Unique | June | 0.041 | 0.396 |
| $CPUE_{mj}$ | 2014, 2015, 2017-2022 | Unique | Partial May & June | 0.038 | 0.463 |

**Table 2.3:** Total net-hours of sampling effort and captures of age-1 Gulf Sturgeon in the Apalachicola River system between 2014–2022. Captures are reported as both the total number of capture events of age-1 Gulf Sturgeon and the unique number of individuals captured each year of the study.

| Year | Net-hours | Total captures | Unique captures |
|---|---|---|---|
| 2014 | 455 | 147 | 145 |
| 2015 | 356 | 23 | 17 |
| 2016 | 278 | 65 | 39 |
| 2017 | 311 | 45 | 24 |
| 2018 | 535 | 25 | 19 |
| 2019 | 692 | 125 | 80 |
| 2020 | 314 | 102 | 87 |
| 2021 | 379 | 62 | 47 |
| 2022 | 282 | 113 | 77 |
| *Total* | *3602* | *707* | *535* |

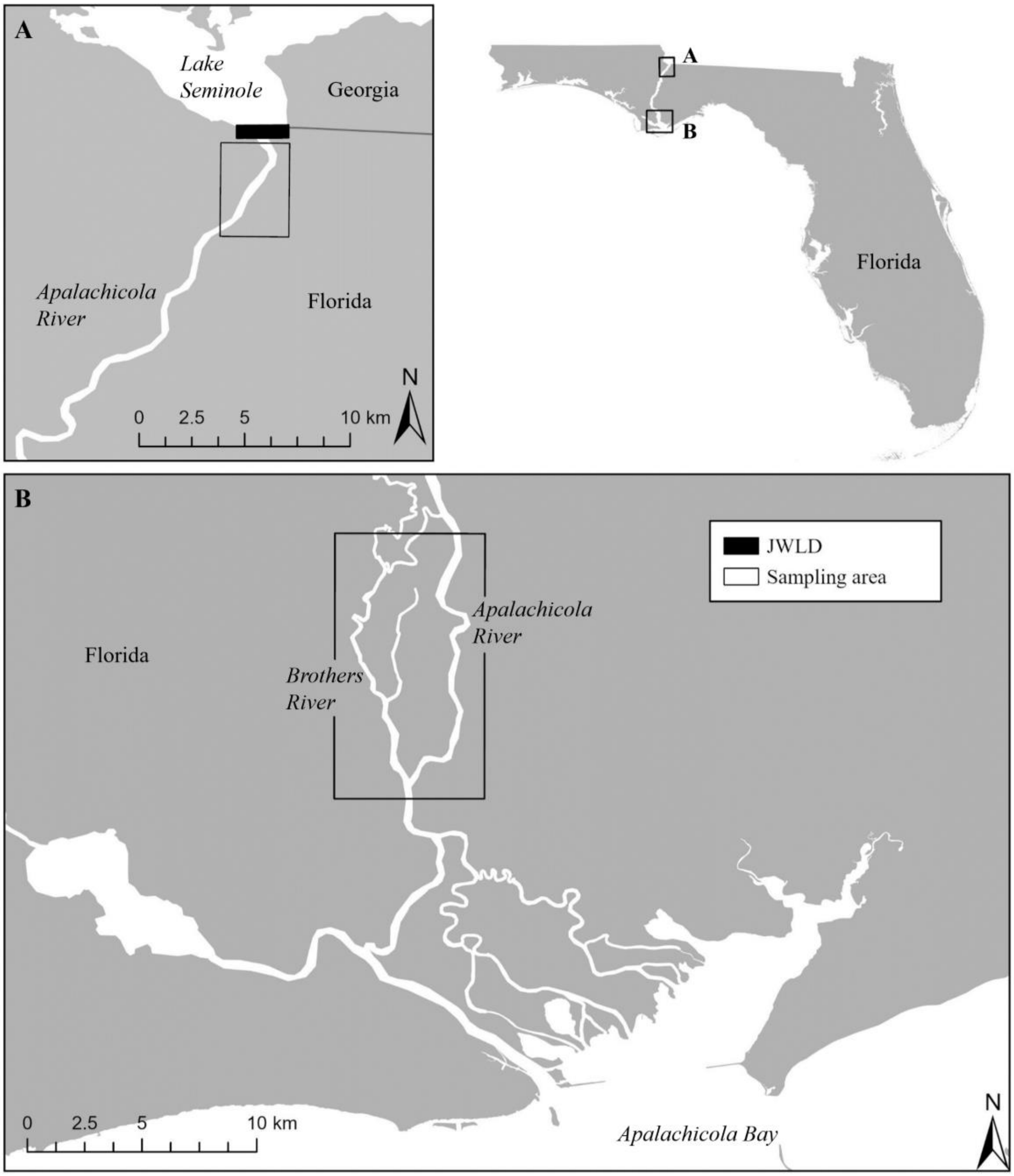


**Figure 2.1:** Map of the study site in the Apalachicola River in Florida: (**A**) map of the upper Apalachicola River downstream of the Jim Woodruff Lock and Dam (JWLD), indicated by a black rectangle) and (**B**) the lower Apalachicola River and Brothers River. Sampling for juvenile Gulf Sturgeon between 2014–2022 occurred within the boxes outlined in black.

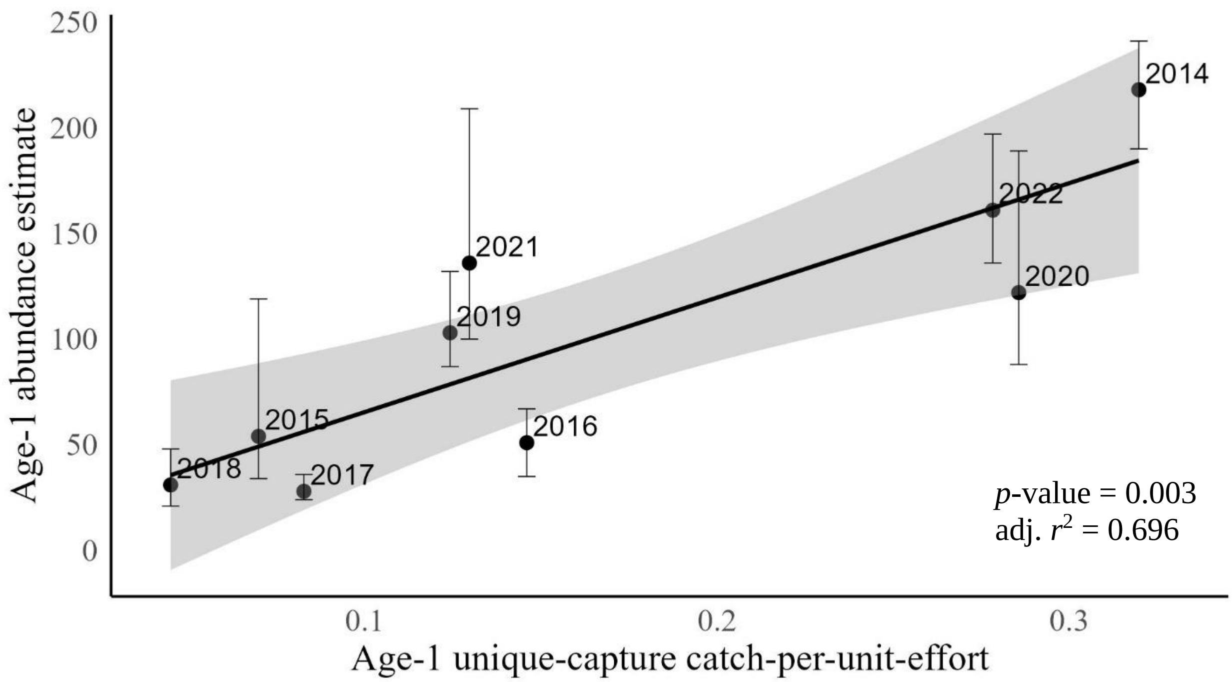


**Figure 2.2:** Linear regression analysis of catch-per-unit-effort (CPUE) and abundance estimates of age-1 Gulf Sturgeon in the Apalachicola River, Florida between 2014–2022. CPUE represents the total captures of unique Gulf Sturgeon by the total net hours during each sampling season. Abundance estimates came from previously reported estimates with 95% confidence intervals shown by vertical black bars (Fox et al. 2021, Dula et al. 2022, D'Ercole 2023). The linear trend line is displayed in black with the 95% confidence interval area shown in gray.

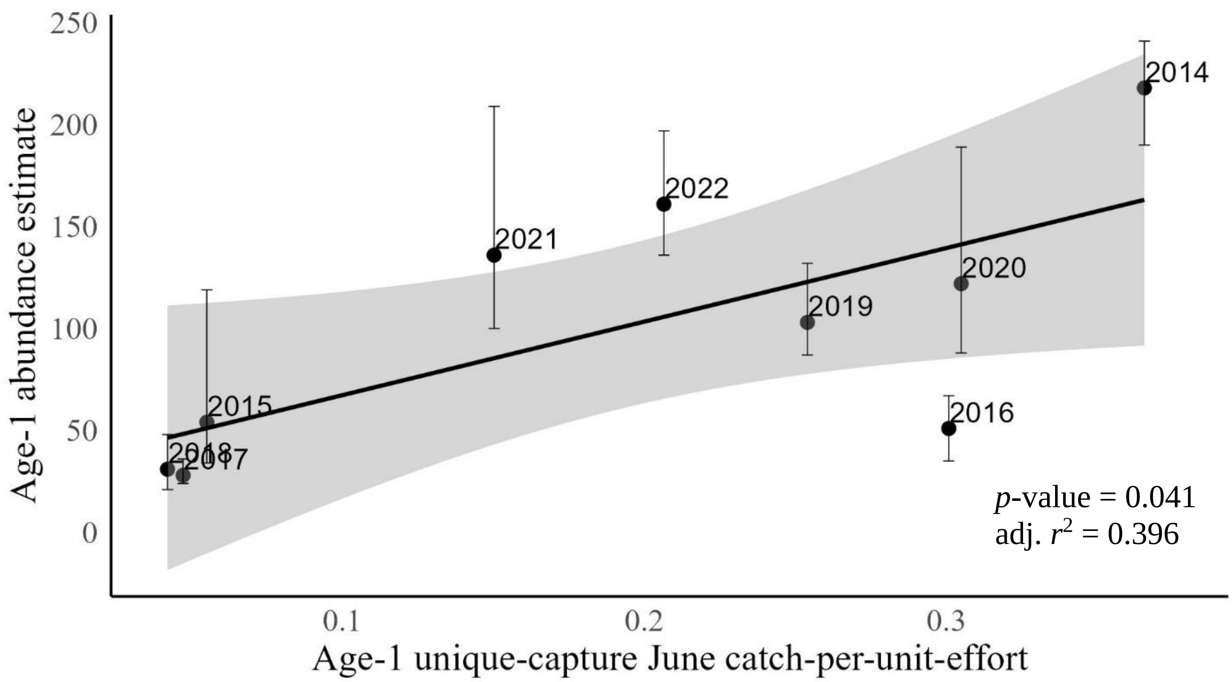


**Figure 2.3:** Linear regression analysis of catch-per-unit-effort (CPUE) and abundance estimates of age-1 Gulf Sturgeon in the Apalachicola River, Florida between 2014–2022. CPUE represents the total captures of unique Gulf Sturgeon in the month of June by the total net hours during that time. Abundance estimates came from previously reported estimates with 95% confidence intervals shown by vertical black bars (Fox et al. 2021, Dula et al. 2022, D’Ercole 2023). The linear trend line is displayed in black with the 95% confidence interval area shown in gray.

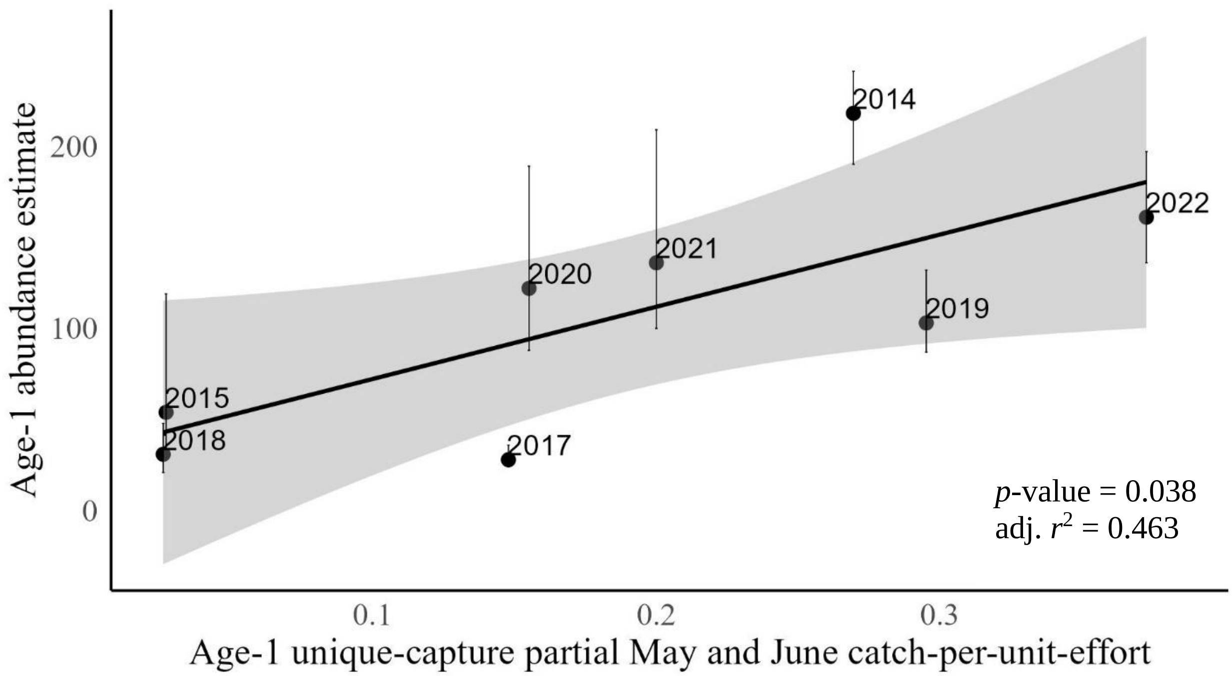


**Figure 2.4:** Linear regression analysis of catch-per-unit-effort (CPUE) and abundance estimates of age-1 Gulf Sturgeon in the Apalachicola River, Florida from 2014, 2015, and 2017–2022. CPUE represents the total captures of unique Gulf Sturgeon in the first week sampling in May and June by the total net hours during that time. Abundance estimates came from previously reported estimates with 95% confidence intervals shown by vertical black bars (Fox et al. 2021, Dula et al. 2022, D'Ercole 2023). The linear trend line is displayed in black with the 95% confidence interval area shown in gray.

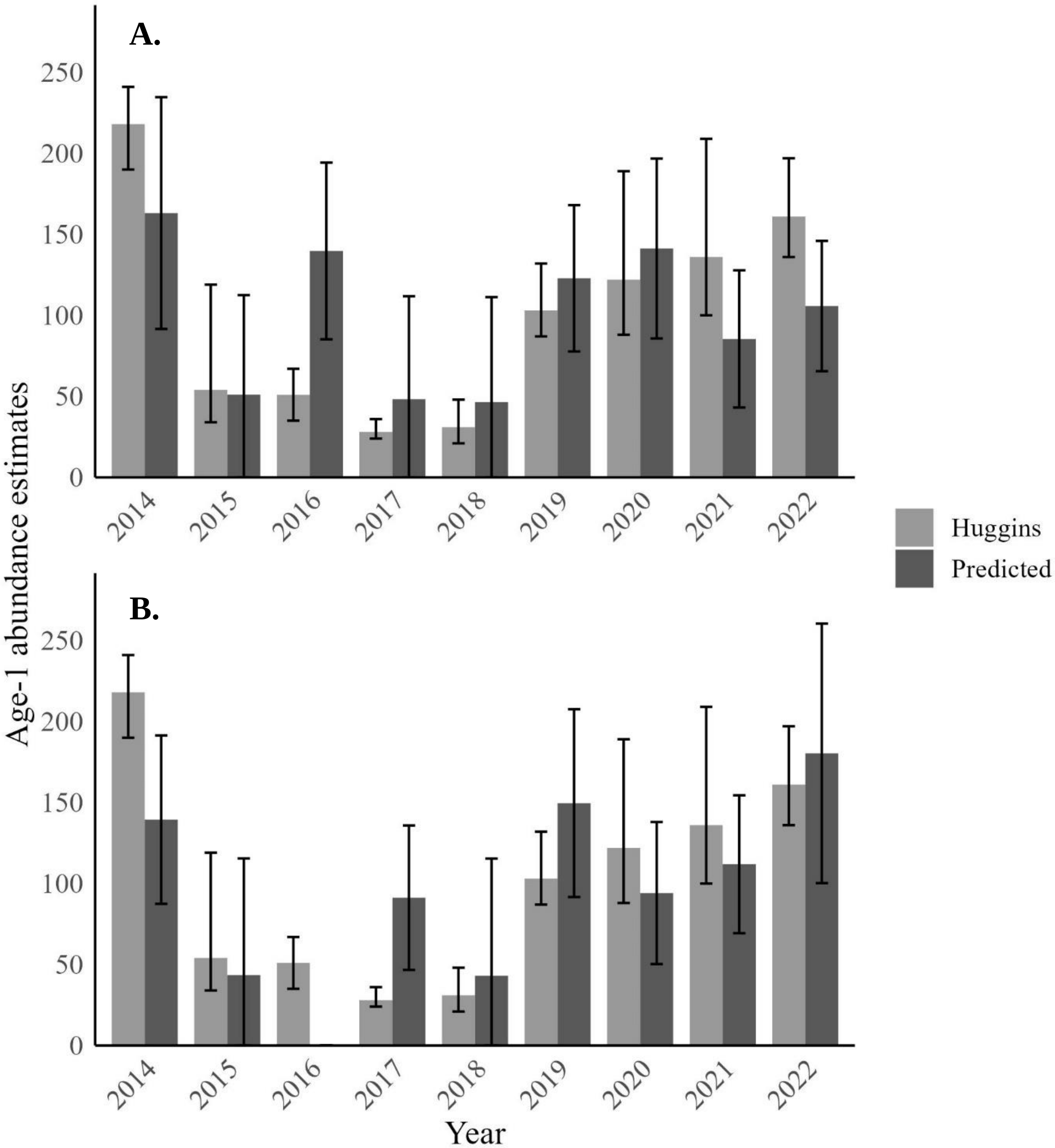


**Figure 2.5:** Comparisons between abundance estimates from Huggins mark recapture estimates and linear regression predicted values of age-1 Gulf Sturgeon in the Apalachicola River, Florida from 2014–2022. Predicted estimates (dark gray) came from linear regression analysis of (**A**) unique capture CPUE during June sampling and (**B**) unique capture CPUE during partial sampling in May and June. Huggins mark recapture estimates (light grey; **A** & **B**) came from previously publications (Fox et al. 2021, Dula et al. 2022, D'Ercole 2023). Confidence intervals (95% CI) are shown with black error bars for all estimates. There is no predicted estimate for 2016 in the May and June partial sampling comparison (**B**) as sampling did not occur during May that year.

CHAPTER 3

# SEASONAL AND ANNUAL SURVIVAL OF JUVENILE GULF STURGEON IN THE APALACHICOLA RIVER, FLORIDA[1]

[1]R.T. Wilson, A.J. Kaeser, B.J. Irwin, M.J. Hamel, and A.G. Fox. To be submitted to *Endangered Species Research*.

## Abstract

The Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) is an anadromous sturgeon that has undergone major population declines throughout their range. Habitat alteration and overharvest in commercial fisheries led to the species being listed as threatened under the Endangered Species Act in 1991. To accurately monitor populations trends and recovery, an accurate understanding of population dynamics – including survival – is necessary. Juvenile Gulf Sturgeon are migratory within their natal river system; their survival is not well-studied, but the over-winter period when they inhabit more saline waters has been identified as a potential bottleneck to juvenile survival. The objective of this study was to quantify over-winter and annual survival of age-1 Gulf Sturgeon in the Apalachicola River system. From 2014–2022 we used acoustic telemetry and Cormack-Jolly-Seber models to estimate apparent survival rates in each seasonal period. Seasonal apparent survival rates ranged from 0.913 in the fall to 0.995 in the winter. Contrary to our hypothesis, our results indicated that survival was high across all seasons with no significant difference in overwinter survival compared to other periods. We also observed high annual survival rates in most years. These findings suggest that overwinter mortality of age-1 juveniles is not a major bottleneck to Gulf Sturgeon population recovery within the Apalachicola River.

## Introduction

Gulf Sturgeon (*Acipenser oxyrinchus desotoi*) are a large bodied, long-lived, ray-finned fish native to the northern Gulf of Mexico (GOM). They are a subspecies of Atlantic Sturgeon (*A. o. oxyrinchus*) and are differentiated genetically (King et al. 2001), as well as by their geographic distribution and relative head, spleen, and pectoral fin size (Vladykov 1955). Gulf

Sturgeon are anadromous and require both fresh- and saltwater habitat on an annual basis. During the early 20th century, a robust Gulf Sturgeon fishery was established leading to declines in populations range-wide, including extirpation from several river systems (Huff 1975, Sulak et al. 2016). Prior to commercial exploitation, their range spanned much of the northern GOM including major coastal river systems from southeast Texas to Tampa Bay, Florida (Sulak et al. 2016). Currently, only seven coastal river systems support spawning populations – the Pearl, Pascagoula, Escambia, Yellow/Blackwater, Choctawhatchee, Apalachicola, and Suwannee Rivers. Population declines led to fishing moratoriums on a state-by-state basis until 1991, when Gulf Sturgeon were listed as threatened under the Endangered Species Act (ESA).

Although harvest of the species has been halted for several decades, threats to the species persist. The construction of dams and other river modifications continue to affect Gulf Sturgeon by fragmenting their historic freshwater range, altering their physical habitat, and regulating flow regime (USFWS and NMFS 2022). Other anthropogenic threats to Gulf Sturgeon include bycatch in entanglement and trawl fisheries, dredging and channelization, vessel strikes, and contamination releases such as the Deepwater Horizon oil spill (Wooly and Crateau 1985, Sulak et al. 2016, USFWS and NMFS 2022). Gulf Sturgeon are also exposed to a number of natural sources of mortality. Like most fishes, mortality of young fish is high – especially for age-0 (young-of-year [YOY]) fish: less than 1% of spawned eggs are believed to survive to age-1 (Pine et al. 2001). Hurricanes have been shown to cause episodic mass mortality to adult populations if they occur while Gulf Sturgeon are river resident (Dula et al. 2022). During winter months, as Gulf Sturgeon occupy brackish and marine habitat to feed, small-bodied juveniles are thought to be at a higher risk of mortality compared to older cohorts. Estuarine threats include predation from large-bodied marine predators and birds of prey, as well as environmental stressors (Sulak et al. 2016, USFWS and NMFS 2022). Altinok et al. (1998) found that salinity tolerance increases with size in Gulf Sturgeon meaning juvenile individuals, especially age-1, are thought to be most susceptible to environmental stress while they are in the estuary. The combination of these threats have led to a hypothesis that low overwinter survival of young juvenile Gulf Sturgeon may be acting as a bottleneck to recruitment to the adult population (USFWS and NMFS 2022).

The U.S. Fish and Wildlife Service and the National Marine Fisheries Service are responsible for conservation and management of Gulf Sturgeon. The species is managed at the whole population level – there are no distinct population segments or separate goals for each spawning population. The long-term recovery objective for Gulf Sturgeon states that the natural rate of population recruitment must be greater or equal to the average mortality rate over 12 years (USFWS and GSMFC 1995). To identify if Gulf Sturgeon are meeting this recovery criteria, recruitment and mortality rates need to be calculated to assess if populations are stable or increasing. Gulf Sturgeon demonstrate high fidelity to their natal river (i.e., river populations do not intermix), so these population parameters must be determined separately for each river (Rudd et al. 2014). This study focuses on the Apalachicola River in Florida, which historically had the largest population of Gulf Sturgeon – an estimated 18,000 adults (Ahrens and Pine 2014). This river was also subjected to a robust commercial fishery, which led to a rapid decline in the Gulf Sturgeon population during the 20$^{th}$ century (USCFF 1902, USFWS and GSMFC 1995). Several recent studies in the Apalachicola River have quantified annual recruitment (i.e., age-1 juvenile abundance) of Gulf Sturgeon (Fox et al 2021, Dula et al 2022, D'Ercole 2023), demonstrating that recruitment occurs annually at a relatively low rate: during 2013–2022, estimates of annual abundance of age-1 Gulf Sturgeon varied from a low of 28 to a high of 218 individuals.

Although we now have a decade of data on recruitment, current estimates of juvenile mortality are lacking for this population.

In recent years, acoustic telemetry detection data has been implemented into mark-recapture models to estimate survival for migratory sturgeon species (Rudd et al. 2014, Withers et al. 2019, Colbourne et al. 2021, Parker 2023). Since 2014, a subset of juvenile Gulf Sturgeon captured during recruitment-focused projects in the Apalachicola River have been implanted with acoustic transmitters as part of an effort to determine population closure during sampling. A passive array of acoustic telemetry receivers has been in place in the river and estuary since 2014, with a priority on coverage of entry and exit locations from the river (Figure 3.1). Due to the migratory life history of Gulf Sturgeon, we expect fish to migrate into the lower river and Apalachicola Bay in the winter, and then return to the upper estuary each spring. Based on return rates for acoustically tagged fish, Fox et al. (2021) estimated survival estimates of 33.3–90.0% for age-1 to age-2 Gulf Sturgeon – however, the simple models used in that study only examined survival at the annual scale and did not account for detection probability, making their results very conservative.

The objectives for this study were threefold. Firstly, we tested the hypothesis of decreased overwinter survival for age-1 Gulf Sturgeon in the Apalachicola River system. Then, we investigated annual survival rates of age-1 Gulf Sturgeon. Finally, we sought to estimate survival for age-2+ juvenile Gulf Sturgeon in the Apalachicola River.

## Methods

### *Study Site*

The Apalachicola River is formed by the confluence of the Chattahoochee and Flint Rivers near the Florida Georgia border. The three rivers form the ACF basin which drains approximately 48,500 $km^2$ in Georgia, Alabama, and Florida (Livingston 2008). The Jim Woodruff lock and dam (JWLD), at the confluence of the Chattahoochee and Flint rivers, is the lowest dam on the ACF basin. From the JWLD the Apalachicola River flows 171 km to Apalachicola Bay and the Gulf of Mexico (Livingston 2008). The Brothers River is a coastal plain tributary that flows into the Apalachicola River near river kilometer (rkm; kilometers from the mouth of the river) 19 and supports summer aggregation areas for Gulf Sturgeon (Wooley and Crateau 1985). Apalachicola Bay is a shallow estuary (average depth: 2 m) formed by a series of barrier islands located around the mouth of the Apalachicola River (Twichell et al. 2007). The salinity gradient within the bay is primarily governed by tidal fluctuation and discharge from the Apalachicola River (Morey and Dukhovsky 2012).

### *Sturgeon Capture*

Gulf Sturgeon used in this study were captured during studies on juvenile recruitment that occurred from 2014–2022 (Marbury 2016, Hancock 2019, Fox et al. 2021, Dula et al. 2022, D'Ercole 2023). Most sampling occurred between May and July, although in some years sampling continued as late as October. Sampling procedure is described in detail in Fox et al. (2021) and was the same each year. Primary netting sites were on the Brothers River (Figure 3.1) with occasional netting on the Apalachicola River below the JWLD and elsewhere in the estuary and lower river. Anchored experimental gill nets composed of three 15-meter panels of 7.6-, 8.9-, and 10.2-cm stretch monofilament mesh were set for 30–120 minutes depending on weather conditions, water temperature, and dissolved oxygen levels. Captured sturgeon were measured, weighed, and scanned for external (*e.g*., Floy) and internal (*e.g*., passive integrated transponder [PIT]) tags. If no PIT tag was present, one was implanted at the base of the dorsal fin. A 1-cm$^2$ fin clip was taken from the anal fin of each fish upon their first capture and preserved in ethanol to be sent to researchers at the University of Southern Mississippi for genetic assignment. A length-frequency histogram was used to assign an age to each fish (Moran 2018, Fox et al. 2021). Captured fish with a fork length (FL) of less than 1000 mm had a 1-cm section of the second marginal fin ray removed according to procedures outlined in Baremore and Rosati (2014) for future age analysis by researchers with U.S. Fish and Wildlife Service and the University of Southern Mississippi. All fish were then immediately released near their capture location.

*Acoustic Telemetry*

Between 2014–2022 a subset of captured juvenile Gulf Sturgeon were surgically implanted with acoustic transmitters as part of an effort to assess population closure during sampling. Tags types were a combination of Innovasea V7 and V9 (Innovasea Systems Inc., Boston, MA) acoustic transmitters that had an expected battery life of between 290–912 days depending on tag type and transmitter sequence delay. Surgical implantation procedures occurred as described in Fox et al. (2021). Each fish was placed in a V-shaped surgical board with a battery powered pump continuously supplying river water over their gills during the procedure. A 2–3 cm incision was made on the lower abdomen alongside the mid-line using a surgical scalpel. The transmitter was then inserted into the body cavity through the incision, and the incision was closed with 2/0 Monocryl suture with a single interrupted pattern (Boone et al.

2013). After the procedure, fish were allowed to recover and released in the river near their site of capture.

An array of VR2W-69 kHz acoustic receivers (Innovasea Systems Inc.) was deployed through the study system (Figure 3.1) in 2013. The array was designed to monitor fish movements through the lower Apalachicola River and its estuary. Movements between the river and Apalachicola Bay were monitored by “gates,” receivers located at the mouths of the main channel and each distributary. The array was maintained and detection data were offloaded from each receiver quarterly throughout the study period. The total number of receivers deployed varied through the study period as receivers were lost, removed, or added. However, gate receivers were in place throughout the study.

*Survival Estimates*

Survival was estimated using Cormack-Jolly-Seber (CJS) models through package RMark (Laake 2013) in program R (R Core Team 2023). Cormack-Jolly-Seber models are mark-recapture, open population models that estimate apparent survival (Φ), the probability that a marked animal at period *i* will survive and not permanently emigrate in period *i*+1. These CJS models also estimate detection probability (*p*), the probability that a marked individual in the population will be detected during resight occasion *k* (Figure 3.2).

Assumptions of CJS models are:

(1) every marked individual present at period *i* has the same probability of recapture or resight ($p_i$),

(2) every marked individual has the same probability of survival from period *i* to period *i+1*,

(3) marks are not lost and are correctly recorded,

(4) sampling is instantaneous,

(5) all emigration is permanent, and

(6) and individual animal fates are independent.

Due to the use of telemetry and a consistent tagging protocol to gain resight (non-physical recapture) data, the marking methods should not influence individual $p$ or Φ, satisfying assumptions 1, 2, and 6. Although we cannot be certain no marks were lost during the study, the methods we used to implant transmitters was consistent with common practices to reduce transmitter loss (Kahn and Mohead 2010, Boone et al. 2013), and all tags were tested before implantation; this should satisfy assumption 3. Sampling was not instantaneous – detection of tagged fish occurred throughout the study period. However, all resights were condensed to monthly intervals (i.e., the capture history for each fish indicated fish detection/absence at a monthly scale, regardless of how many detections occurred within a month); this addresses assumption 4. Juvenile Gulf Sturgeon do not emigrate from their natal river, satisfying assumption 5, meaning that Φ should be a representative of true survival.

Two techniques were used to assign fish to age cohorts. One method relied on modal distribution of a length frequency histogram (based on Schueller and Peterson 2010), which has been used to assign juvenile Gulf Sturgeon ages in previous Apalachicola River studies (Fox et al. 2021, Dula et al. 2022). The second method relied on the aging of sections of the 2$^{nd}$ marginal pectoral fin ray that were collected from each fish using protocol outlined by Baremore and Rosati (2014). These samples were processed and read by research collaborators at USFWS and the University of Southern Mississippi, who assigned each fish an age by counting visible growth bands (annuli) in the pectoral fin ray section. For our analysis, fish were assigned to one of two groups: age-1 juveniles were either ≤520 mm FL, or had a single visible annulus, and age-2+ juveniles were 521–609 mm FL or had ≥2 visible annuli.

Survival was investigated on a seasonal scale for age-1 Gulf Sturgeon, with seasons defined as: spring = March–May, summer = June–August, fall = September–November, and winter = December–February. Telemetry detections from each month were indexed to a season and a year, to parameterize both Φ and *p* on different temporal scales. To evaluate survival, we constructed a suite of three candidate models that held Φ and *p* constant or allowed those parameters to vary by season, month, or year (Table 3.1). Because there were two different ways of assigning fish age (either by length or by pectoral fin ray analysis), we ran models independently for each age-assignment method. Models 1–3 featured fish assigned to the age-1 cohort based on their length, and models 4–6 used the same parameters but featured fish assigned to the age-1 cohort based on pectoral fin ray analysis. Akaike's Information Criterion (AIC) was used to select a top model for each cohort assignment technique. Survival was also estimated on an annual scale for each year of the study period for age-1 Gulf Sturgeon, based on fin ray age assignment, by comparing a suite of candidate CJS models that allowed *p* to vary based on different temporal scales (models M7, M8, and M9 Table 3.1); the top model was selected using AIC. Survival was similarly estimated for the age 2+ cohort using the fin ray cohort assignment (models M10, M11, M12, and M13; Table 3.1).

## Results

### *Capture and Tagging*

A total of 3,367 nets were set in the Brothers and Apalachicola Rivers during the study period for a total of 3,602 net-hours. Yearly effort varied from a low of 278 net-hours in 2016 to a high of 692 net-hours in 2019. The study-wide average soak time was 64 minutes per net. This effort resulted in the capture of 3,489 sturgeons. We captured a total of 2,135 juvenile (<890 mm FL) Gulf Sturgeon, including 535 age-1 individuals. A total of 185 individual juvenile Gulf Sturgeon were captured and implanted with acoustic transmitters. Based on length, 157 individuals were assigned to the age-1 cohort and 28 were assigned to the age 2+ cohort (Table 3.2). Based on fin ray annuli count, 144 individuals were assigned to the age-1 cohort, and 41 were assigned to the age-2+ cohort (Table 3.2). Across all years of this study, there were a total of 19 discrepancies between individual age assignments using the two techniques. The number of juvenile Gulf Sturgeon implanted with acoustic transmitters varied annually from 5–51 (Table 3.2) with a median of 23 transmitters implanted per year. Between May 2014 and December 2023, we collected a total of 1,055,431 detections of juvenile Gulf Sturgeon in the Apalachicola River.

*Acoustic Telemetry*

Fish demonstrated consistent annual movement patterns. During the summer and early fall, most juvenile sturgeon stayed within the Brothers River. As fall progressed, fish moved down the estuary through the lower Apalachicola River and its distributaries. During the winter months, most juvenile sturgeon were detected less frequently and primarily on receivers located in the estuary and around the mouth of the Apalachicola River and its distributaries. In the spring, juvenile sturgeon moved through the lower Apalachicola River and into the Brothers River.

*Age-1 Seasonal Survival*

Our seasonal survival analysis based on ages assigned from length included 157 age-1 individuals. The top seasonal survival model for this analysis, carrying 100% of the weight, was

M3 – in which Φ and *p* varied by season (Table 3.3). Our seasonal survival analysis based on ages assigned by fin ray annuli count included 144 age-1 individuals. The top seasonal survival model for this analysis, also carrying 100% of the weight, was M5 – in which Φ and *p* varied by season (Table 3.4). Because the results for these two models were essentially the same (Figure 3.3), we used ages derived from fin rays for all subsequent analyses. Thus, our point estimates (and 95% confidence intervals [CIs]) from model M5, indicate that seasonal survival varied from 0.903 (0.826–0.948) in spring to 0.981 (0.920–0.995) in winter (Table 3.5). Although winter had the greatest point estimate of survival, an overlap in CIs was observed across all season (Figure 3.3), indicating that there was no significant difference between any season in the study.

*Age-1 Annual Survival*

When we examined survival at the annual scale, AIC indicated that the top model, carrying 100% of the weight, was M7, in which Φ varied by year and *p* varied by month (Table 3.6). Yearly survival estimates varied from a low of 0.758 (95% CI: 0.606–0.864) in 2016 to a high of 0.975 (95% CI: 0.922–0.992) in 2020 (Figure 3.4). There were significant differences among several years in the study period: survival in 2016 was significantly lower than in 2017 and 2019–2022. Survival in 2018, which had the greatest uncertainty (i.e., widest CIs), was significantly lower than in 2020 and 2021 (Figure 3.4).

*Age-2+ Annual Survival*

Although some fish in the age-2+ cohort were implanted with acoustic transmitters prior to 2020, those fish were excluded from our analysis due to low yearly sample size (Table 3.2). Our analysis dataset contained 41 individuals that were tagged in 2020–2022. We were not able to address seasonal survival for age-2+ juvenile Gulf Sturgeon in the Apalachicola River because seasonal survival models failed to converge. Of the remaining models, AIC analysis indicated the top model, carrying 83% of the weight, was M11, in which Φ varied by year and *p* varied by month (Table 3.7). Point estimates of annual survival for age-2+ Gulf Sturgeon varied from a low of 0.951 to a high of 0.974 across the study (Table 3.8). There were no significant differences in survival among any years (Figure 3.5).

## Discussion

This study used 10 years of acoustic telemetry detection data to investigate survival of juvenile Gulf Sturgeon within the Apalachicola River on different temporal scales. This was done in order to address the hypothesis of poor survival during winter months as a bottleneck to adult recruitment, and to estimate yearly survival rates needed to address the growth rate of this population.

### *Seasonal Survival*

During winter months, Gulf Sturgeon occupy brackish to marine waters. During this time, they are exposed to a number of threats not found in their river habitat including marine predators, mortality related to bycatch in trawl or entanglement fisheries, dredging operations, vessel strikes, and environmental stressors (Wooly and Crateau 1985, Sulak et al. 2016, Dula et al. 2022, USFWS and NMFS 2022). Juvenile Gulf Sturgeon are thought to be at a higher risk of predation while in the estuary due to the higher salinity habitat they occupy exposing them to larger-bodied marine predators such as sharks and dolphins that aren't present in the river. Apalachicola Bay is relatively shallow, with an average depth of around two meters (Twichell et al. 2007), making juvenile Gulf Sturgeon susceptible to predation from birds of prey as well. Environmental stress is also thought to be highest during winter months for juveniles as they are exposed to the highest levels of salinity they encounter within a year. The ability for juvenile

Gulf Sturgeon to osmoregulate has been linked to their size such that larger individuals are able to osmoregulate more efficiently while in higher salinity waters compared to smaller bodied individuals (Altinok et al. 1998). The combination of these factors led to the hypothesis that survival is lower during the winter for juvenile cohorts than during the rest of the year.

In order to address this hypothesis, we looked at a suite of CJS open population survival models that estimated survival on a seasonal basis between 2014–2023. We focused on individuals in the age-1 cohort between 2014–2022 since the threats that we expected to affect survival were related to size, making the age 1 year class the most susceptible. Our results did not support the hypothesis of decreased survival during winter months and instead showed that survival was similar among all seasons with overlapping 95% CIs (Table 3.5). Our point estimates showed that winter survival (0.981) was higher than spring survival (0.903). From these findings we believe it is unlikely that the survival of these age-1 individuals while in the estuary is resulting in a bottleneck to adult recruitment.

Osmoregulation ability has been shown to increase with body size in Gulf Sturgeon (Altinok et al. 1998), and osmoregulatory stress has been hypothesized to lead to decreased fitness of juveniles as has been demonstrated in juvenile Atlantic Sturgeon (*A. o. oxyrinchus*), the sister subspecies of Gulf Sturgeon (Allen et al. 2014). However, in YOY Atlantic Sturgeon, salinity tolerance is dependent on both water temperature and dissolved oxygen (Niklitschek and Secor 2009). Temperature was demonstrated to be a controlling factor in Atlantic Sturgeon growth, whereas salinity acted as a masking factor, reducing consumption of prey and instantaneous growth rates when both temperature and salinity where near their minimum or maximum thresholds. Although increased salinity may negatively affect Gulf Sturgeon, those negative effects may be mitigated during winter months by lower environmental temperatures. In addition, the negative physiological effects of salinity may be mitigated by river discharge in the estuary. Morey and Dukhovskoy (2012) found that salinity trends in Apalachicola Bay closely followed river discharge with salinity being highest between September–November when river discharge is low, followed by declining salinity throughout the winter months into spring as river discharge increased. Previous studies (*e.g.*, Hancock 2019) found that acoustically tagged age-1 Gulf Sturgeon stay within or close to the river mouth during their time in the estuary, the area that would typically have the lowest salinity due to freshwater input from the river. Decreased salinity due to increased flow in the estuary, with the tendency of juvenile sturgeon to remain near the river mouth, may also be reducing encounters with large marine predators, reducing another potential source of winter mortality.

*Annual Survival*

We found that annual survival rates were estimated to be relatively high for a majority of years for age-1 Gulf Sturgeon with seven out of the nine years of the study having apparent survival estimated above 0.91 (Figure 3.4). These juvenile estimates are similar to five year survival estimates of adults in the system of between 0.82–0.97, which were estimated using similar mark-recapture models (Parker 2023). We found that juvenile survival estimates were lower in two years, 2016 and 2018. During 2016, sturgeon capture was ineffective in the late spring and early summer which made the tagging protocol differ from other years in the study. While fish were typically implanted with acoustic transmitters during May or June, in 2016 a majority of fish were implanted with transmitters during the fall. Fish captured post implantation that year were also noted to have abnormally high rates of infection around the surgical sites observed during recaptures of tagged fish (Hancock 2019). This leads us to believe that the combination of change in tagging protocol, and possibly high infection rates from tagging, led to decreased survival estimates of tagged fish in 2016. In October 2018, Hurricane Michael made landfall near the Apalachicola River. The storm caused a hypoxia event in the river that led to a mass mortality event for adult Gulf Sturgeon in the system (Dula et al. 2022). Hurricane Michael likely resulted in increased juvenile mortality rate as well, which may explain the low survival rate we observed that year (Figure 3.4). In addition, the sample size of acoustically tagged juvenile sturgeon was low that year (Table 3.2), which may have increased uncertainty and resulted in the relatively wide 95% CI in 2018 (Figure 3.4).

Although the majority of tagging was targeted for the age-1 cohort of each year, a subset of larger age-2+ juveniles were tagged opportunistically over the course of the study (Table 3.2). We estimated survival for these fish that were captured during the 2020–2022 field seasons and found that survival point estimates were relatively high with each year above 0.95 (Table 3.8). These rates were similar to annual survival estimates for age-1 fish during 2020–2022 (Figure 3.4) with a high degree of overlap of the 95% CIs between the two cohorts within each year.

*Age Assignments*

During the course of this study, age was assigned to each fish using two different techniques. Length bins from previous length frequency histograms were used to determine likely age-1 fish in the field. Fin ray sections were also collected during sampling for juvenile Gulf Sturgeon and sent to collaborators to assign ages based on visible growth ring (annuli) count. Both methods were used to assess seasonal survival rates of age-1 Gulf Sturgeon, and the resulting estimates were compared to assess if age estimation technique changed the outcome of the survival models. We found that survival estimates for each season were not significantly different between the two aging techniques with a high degree of overlap in 95% CIs between the two age assignment groups (Figure 3.3). This is likely due to there being a high degree of overlap between age assignments of individuals to age cohorts with a 10% discrepancy of age assignment between the two techniques. Since there was little difference between results using the two different approaches, we opted to use fin ray age estimates for the remainder of the models to keep with current practices in juvenile Gulf Sturgeon research.

*Future Research Directions*

It was previously believed that all Gulf Sturgeon within a river system belonged to the same population, but recently, evidence has suggested that there are two distinct populations within some of the natal river systems that the species occurs in (Randall and Sulak 2012). These two populations are differentiated most notably by the timing of their spawning: spring or fall. Collaborating researchers at the University of Mississippi have identified the Apalachicola as a system where two genetically distinct populations of Gulf Sturgeon occur (B. Kreiser pers. comm.). The survival models we used for these analyses did not differentiate between these two populations and grouped them as one. Due to unknown life history differences between these two populations, inclusion of fall spawned individuals could skew results if they are exposed to threats at a different rate than the spring spawned individuals. We do not believe this to be the case for our study as a minority (~5%) of the total fish included in these analyses were genetically identified to be fall spawned individuals. Because of this small proportion of fall spawned individuals, as well as our hypothesis tested relating to exposure to threats as a function of body size, we do not think that inclusion of these fish has changed the outcome of the study. Future analyses should look into life history trends of each population to assess if they do differ substantially.

Our results refuted the hypothesis of low survival of smaller juvenile Gulf Sturgeon during winter causing a bottleneck to adult recruitment. While there was similar survival among seasons, it is possible that the seasonal focus of this study may have masked increased mortality that occurred over shorter time intervals within each season. Survival bottlenecks could occur over monthly (or shorter) time intervals, such as the couple weeks each year where juveniles transition from the river to the estuary. Additionally, adding a spatial aspect to the analysis could identify areas where sturgeon are experiencing increased mortality. Finally, although this analysis saw similar annual survival rates between age-1 and age-2+ Gulf Sturgeon in the Apalachicola River, our emphasis on tagging smaller bodied fish (<600 mm FL) did not allow us to investigate survival of larger bodied juvenile Gulf. We focused our tagging on small juveniles as they were hypothesized to be more susceptible to mortality while in the estuary, but it is possible that as juvenile Gulf Sturgeon grow, they may move further from the relative refuge of the river mouth where they could encounter higher salinity, be more susceptible to bycatch, and encounter more marine predators.

*Management Implications*

We demonstrated the utility of telemetry detection data in assessing survival at a finer temporal scale than annual estimates. In addition, we found evidence that current annual survival rates are relatively stable above 0.90. We also found that threats of episodic mortality, from events such as hurricanes, are present for juvenile Gulf Sturgeon in the Apalachicola River. The continued monitoring of this population through acoustic telemetry is recommended as Gulf Sturgeon within the Apalachicola River system continue to be faced with anthropogenic input that may affect their survival such as dredging operations and flow regulation, as well as the threat of episodic mortality events from hurricanes and possible point source contamination events (such as the Deepwater Horizon oil spill). We also recommend additional investigation of survival of older juvenile Gulf Sturgeon. Recently, Parker (2023) estimated survival of sub-adult and adult (>900 mm total length) Gulf Sturgeon , but there is no information available on larger-bodied juveniles (600–900mm total length). Evaluation of survival of these older juveniles may provide insights to inform management of this threatened species.

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**Tables and Figures**

**Table 3.1:** Suite of candidate Cormack-Jolly-Seber open population survival models for juvenile Gulf Sturgeon in the Apalachicola River, Florida. Each model includes the years from which individuals were tagged, the age cohort being evaluated for survival, the technique used to assign the ages to individuals, the temporal scale in which apparent survival is being evaluated (Φ), and the temporal scale in which detection probability varies (*p*).

| Model | Tagging years | Age | Aging technique | Φ | *p* |
|---|---|---|---|---|---|
| M1 | 2014–2022 | 1 | Length Frequency | ~1 | ~1 |
| M2 | 2014–2022 | 1 | Length Frequency | season | season |
| M3 | 2014–2022 | 1 | Length Frequency | season | year |
| M4 | 2014–2022 | 1 | Fin Ray | ~1 | ~1 |
| M5 | 2014–2022 | 1 | Fin Ray | season | season |
| M6 | 2014–2022 | 1 | Fin Ray | season | year |
| M7 | 2014–2022 | 1 | Fin Ray | year | month |
| M8 | 2014–2022 | 1 | Fin Ray | year | season |
| M9 | 2014–2022 | 1 | Fin Ray | year | year |
| M10 | 2020–2022 | 2+ | Fin Ray | ~1 | ~1 |
| M11 | 2020–2022 | 2+ | Fin Ray | year | month |
| M12 | 2020–2022 | 2+ | Fin Ray | year | season |
| M13 | 2020–2022 | 2+ | Fin Ray | year | year |

**Table 3.2:** Number of juvenile Gulf Sturgeon implanted with acoustic transmitters in the Apalachicola River, Florida for each tagging year of the study period. Fish are classified by age cohorts of either age-1 or age-2+ based on two separate age estimating techniques. Modal distribution of a length frequency histogram was the first method used to assess cohort placement for individuals. The second methods relied on annuli counts on the $2^{nd}$ marginal pectoral fin ray for each individual.

| | | Age and assignment method | | | |
|---|---|---|---|---|---|
| | | Length frequency | | Fin ray | |
| Year | Total tagged | n Age 1 | n Age 2+ | n Age 1 | n Age 2+ |
| 2014 | 10 | 10 | 0 | 10 | 0 |
| 2015 | 9 | 8 | 1 | 8 | 1 |
| 2016 | 12 | 12 | 0 | 12 | 0 |
| 2017 | 23 | 19 | 4 | 18 | 5 |
| 2018 | 5 | 5 | 0 | 4 | 1 |
| 2019 | 24 | 23 | 1 | 23 | 1 |
| 2020 | 23 | 16 | 7 | 13 | 10 |
| 2021 | 28 | 22 | 6 | 23 | 5 |
| 2022 | 51 | 42 | 9 | 33 | 18 |
| *Total* | *185* | *157* | *28* | *144* | *41* |

**Table 3.3:** Results of Cormack-Jolly-Seber open population models of seasonal survival for age-1 Gulf Sturgeon (age assigned based on length) in the Apalachicola River from 2014–2023. The null model (M1) assumes constant apparent survival probability (Φ) and constant recapture probability (p). The other models allow Φ to vary based on season with p varying on a yearly basis (M2) or seasonal basis (M3). Models are ranked by Akaike's information criteria corrected for small sample size (AICc). For each model, we provide the number of parameters (K), the AICc value, the ΔAICc, the model weight (W), and the negative log likelihood (nll).

| **Model** | **Model parameterization** | **K** | **AICc** | **ΔAICc** | **W** | **nll** |
|---|---|---|---|---|---|---|
| M3 | Φ(~season)*p*(~season) | 8 | 2177.38 | 0 | 1.00 | 2161.21 |
| M2 | Φ(~season)*p*(~year) | 14 | 2246.69 | 69.31 | <0.01 | 2218.18 |
| M1 | Φ(~1)*p*(~1) | 2 | 2399.84 | 222.47 | <0.01 | 2395.83 |

**Table 3.4:** Results of Cormack-Jolly-Seber open population models of seasonal survival for age-1 Gulf Sturgeon (age assigned from pectoral fin spine analysis) in the Apalachicola River from 2014–2023. The null model (M4) assumes constant apparent survival probability (Φ) and constant recapture probability (p). The other models allow Φ to vary based on season with p varying on a yearly basis (M6) or seasonal basis (M5). Models are ranked by Akaike's information criteria corrected for small sample size (AICc). For each model, we provide the number of parameters (K), the AICc value, the ΔAICc, the model weight (W), and the negative log likelihood (nll).

| Model | Model parameterization | K | AICc | ΔAICc | W | nll |
|---|---|---|---|---|---|---|
| M5 | Φ(~season)*p*(~season) | 8 | 1890.6 | 0 | 1.00 | 1874.4 |
| M6 | Φ (~season)*p*(~year) | 15 | 2032.9 | 142.3 | <0.01 | 2002.2 |
| M4 | Φ(~1)*p*(~1) | 2 | 2152.8 | 262.2 | <0.01 | 2148.8 |

**Table 3.5:** Results of a Cormack-Jolly-Seber open population model of seasonal apparent survival (M5) for age-1 juvenile Gulf Sturgeon in the Apalachicola River, Florida between 2014–2022. For each season (spring: March–May, summer: June–August, fall: September–November, winter: December–February) the apparent survival probability estimate (Φ), standard error (SE) and 95% confidence intervals (CI) are given.

| Season | Estimate | SE | 95% CI |
|---|---|---|---|
| Spring | 0.903 | 0.030 | 0.826–0.948 |
| Summer | 0.937 | 0.015 | 0.901–0.961 |
| Fall | 0.939 | 0.016 | 0.899–0.964 |
| Winter | 0.981 | 0.014 | 0.920–0.995 |

**Table 3.6:** Results of Cormack-Jolly-Seber open population models of survival for age-1 Gulf Sturgeon in the Apalachicola River from 2014–2022. The null model (M4) assumes constant apparent survival probability (Φ) and constant recapture probability (*p*). The other models allow Φ to vary based on season or year with *p* varying on a yearly, seasonal, or monthly basis. Models are ranked by Akaike's information criteria corrected for small sample size (AICc). For each model, we provide the number of parameters (K), the AICc value, the ΔAICc, the model weight (W), and the negative log likelihood (nll).

| Model | Model parameterization | K | AICc | ΔAICc | W | nll |
|---|---|---|---|---|---|---|
| M7 | Φ(~year)*p*(~month) | 21 | 1705.9 | 0 | 1.00 | 1662.6 |
| M8 | Φ(~year)*p*(~season) | 13 | 1878.2 | 172.3 | <0.01 | 1851.7 |
| M5 | Φ(~season)*p*(~season) | 8 | 1890.6 | 184.7 | <0.01 | 1874.4 |
| M9 | Φ ~year)*p*(~year) | 20 | 2030.2 | 324.3 | <0.01 | 1989.1 |
| M6 | Φ(~season)*p*(~year) | 15 | 2032.9 | 327.0 | <0.01 | 2002.2 |
| M4 | Φ(~1)*p*(~1) | 2 | 2152.8 | 446.9 | <0.01 | 2148.8 |

**Table 3.7:** Results of Cormack-Jolly-Seber open population models of seasonal survival for age-2+ Gulf Sturgeon in the Apalachicola River from 2020–2022. The null model (M10) assumes constant apparent survival probability (Φ) and constant recapture probability (p). The other models allow Φ to vary based on year with p varying on a yearly, seasonal, or monthly basis. Models are ranked by Akaike's information criteria corrected for small sample size (AICc). For each model, we provide the number of parameters (K), the AICc value, the ΔAICc, the model weight (W), and the negative log likelihood (nll).

| Model | Model parameterization | K | AICc | ΔAICc | W | nll |
|---|---|---|---|---|---|---|
| M11 | Φ(~year)*p*(~month) | 15 | 529.0 | 0 | 0.83 | 496.7 |
| M13 | Φ(~year)*p*(~year) | 7 | 532.1 | 3.1 | 0.17 | 517.6 |
| M12 | Φ(~year)*p*(~season) | 7 | 554.7 | 25.7 | <0.01 | 540.2 |
| M10 | Φ(~1)*p*(~1) | 2 | 566.8 | 37.8 | <0.01 | 562.7 |

**Table 3.8:** Results of Cormack-Jolly-Seber (CJS) open population model of seasonal apparent survival (M11) for age-2+ juvenile Gulf Sturgeon in the Apalachicola River, Florida between 2020–2023. For each year the apparent survival probability estimate (Φ), standard error (SE) and 95% confidence intervals (CI) are given.

| Year | Estimate | SE | 95% CI |
|---|---|---|---|
| 2020 | 0.974 | 0.015 | 0.921–0.992 |
| 2021 | 0.952 | 0.027 | 0.861–0.984 |
| 2022 | 0.951 | 0.016 | 0.907–0.974 |

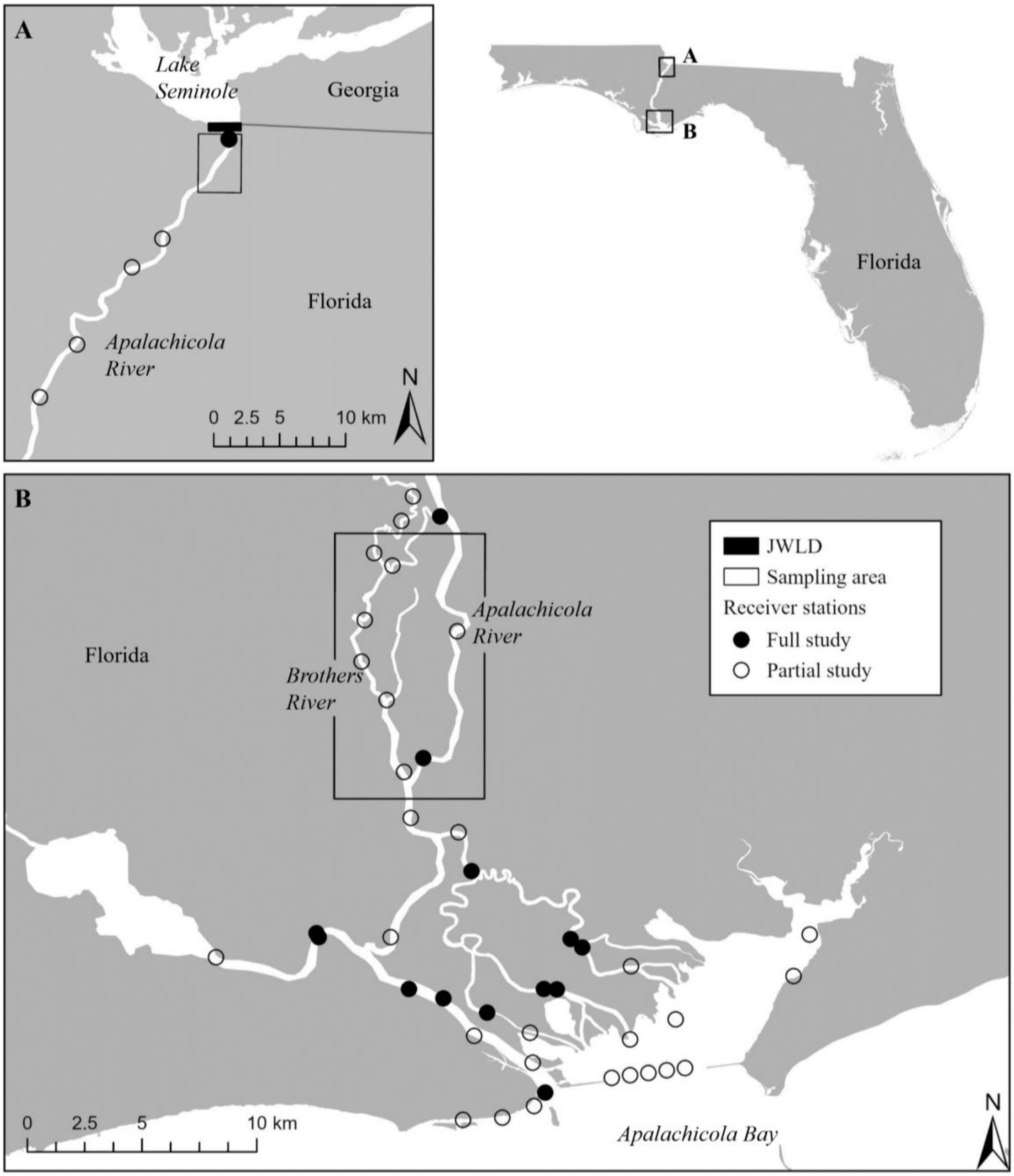


**Figure 3.1:** Map of the study site in the Apalachicola River in Florida: (**A**) map of the upper Apalachicola River downstream of the Jim Woodruff Lock and Dam (JWLD), indicated by a black rectangle) and (**B**) the lower Apalachicola River and Brothers River. Acoustic receiver station locations are indicated by circles (full black circles indicate receiver stations that were active for the full study period from 2014–2023 and open circles indicate those that were active for a portion of the study period. Sampling for juvenile Gulf Sturgeon between 2014–2022 occurred within the boxes outlined in black.

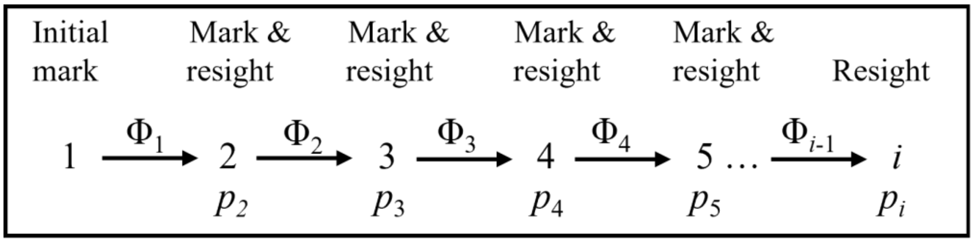


**Figure 3.2:** Structure of Cormack-Jolly-Seber models. Apparent survival (Φ), the probability that an animal will survive and not permanently emigrate from the study area, and detection probability ($p$), the probability that an animal with be detected between study periods, are parameters estimated by the model.

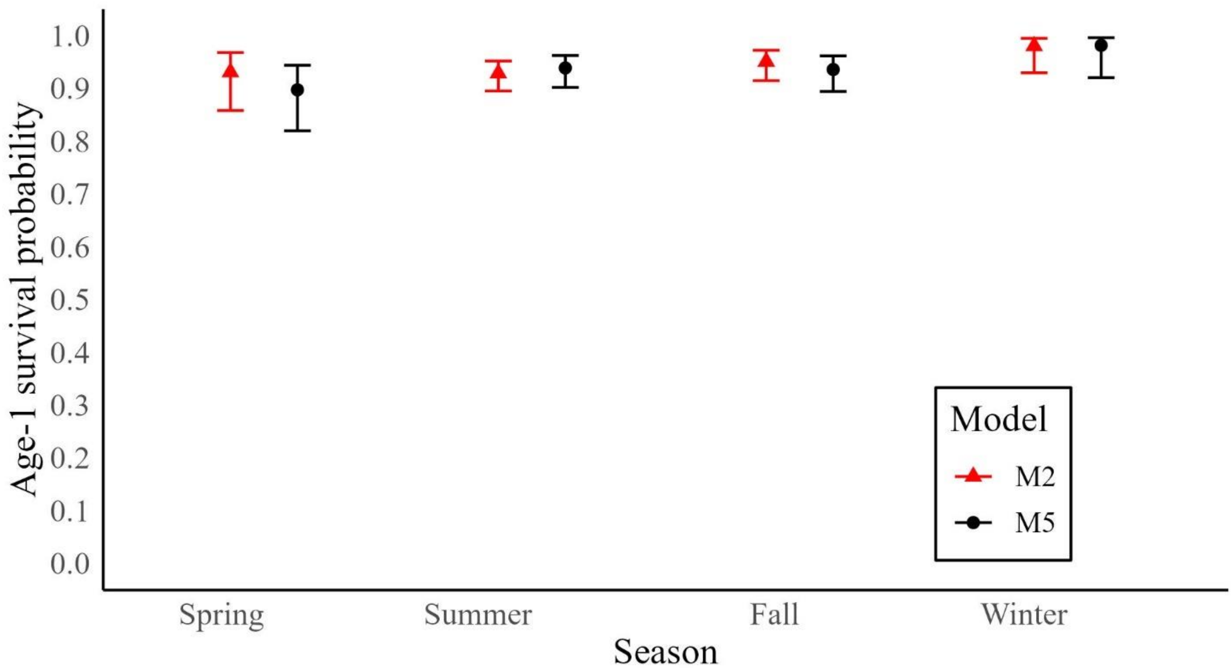


**Figure 3.3:** Survival estimates for age-1 Gulf Sturgeon in the Apalachicola River, Florida from two Cormack-Jolly-Seber models. Individuals were assigned to the age-1 cohort based on length frequency (M2; estimates indicated by red triangles) or by fin ray annuli count (M5; estimates indicated by black circles). Both models are estimating apparent seasonal survival probability with 95% confidence intervals from acoustic telemetry detections collected between 2014–2023. Model parameters Φ and $p$ varied seasonally for both models.

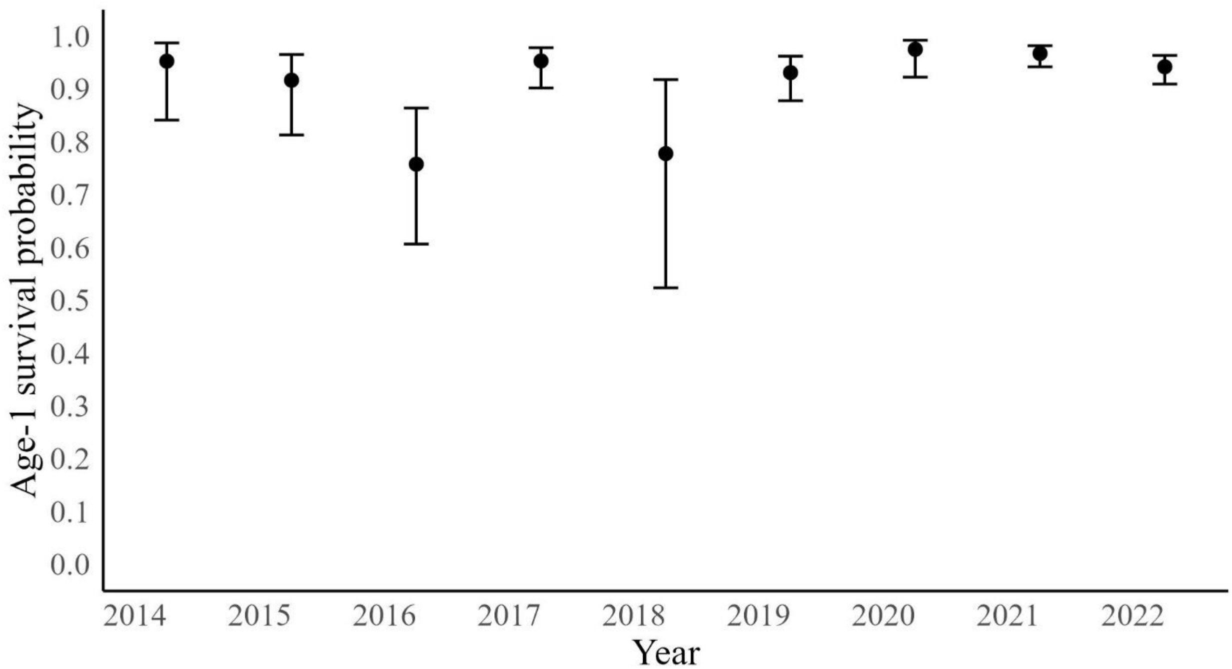


**Figure 3.4:** Survival estimates for age-1 Gulf Sturgeon in the Apalachicola River, Florida from a Cormack-Jolly-Seber model (M7) estimating apparent annual survival probability with 95% confidence intervals from acoustic telemetry detections collected between 2014–2023. Model parameters varied annually for apparent survival and monthly for detection probability.

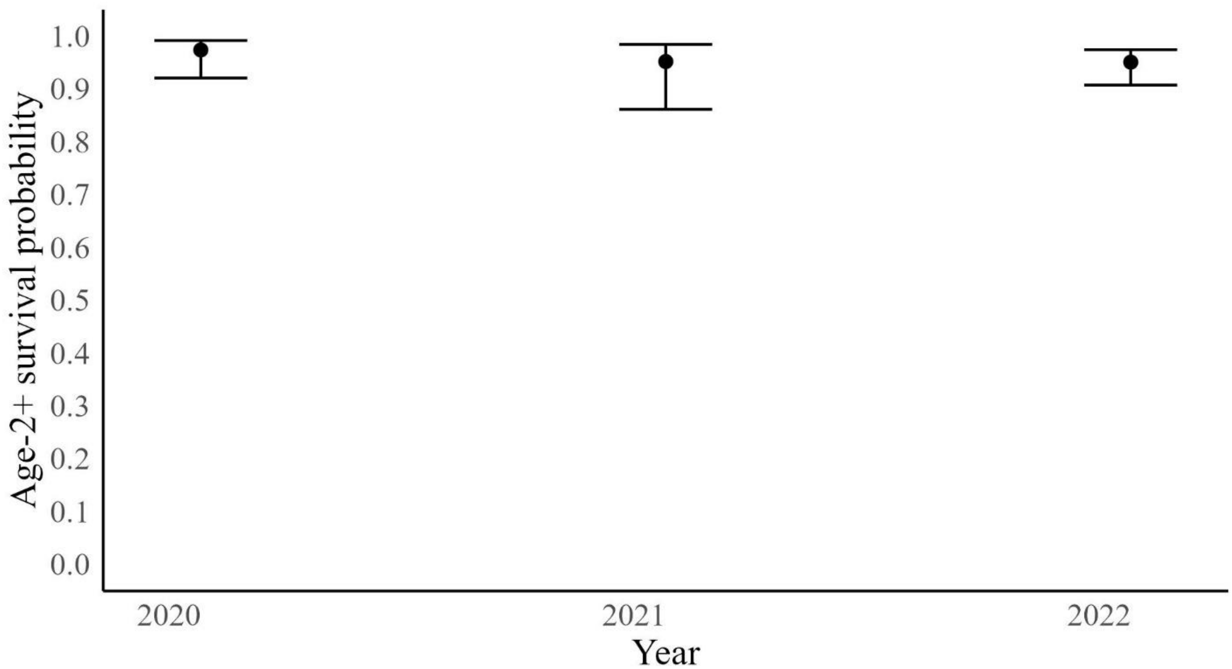


**Figure 3.5:** Survival estimates for age-2+ juvenile Gulf Sturgeon in the Apalachicola River, Florida from a Cormack-Jolly-Seber model ($M_{y,m}$) estimating apparent survival probability with 95% confidence intervals from acoustic telemetry detections collected between 2020–2023. Model parameters varied annually for apparent survival and monthly for detection probability.

# CHAPTER 4

## CONCLUSIONS

In order to assess whether the recovery objectives defined in the Gulf Sturgeon Recovery/Management Plan (USFWS and GSMFC 1995) are being met, long term population monitoring is a priority. Long term objectives for delisting focus on the need for self-sustaining populations in each of the natal river systems. Due to the protracted life history of Gulf Sturgeon, there is a lag time between management actions and changes to the adult population. Because of this there has been a recent emphasis on evaluating juvenile population dynamics to better track immediate trends in the overall population. Recent research in the Apalachicola River has focused largely on age-1 juveniles. There are two reasons for this focus on the age-1 cohort instead of age-0 Gulf Sturgeon: 1.) age-0 individuals disperse widely throughout the river system making targeted capture impractical (Sulak and Clugston 1999, Kirk et al. 2010), and 2.) age-0 Gulf Sturgeon have naturally low survival rates with less than 1% expected to survive from egg to age-1 (Pine et al. 2001).

Although the Gulf Sturgeon Recovery/Management Plan intended for the use of catch-per-unit-effort (CPUE) as a means to monitor population abundance, mark-recapture derived estimates have instead been used to track trends in abundance of juveniles (USFWS and NMFS 2022). In the Apalachicola River, a number of studies have used mark-recapture methods to quantify age-1 abundance (i.e., annual recruitment) (Fox et al. 2021, Dula et al. 2022, D’Ercole 2023). However, CPUE can be useful in tracking changes of relative abundance in a population if the sampling protocol is standardized and the number of fish captured is proportional to the effort expended. This underlying assumption of constant catchability often is not realized though as fish behavior can change in response to differing densities, environmental conditions, or other factors, thus making CPUE a poor measure of abundance. Because the precision of mark-recapture estimates relies on a suitable recapture rate (Conroy and Carroll 2009), quantifying annual recruitment with this method requires more sampling effort than CPUE. With that in mind, Chapter 2 of this thesis compared CPUE of age-1 Gulf Sturgeon to the abundance estimates derived from mark-recapture models. We found a significant ($\alpha < 0.05$) positive linear relationship between the age-1 abundance and CPUE of age-1 Gulf Sturgeon in the Apalachicola River.

We found a significant relationship between age-1 abundance and CPUE for two different shortened sampling periods: partial sampling in May and June and sampling in June. Although these results indicate that CPUE during these periods reflect total abundance (as estimated through mark-recapture) and suggest the possibility of using a reduced sampling scenario for tracking trends in age-1 abundance, we would still recommend continuing with mark-recapture abundance estimates for a number of reasons. The sample sizes available for the analyses in Chapter 2 were low with only 9 years of data to assess this relationship. The predictive model we built from the CPUE data had a high degree of uncertainty in the predicted yearly abundance, including years where the predicted abundance from CPUE was outside of the 95% confidence intervals (CI) of the mark-recapture estimates. Thus, we caution managers that CPUE may not be an appropriate metric to track abundance of age-1 Gulf Sturgeon in the Apalachicola River. However, CPUE does have utility for obtaining relative abundance information when adverse conditions preclude full summer sampling required for mark-recapture estimates.

Although there is a good understanding of recent annual Gulf Sturgeon recruitment in the Apalachicola River, critical knowledge gaps remain relating to mortality rates of the juvenile population. Multiple threats to Gulf Sturgeon persist from both anthropogenic and natural input such as dams, dredging, potential bycatch in commercial fisheries, hurricanes, and point source contamination events. Juvenile Gulf Sturgeon are proposed to be at higher risk of mortality while in the estuary or marine waters near their natal river, owing to their smaller body size and decreased salinity tolerance (Altinok et al. 1998) compared to adults. These additional proposed threats to juveniles led to the hypothesis of decreased overwinter survival as juveniles resulting in poor adult recruitment (USFWS and NMFS 2022). In Chapter 3 of this thesis, we used open population Cormack-Jolly-Seber survival models to address this hypothesis. We did not observe decreased survival of age-1 juveniles during the winter season, or any season during our study. Overall, annual survival for age-1 Gulf Sturgeon was relatively high in the Apalachicola River at or above 0.91 in seven out of the nine years of the study for the age-1 cohort. Additionally, survival was above 0.95 for the three years of data we had on the age-2+ Gulf Sturgeon cohort.

Although we did not find evidence of decreased overwinter survival in age-1 Gulf Sturgeon, we demonstrated the utility of acoustic telemetry data in assessing survival in this population. We recommend the continued use of acoustic telemetry to monitor juvenile survival in the Apalachicola River, as this population continues to be threatened by dredging, bycatch, flow regulation, and episodic mortality from hurricanes or point source contamination events. This project focused primarily on age-1 juveniles, larger-bodied juveniles or sub-adults may be more at risk as they transition to higher levels of salinity during the winter. Therefore, we recommend that research should be directed at these older juvenile cohorts to address whether survival decreases as juveniles mature and leave the relative refuge of the subarea around their natal river mouth during the winter.

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