# THE POPULATION DYNAMICS OF SHORTNOSE GAR IN THE ILLINOIS RIVER TO INFORM MANAGEMENT OF AN EMERGING RECREATIONAL FISHERY

BY

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THESIS

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**ABSTRACT**

Understanding the impact of recreational harvest is crucial for the effective management of ecologically and economically important fisheries. The extent of participation in and magnitude of harvest from bowfishing is largely unknown; however, this lethal angling method may be the primary source of fishing mortality for some native species. Among the “rough” fishes bow anglers target, gars (*Lepisosteidae*) may be at greater risk of overharvest because of their periodic life history strategies. In my first study, I utilized standardized population assessments to estimate the relative abundance, stock structure and vital rates of Shortnose Gar (*Lepisosteus platostomus*) in the lower Illinois River. The findings indicate that Shortnose Gar exhibit slow growth rates, large body size, variable recruitment and long life spans characteristic of a periodic life history strategy. In my second study, I utilized a creel survey of Illinois bowfishing tournaments to characterize bow angler fishing habits and harvest with an emphasis on gars. Although invasive carp species (*Cyprinidae*) dominate the harvest composition, gar populations may be vulnerable to overharvest as bow anglers favor targeting them and selectively harvest large individuals. Together these studies provide the necessary information to develop management strategies that promote sustainable gar fisheries and provide quality recreational opportunities to anglers.

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# CHAPTER 1: LITERATURE REVIEW

Overexploitation is one of five major threats to freshwater biodiversity (Dudgeon et al. 2006), and has led to collapses of the world's largest commercial fisheries (Cook et al. 1997; Hutchings 2000; Jackson et al. 2001; Froese et al. 2009). Driven by economic motives, commercial fishers will increase effort and seek ways to improve capture efficiency even as fish stocks decline, which may drive populations to commercial, if not biological, extinction (Post et al. 2002). In contrast, recreational anglers are free from the economic motives to continue fishing depleted stocks and may abandon fishing opportunities that fail to meet their expectations and choose to participate in other recreational opportunities as fisheries decline (Johnson and Carpenter 1994; Hansen et al. 2000). However, time series analysis of the Rainbow Trout (*Oncorhynchus mykiss*) fishery in British Columbia, and the Walleye (*Sander vitreus*) and Northern Pike (*Esox lucius*) fisheries in Alberta showed reductions in catch rates coupled with substantial increases in total angler effort (Post et al. 2002), suggesting that recreational fisheries may be vulnerable to collapse via mechanisms similar to those observed in commercial fisheries. As recreational fishing may be the primary source of harvest for many inland fisheries (McPhee et al. 2002), understanding the contributions of recreational harvest to freshwater fisheries declines is crucial for the effective management of ecologically and economically important resources (Cooke and Cowx 2004).

Recreational anglers targeting black bass (*Micropterus spp.*), catfish (*Ictalurus spp.*), and sunfish (*Lepomis spp.*) with rod-and-reel have dominated freshwater fisheries in the USA, and specifically in Illinois, over half of all recreational anglers target black bass using rod-and-reel (USFWS 2016). While high catch rates and large fish of targeted species primarily drive recreational angler satisfaction, a diversified catch can also increase angler satisfaction

(Beardmore et al. 2015). Furthermore, if their preferred fishing is constrained by declining fish stocks or regulations, recreational anglers may choose to fish in new locations (Hunt 2005, Hunt et al. 2007), target different species (Fisher and Ditton 1993, Sutton and Ditton 2005) or seek other recreational opportunities (Ditton and Sutton 2004). If anglers choose to substitute new fishing methods, specialized recreational fisheries, such as bowfishing, may attract new participants.

Although legally practiced throughout the United States, the current extent and magnitude of bowfishing is largely unknown (Quinn 2010; Bennett and Bonds 2012; Bennett et al. 2015). Estimates of how many individuals participate in bowfishing are not reported in state or federal fishing surveys that describe the human dimensions and economic impact of fishing (e.g. USFWS 2016); however, a study on angler demographics in Texas found that bow anglers accounted for just 3% of freshwater anglers in 2012 (Kyle et al. 2013). Historically, bowfishing was infrequently used by a small constituency of anglers (Quinn 2010; Bennett et al. 2015) but has experienced an apparent growth in popularity throughout the USA in recent years (Johnson 2014; Lander 2014; Geiser 2016; Skurzewski 2017). In Illinois, fisheries managers have also reported an increased interest in the method (M. McClelland, Illinois Department of Natural Resources, personal communications). Traditional creel survey methods are often ineffective at surveying specialized sport fisheries (Griffiths et al. 2010), and bow anglers are typically not intercepted as bowfishing activity often happens at night (Bennett and Bonds 2012). Thus, little information is available on bowfishing effort and harvest, although these “cryptic” bow anglers may be the primary source of fishing mortality for some species (Griffiths et al. 2010; Bennett et al. 2015).

In Illinois, bow anglers commonly target “rough fish” such as invasive carp species (*Cyprinidae*), buffalo and other sucker spp. (*Catostomidae*), and gars (*Lepisosteidae*). Gars in particular appear to be important targets for bow anglers. For example, Buckmeier (2008) asserts that bowfishing accounts for the majority of recreational harvest of Alligator Gar (*Atractosteus spatula*). Sixty-seven percent of bow anglers in Texas reported that gars other than Alligator Gar were among their top three target species (Bennett et al. 2015), suggesting that other gars are also of recreational importance. Additionally, a creel survey of bowfishing tournaments in Arkansas found that Spotted Gar (*Lepisosteus oculatus*) and Shortnose Gar (*L. platostomus*) were among the top five species harvested and represented 24% and 17% of total harvest respectively (Quinn 2010). Although the magnitude of harvest by either rod-and-reel or bow anglers is poorly understood in Illinois, all gars of any size can legally be harvested in unlimited numbers by recreational anglers. As the lethal nature of bowfishing limits the management options available to fishery managers, understanding the fishing effort, species composition of harvest and harvest rates of bowfishing, as well as the habits and preferences of bow anglers will be crucial to ensure these emerging fisheries are sustainable.

Historically, gars were considered nuisance species by anglers and resource managers due to their reputation for consuming and competing with more desired game fish (Caldwell 1913; Holloway 1954; Suttkus 1963; Scarnecchia 1992), often resulting in management approaches that included eradication efforts (Scarnecchia 1992). However, gars promote ecosystem balance through predation of other fishes (Holloway 1954; Scarnecchia 1992; Ostrand et al. 2004), serve as hosts for glochidia of freshwater mussel species (e.g. Trdan and Hoeh 1982; Keller and Ruessler 1997), and have been recognized as environmental indicators (e.g. Hartley et al. 1996; Huang et al. 1997; Watanabe et al. 2003; Burger et al. 2004).

Gars are widely distributed throughout the eastern US (Netsch and Witt 1962; Etnier and Starnes 1993; Helfman et al.1999), except for Alligator Gar, which are currently restricted to more southern latitudes (Sakaris et al. 2003). Longnose Gar (*L. osseus*) are most often found in the main channel of streams and rivers (Holloway 1954; Johnson and Noltie 1997), and opportunistically move into river floodplains during inundation to utilize the abundant of prey resources (Robertson et al. 2008). Spotted and Shortnose gars are primarily found in vegetated lakes, bayous and backwater floodplains with slow-moving water (Holloway 1954; Suttkus 1963; Snedden et al.1999; Smith 2006), and utilize river channels to move among backwater habitats (Dettmers et al. 2001). Longnose and Spotted gars seemingly avoid competition by inhabiting different habitats (Robertson et al. 2008), whereas Spotted and Shortnose gars partition food resources in shared habitats (Walker et al. 2013). Generally, gars are opportunistic ambush predators that primarily consume fishes, but will also consume crustaceans, aquatic and terrestrial insects, and amphibians (Tyler and Granger 1984; Vokoun 2001; Robertson et al. 2008; Walker et al. 2013; VanMiddlesworth et al. 2016). Female gars live longer and reach larger sizes and weights than male gars (e.g. Johnson & Noltie 1996; Smith 2006; Kelley 2012), but their sex is not readily determined by external features (see McDonald et al. 2018). Gars exhibit periodic life history strategies characterized by large adult body sizes, late maturation, large egg size, high fecundity, sporadic recruitment and long life spans (Winemiller and Rose 1992; Ferrara 2001; Smith 2006; Smith et al. 2018). Despite commonly remaining motionless at the surface (Suttkus 1963), Longnose, Spotted and Alligator gars undergo long-distance migrations associated with spawning (Snedden et al. 1999; McGrath et al. 2012; Buckmeier et al. 2013). During spawning gars are typically found in large groups, where multiple males compete to spawn with one large female (Holloway 1954; Suttkus 1963; Mendoza-Alfaro et al. 2008).

Of all the gar species, Alligator Gar are the most studied because of its vulnerable status (Jelks et al. 2008) and booming recreational importance as a trophy fishery in southern states (Ferrara 2001; Buckmeier 2008; Bennet and Bonds 2012; Bennet et al. 2015; Binion et al. 2015). While others have evaluated the population dynamics and life history of Spotted Gar (Echelle and Riggs 1972; Ferrara 2001; Love 2004; Smith 2006; David 2012; Glass et al. 2012), Longnose Gar (Netsch and Witt 1962; Echelle and Riggs 1972; Klaassen and Morgan 1974; Johnson and Noltie 1997; Ferrara 2001; Sutton et al. 2009; Kelley 2012; McGrath et al. 2012) and Florida Gar (Murie et al. 2009), Shortnose Gar have received little attention. At this time, I am only aware of two studies that describe the age and growth of Shortnose Gar (Holloway 1954; Sutton et al. 2009). Sutton et al. (2009) examined the age structure, growth and mortality of Shortnose Gars in the Wabash River, and suggested that the population has potential to support sustainable recreational and commercial fisheries. However, the authors also suggested that the low annual mortality rates they found were likely due to low recreational angler exploitation and lack of a commercial fishery. The emerging recreational importance of gars coupled with the growing popularity of bowfishing (Johnson 2014; Lander 2014; Geiser 2016; Skurzewski 2017) creates a critical need to determine the status of gar populations and the level of exploitation in Illinois.

To develop a better understanding of the population dynamics of Shortnose Gar and the characteristics of tournament bowfishing in Illinois, I conducted two complementary studies. In chapter 2, I utilize standardized population assessments to estimate the relative abundance, stock structure and vital rates of Shortnose Gar in the lower Illinois River. In chapter 3, I utilize a point-access creel survey of Illinois bowfishing tournaments to characterize participation and harvest with an emphasis on gars, and to describe bow angler favored target species and fishing habits. Together this work will aid in the development of appropriate management strategies that generate sustainable populations and provide quality recreational opportunities to anglers.

# CHAPTER 2: POPULATION TRENDS, VITAL RATES AND AGE STRUCTURE OF SHORTNOSE GAR IN A LARGE FLOODPLAIN RIVER

## Introduction

Although Shortnose Gar (*Lepisosteus platostomus*) are widely distributed throughout the eastern United States and are prevalent in many floodplain river systems, little is known about their population dynamics. The reputation of gars among anglers and resource managers as nuisance species for consuming and competing with more desired game fish (Caldwell 1913; Holloway 1954; Suttkus 1963; Scarnecchia 1992) has led to a notable lack of basic understanding of gar populations. However, gars promote ecosystem balance as a top predator (Holloway 1954; Scarnecchia 1992; Ostrand et al. 2004), serve as hosts for glochidia of freshwater mussel species (e.g. Trdan and Hoeh 1982; Keller and Ruessler 1997), and have been recognized as environmental indicators (e.g. Hartley et al. 1996; Huang et al. 1997; Watanabe et al. 2003; Burger et al. 2004). While studies involving Shortnose Gar have addressed fish community composition (e.g. Solomon et al. 2016), diet (Vokoun 2001; Walker et al. 2013) and aging methods (King et al. 2018), studies that examine the stock structure or vital rates of Shortnose Gars are outdated or limited. For example, Echelle and Riggs (1972) examined the early life history of gars in Lake Texoma, but collected few Shortnose Gar and often combined them with the closely related Spotted Gar (*L. oculatus*). While Holloway (1954) described the feeding habits, sex ratio, size distribution and spawning characteristics of Shortnose Gar in Ocala National Forest in Florida, their findings are largely descriptive as compared to more rigorous methodologies that are available today. Sutton et al. (2009) examined the size and age structure, growth, mortality and condition of Shortnose Gar in the Wabash River; however, the scope of their investigation is limited by small sample size and is temporally limited to a three-month sampling window in a single year. Due to this limited knowledge, managers are left to assume that the life history strategies of Shortnose Gar are similar to the other extant gar species, specifically Spotted Gar and Longnose Gar (*L. osseus*).

In contrast to historic angler attitudes, the large body size, predatory nature and distinctive attributes of gars are desirable trophy characteristics to modern anglers (Scarnecchia 1992), which has resulted in a growing interest for recreational gar fisheries. Surveys in Texas, Oklahoma and Illinois indicate that the majority of bow anglers enjoy targeting gar species (Bennett et al. 2015; Schooley et al. 2019; Chapter 3). Bow anglers currently represent a small percentage of freshwater anglers (Kyle et al. 2013), yet bowfishing appears to be growing in popularity throughout the US (Johnson 2014; Lander 2014; Geiser 2016; Skurzewski 2017) suggesting that recreational harvest of gars may expand. Although the current magnitude of bowfishing harvest is largely unknown, Shortnose Gar were among the top five species harvested at bowfishing tournaments in Arkansas (Quinn 2010) and bow anglers appear to selectively harvest large, mature individuals (Quinn 2010; Chapter 3). Due to their long life span and variable recruitment, gars may be at greater risk for growth and recruitment overfishing (Ferrara 2001; Smith et al. 2018), particularly if they are targeted during spatially and temporally predictable spawning aggregations (van Overzee and Rijnsdorp 2015; de Mitcheson 2016; Hall et al. 2018). Smith et al. (2018) demonstrated that modeled exploitation rates of just 7% caused the mean population size of Alligator Gar (*Atractosteus spatula*) to decline by 50%. Considering the unknown exploitation rates and emerging recreational importance of Shortnose Gar, a better understanding of their vital rates and population dynamics is crucial to effectively manage for sustainable populations.

The goal of this study was to describe the relative abundance, size and age structure, condition, growth and mortality of Shortnose Gar in the lower Illinois River. Over several years, I utilized a multi-gear sampling strategy in a variety of habitat types to generate insights into the spatial, feeding and spawning ecology of the species. Results of this study will increase the knowledge of Shortnose Gar population dynamics in large floodplain rivers and aid in the development of effective management strategies that promote sustainable populations and provide quality recreational opportunities for anglers.

**Methods**

*Study Area*

The Illinois River is a 440km commercially navigable tributary of the Mississippi River, and drains 44% of the largely agricultural central region of Illinois (Delong 2005). The La Grange reach is one of six navigation reaches of the Illinois Waterway, and is situated between the Peoria Lock and Dam at river kilometer 254 and the La Grange Lock and Dam at river kilometer 129. Both are wicket dams that do not control water levels during high flows but are raised to maintain a commercial navigation channel during moderate and low flows (Sparks et al. 1998; Koel and Sparks 2002). This portion of the river is characterized by a wide basin, low gradient and soft substrates, and contains a mixture of main channel, side channel and floodplain lake habitats (Sparks et al. 1998; McClelland et al. 2012). Despite unnatural water level variability throughout the year (Koel and Sparks 2002), increased sedimentation (Bhowmik and Demissie 1989), and the establishment of invasive Asian Carp (Chick and Pegg 2001, Irons et al. 2007), the La Grange reach supports a diverse fish assemblage (McClelland et al. 2012).

*Sampling Procedures*

Shortnose Gar were collected throughout the La Grange reach periodically between May 2015 and October 2018. I used a multi-gear sampling approach, employing direct current day electrofishing (DC EF), mini fyke nets and fyke nets to sample all habitat types and to compensate for gear selectivity. Data were obtained from the US Army Corps of Engineer's Upper Mississippi River Restoration Program Long-Term Resource Monitoring element (LTRM) and the Long Term Survey and Assessment of Large River Fishes in Illinois (LTEF), and were supplemented by additional sampling events and data acquired from a creel survey of bowfishing tournaments in Illinois (Table 2.1). LTRM sampling uses a stratified-random design that employs standardized, multi-gear protocols, which generates unbiased fish population estimates that can be extrapolated from individual river habitats to an entire river reach over time (Ratcliff et al. 2014). From 15 June – 31 October each year, LTRM samples the La Grange reach in main channel border habitats (MCB) using DC EF and mini fyke nets, side channel border habitats (SCB) using DC EF and mini fyke nets, and connected back water habitats (BWC) using DC EF, mini fyke nets and fyke nets. Nets are set for approximately 24 h and DC EF runs are approximately 15 minutes. Net specifications and further details on LTRM sampling protocols can be found in Ratcliff et al. (2014). Annually, LTEF conducts fish community assessments using electrofishing at six fixed sampling sites in the SCB or MCB habitats of the La Grange reach (McClelland et al. 2012). LTEF adopted DC EF sampling protocols similar to that of LTRM in 2016 (Fritts et al. 2017), so I excluded LTEF sampling events from 2015 from my analyses. Supplemental sampling events were conducted using LTRM sampling protocols for the three gears at additional sites. Shortnose Gar harvested during a bowfishing tournament hosted by the Bowfishing Association of Illinois on 14 July 2018 in the La Grange reach at Havana, IL were also included. Fishing effort for the tournament was obtained from data reported in Chapter 3.

For all samples, captured Shortnose Gar were measured for total length (TL) to the nearest millimeter (mm) and wet weight (W) to the nearest gram (g). The left, anterior-most pectoral fin ray was collected for age estimation from all Shortnose Gar collected in 2015 – 2017 by cutting as close to the base as possible and separating the ray from the rest of the fin (Koch et al. 2008; Quist et al. 2012; King et al. 2018). In 2018, the pectoral fin ray was only collected from fish less than 360 mm or greater than 620 mm to complete acquisition of samples across a representative range of sizes. Gar were marked with a uniquely numbered T-bar anchor tag (Floy Tag & Mfg., Inc.; Seattle, Washington) and released at the sampling location for an ongoing mark-recapture project.

*Sample Preparation and aging techniques*

Pectoral fin rays were prepared and aged following the methods outlined by King et al. (2018). Briefly, the fin rays were dried in labeled coin envelopes for at least 24 h, and then were set in epoxy resin (Epofix cold-setting embedding resin #1232; Electron Microscopy Sciences, Hatfield, Pennsylvania) using 1.5-mL centrifuge tubes as molds (Koch and Quist 2007). When the epoxy containing the fin ray hardened (approximately 24 h), it was removed from the centrifuge tube mold, and a minimum of three transverse sections (0.6 – 0.75 mm) were cut with an IsoMet Low Speed Precision Cutter (Model 11-1280-160; Buehler, Lake Bluff, Illinois). Sections were cut from the end most proximal to the fish's body to ensure the inner annulus was present (Koch et al. 2008; Quist et al. 2012).

Pectoral fin ray sections were placed in a dark dish, immersed in mineral oil and viewed using a dissection microscope (FZ6-ILST Stereo Zoom; Fein Optic) at 15× magnification with reflected light. Two experienced readers aged each structure independently without prior knowledge of fish size. If the reader's independently assigned ages differed by more than three years, each reader independently aged the structure a second time. Disagreements in the age estimates between the readers were reconciled with a consensus read, and if agreement could not be reached the fish was not assigned a consensus age.

*Data Analysis*

*Relative Abundance* – Mean catch per unit effort (CPUE) of Shortnose Gar in the La Grange reach was described across gears, habitats and years from 2013 to 2018. Estimates of CPUE from LTRM random sampling events were obtained from the US Geological Survey Graphical Fisheries Database Browser (https://umesc.usgs.gov/data_library/fisheries/graphical/fish_front.html). I limited the description of CPUE to LTRM random sampling data to prevent uneven sampling effort in the other data sources from introducing bias within comparisons over time.

*Size Structure* – Length frequency distributions were created for Shortnose Gar from all sampling events within and across all years. Differences in TL across gears, habitat and year were compared using ANOVA. As bow anglers selectively harvest large gars (Chapter 3), and I only collected fish from one bowfishing tournament in 2018, these samples were excluded from the analysis. Model assumptions were checked visually, and differences among factor levels were determined using a Tukey test. Habitat was not a significant factor in predicting TL, and so it was removed from the final model.

*Condition* – The length-weight relationship of Shortnose Gar was established with linear regression of log-transformed W and TL measurements (Le Cren 1951) using the 'FSA' package (Ogle et al. 2018). Two outliers were removed due to likely measurement errors and model assumptions were checked visually. To compensate for biases associated with back-transforming from the log scale (Ogle 2016), I multiplied the back-transformed 95% confidence interval by a correction factor (Sprugel 1983). Fish condition was described using the relative condition factor ($K_n$; Le Cren 1951):

$$K_n = \frac{W}{W'}$$

where $W'$ is the predicted mean weight for the population given an individual's observed TL. Welch's ANOVA was used to assess whether mean relative condition differed among years, and the Games-Howell post hoc test from the 'userfriendlyscience' package (Peters 2018) was used to determine differences between years. Linear regression was also used to describe the relationship between relative condition and total length for each year.

*Age Structure* – Comparisons between independent age assignments from the two readers were used to evaluate the relative bias and precision between readers. To visually assess relative bias between readers, age bias plots were created by plotting the mean age assignments from reader two against the assigned ages of reader one. If the points cluster around the 1:1 line, the age assignments are unbiased (Campana et al. 1995). Systematic bias between readers was also assessed statistically using the McNemar (McNemar 1947; Hoenig et al. 1995), Evans-Hoenig (Evans and Hoenig 1998) and Bowker (Bowker 1948; Hoenig et al. 1995) symmetry tests found in the 'FSA' package (Ogle et al. 2018). Results from the symmetry tests indicate significant bias in paired age estimates when $P < 0.05$. Precision between readers was evaluated using percent agreement, percent agreement within 1 and 2 years, and the average coefficient of variation (ACV; Chang 1982, Campana et al. 1995) calculated using the ‘FSA’ package (Ogle et al. 2018).

The consensus age and TL of Shortnose Gar was used to create an observed age length key with 50 mm length intervals across all years using the ‘FSA’ package (Ogle et al. 2018). Consensus ages were also used to create age frequency distributions for Shortnose Gar captured in each year. Only 22 individuals captured in 2018 had available age information, so age frequency distributions were limited to 2015, 2016 and 2017, which provided sufficient samples to evaluate age structure, growth and mortality. To test for differences in age structure among years, Kolmogorov–Smirnov tests were conducted for each pairwise combination of years. Results of the Kolmogorov–Smirnov tests were considered significant at the 95% confidence level adjusted for multiple comparisons using the Bonferroni correction.

*Growth* – The von Bertalanffy growth equation (Ricker 1975) was used to model TL at age for Shortnose Gar using nonlinear regression as:

$$L_t = L_\infty\left(1 - e^{-k[t-t_0]}\right)$$

where $L_t$ is the predicted TL (mm) at time $t$ (age, in years), $L_\infty$ is the estimate of mean maximum TL (asymptotic length, mm), $k$ is Browdy’s growth coefficient, and $t_0$ is the theoretical age (years) when TL would be zero. The model was fit in R using the Gauss-Newton algorithm with starting parameters modified from Sutton et al. (2009) to visually match the curve in a scatterplot of this study’s length at age information: $L_\infty$ = 675 mm, $k$ = 0.25 and $t_0$ = - 1.5. Ninety-five percent confidence intervals of the model parameters were calculated by non-parametric bootstrapping using the ‘nlstools’ package (Baty et al. 2015) and the ‘FSA’ package (Ogle et al. 2018). Model assumptions were checked visually using a residual plot and a histogram of the residuals. To assess if the model converged on the global minimum and was sensitive to algorithm choice, I fit the von Bertalanffy growth model with four additional combinations of starting parameters and algorithms (Ogle et al. 2017). Two versions of the model employed the Gauss-Newton algorithm as in the original model but used alternative starting parameters: 1) $L_\infty$ = 800 mm, $k$ = 0.25 and $t_0$ = 0; and 2) $L_\infty$ = 500 mm, $k$ = 0.35 and $t_0$ = -1. The other two versions of the model used the original starting parameters but employed the Port algorithm or the Levenburg-Marquardt algorithm from the 'minpack.lm' package (Elzhov et al. 2016) to fit the model. The overall model fit was considered robust if the coefficients from all growth model combinations were highly similar (McCollough 2008). If the model coefficients were dissimilar, the combination of starting parameters and algorithm choice that minimized the residual sum of squares (RSS) and the negative log-likelihood (NLLH) values was considered to have converged on the global minimum (Ogle et al. 2017). The strength of fit was assessed qualitatively by evaluating a scatterplot of length at age information with the model overlaid, and quantitatively by comparing the residual standard error and the root mean square prediction error from leave-one-out cross validation from the 'cvTools' package (Alfons 2012) to the range of observed TL as suggested by Ogle et al. (2017).

*Mortality* – Annual survival ($S$) and the instantaneous mortality rate ($Z$) were estimated through catch-curve analysis using two methods. First, I used the Chapman-Robson estimator of $S$ (Robson and Chapman 1961):

$$S = \frac{T}{n + T - 1}$$

and the standard error of the estimate provided by Miranda and Bettoli (2007) is:

$$SE_S = \sqrt{S\left(S - \frac{T-1}{n+T-2}\right)}$$

where $n$ is the total number of fish observed on the descending limb of the catch curve, $T$ is the sum of the recoded ages of fish on the descending limb of the catch curve. The Chapman-Robson estimator of $Z$ modified by Hoenig et al. (1983) is:

$$Z = -\log(S) - \frac{(n-1)(n-2)}{n(T+1)(n+T-1)}$$

and the standard error of the estimate modified by Smith et al. (2012) is:

$$SE_Z = \frac{1-e^{-Z}}{\sqrt{ne^{-Z}}}\sqrt{c}$$

where $c$ is a variance inflation factor (see Smith et al. 2012). As suggested by Smith et al. (2012), I used the "peak plus" method to define the descending limb of the catch-curve. Second, the instantaneous mortality rate was also estimated using the modified Hoenig method suggested by Then et al. (2015):

$$M = 4.889 \times t_{max}{}^{-0.916}$$

where $t_{max}$ is the maximum observed age of the population. Both methods were calculated using the 'FSA' package (Ogle et al. 2018). All tests were conducted using R 3.5.2 (R Core Team, Vienna, Austria), and results were considered significant at the 95% confidence level ($\alpha = 0.05$).

**Results**

*Relative Abundance* – In total, 814 Shortnose Gar were captured throughout the La Grange reach of the Illinois River during the study period (Figure 2.1). Fyke nets consistently produced the highest CPUE, with mean CPUE ranging from 2.26 – 9.57 fish per net night across years. Mini fyke nets were intermediate among the three gears, with mean CPUE ranging from 0.11 – 2.41 fish per net night across years. DC EF was lowest, with mean CPUE ranging from 0.22 – 1.03 fish per 15-minute electrofishing run. Comparisons among all three habitat types were possible only using DC EF and mini fyke nets, which revealed that CPUE was typically highest in the BWC habitat relative to the MCB or SCB habitats. Generally, trends in reach-wide CPUE over time were similar among gear types and were relatively stable (Figure 2.2). However, CPUE of mini fyke nets and DC EF declined from 2013 to 2014, whereas CPUE of fyke nets increased from 2013 to the gear's peak in 2014. Across all gear types, CPUE was lowest in 2015 and increased in the years following.

*Size Structure* – Shortnose Gar ranged from 276 – 789 mm TL (mean = 527 ± 84 mm SD; Figure 2.3). Total length varied among years ($F = 14.16$; df = 3, 793; $P < 0.01$), where 2015 samples contained larger Shortnose Gar than all other years ($P < 0.05$; Figure 2.4). Total length also varied among gears ($F = 4.86$; df = 2, 793; $P < 0.01$), where DC EF captured larger Shortnose Gar than fyke nets ($P < 0.05$; Figure 2.5).

*Condition* – The wet weight of Shortnose Gar ranged from 68 – 2,080 g (N = 768, mean = 539 ± 306 g SD). Forty-three Shortnose Gar were missing W values and so could not be included in length-weight relationship analyses. There was a strong relationship between log-transformed W and TL (adjusted $R^2 = 0.92$, $P < 0.01$; Figure 2.6). Overall, Shortnose Gar in the La Grange reach appear to be in average condition (mean = 1.01 ± 0.01 SE). The variance of relative condition differed among years (df = 3 and 764, $F = 5.83$, $P < 0.01$), with 2017 and 2018 having smaller variance than 2015 and 2016. Mean relative condition also differed among years ($F = 2.85$, df = 3 and 353.95, $P < 0.05$). Shortnose Gar were in better condition in 2018 then 2017 ($P < 0.05$), but all other years were similar. Across years, relative condition was generally most variable for individuals from 400 – 600 mm, whereas fish at the size range extremes exhibited less variation. However, linear regression of relative condition and TL was not significant for gar captured in 2015 (adjusted $R^2$ = -0.004; $P > 0.05$), 2016 (adjusted $R^2$ = -0.010; $P > 0.05$) or 2017 (adjusted $R^2$ = -0.002; $P > 0.05$). The linear regression of relative condition and TL was significant in 2018 but was a poor fit for the data (adjusted $R^2$ = 0.018; $P < 0.05$; Figure 2.7).

*Age Structure* – Eleven individuals were excluded from all age analyses because readers did not reach a consensus age, resulting in 602 Shortnose Gar for age analyses. The age bias plot indicates that for ages 0 – 4 reader 2 aged individuals slightly older relative to reader 1, and for ages 8 – 16 reader 2 aged individuals slightly younger relative to reader 1; however, for many age classes the 95% CI contains the 1:1 line (Figure 2.8). Likewise, results from McNemar ($\chi^2$ = 0.03; df = 1; $P > 0.05$), Evans-Hoenig ($\chi^2$ = 5.45; df = 3; $P > 0.05$), and Bowker symmetry tests ($\chi^2$ = 50.75; df = 43; $P > 0.05$), all indicate there was no systematic bias in age estimates between readers. There was poor precision between readers (percent agreement = 43%; ACV = 11.79), however percent agreement within one and two years was 79% and 94% respectively.

Consensus ages ranged from 1 – 18 years (mean = 6.4 ± 2.98 SD), with 50% of fish falling between 4 and 8 years old. Few individuals were less than 2 years (N = 10) or greater than 15 years (N = 5). Age classes greatly overlap in total length, but within a predicted age the proportion of fish in the larger length bins progressively increases with age. On average, each age class falls into five length intervals representing a possible range of 250 mm. Likewise, each length interval contains multiple age classes, peaking at 13 age classes present in the 550 – 599 mm bin (Figure 2.9). The Kolmogorov-Smirnov tests suggest that the age distribution of Shortnose Gar captured in 2015 is different from the distribution of those captured in 2016 (D =

0.34; P < 0.01) and 2017 (D = 0.36; P < 0.01), but that 2016 and 2017 are not different (D = 0.09; P > 0.01; Figure 2.10).

*Growth* – The von Bertalanffy growth model was fit to Shortnose Gar aged 1 – 14 (Figure 2.11), older age classes were removed due to low samples sizes (N < 5). The four growth models with alternative combinations of starting values and algorithm choice estimated values of L∞ within two decimal places, K within three decimal places, and t0 within four decimal places of the parameters of the original growth model, suggesting that the original growth model was robust to choices in starting parameters and algorithms. The residual sum of squares and negative log-likelihood values were exact among the models, indicating that all combinations of the growth model converged on the global minimum (Table 2.2). Thus, parameters from the original growth model were used hereafter. The residual standard error and the root mean square prediction error (both 48 mm) were minimal in comparison to the range of observed total lengths (276 – 789 mm), indicating that the growth model was a strong fit for the length at age information. The theoretical maximum length ($L_\infty$) predicted from the model was 822 mm (Table 2.3), which is greater than the maximum observed total length in the study.

*Mortality* – With the Chapman-Robson method, mortality estimates were calculated for Shortnose Gar between ages 6 and 16. Shortnose Gar less than age 5 were not fully recruited to the sampling gear, and all age classes older than the peak were included despite small sample sizes in some of the oldest age classes. The Chapman-Robson methods estimated instantaneous mortality rate (Z) as 0.357 (95% CI 0.300 – 0.415), and annual survival (S) as 69.9 (95% CI 67.3 – 72.6). The maximum observed age in this study (18 years) was used to estimate instantaneous mortality by the modified Hoenig method (M), which estimated M as 0.347. This estimate fell within the 95% CI of Z from the Chapman-Robson method, suggesting that the estimates of mortality are robust with respect to choice of methodology.

## Discussion

Support for a recreational Shortnose Gar fishery in Illinois appears to be growing; however, the necessary population information to evaluate the need and substantiate the creation of effective regulations is largely unknown. In this study I found that Shortnose Gar in the lower Illinois River live longer and have the potential to reach larger sizes than previously expected. Trends in the age and size structure suggest Shortnose Gar experience interannual variation in recruitment. The slower growth rates and higher mortality rates of the population in the Illinois River may require a precautionary management approach to avoid overharvest. Additionally, by utilizing multiple gears and sampling in a variety of habitat types, I was able to provide insight into the spatial, feeding and spawning ecology of Shortnose Gar in large river floodplain systems.

Adult Shortnose Gar were more commonly captured in connected backwaters, suggesting these areas provide more suitable habitat relative to main channel or side channel habitats in the Illinois River. This finding supports previous reports that Shortnose Gar prefer shallow, slow-moving backwater habitats (Holloway 1954) and primarily use the river channel as a means to move among backwater habitats (Dettmers et al. 2001). While I captured a limited number of Shortnose Gar in the main channel of the Illinois River, Sutton et al. (2009) collected all Shortnose Gar in their study from main channel habitats of the Wabash River. In contrast to the lower Illinois River, the Wabash River has fewer permanently connected backwaters (Coulter et al. 2016), so slower-moving areas in the main channel and tributaries may serve as primary Shortnose Gar habitat throughout the year where connected backwaters are not common. Like many floodplain fishes however, Shortnose Gar may utilize intermittent lateral connections with backwater habitats during high flows to forage or to spawn (Ross and Baker 1983; Kwak 1988; Robertson et al. 2008; Gorski et al. 2010; Burgess et al. 2013). A survey of nine intermittently connected oxbow lakes on the lower Wabash River, lower White River and Lower West Fork White River found a higher abundance of Shortnose Gars in July than October (Pyron and Robbins 2019), suggesting seasonal use of the oxbow lakes. Presumably, high flows in spring and summer prompt Shortnose Gar to enter the newly connected backwater habitats, and receding waters later in the year cue them to return to the main channel. While the seasonal movement of Shortnose Gar is unclear from existing work, habitat use is clearly driven in part by the availability of still waters, whether that be connected backwaters, slow moving areas in the main channel or smaller tributaries. Ongoing acoustic telemetry work on the lower Illinois River will provide clarification into the seasonal movements and habitat use of Shortnose Gar in large floodplain rivers.

The combined use of multiple gears in this study allowed us to capture a large size range of Shortnose Gar; but specific gears exhibited size selectivity and all gears failed to adequately sample juvenile fish. These results are largely consistent with previous gear selectivity studies, namely that fyke nets caught more fish when set in the same habitat as the mini fyke nets (Shoup et al. 2003) and DC EF selected for larger individuals than fyke nets (Ruetz et al. 2007). While I expected the reduced throat sizes of the mini fyke nets to prohibit larger individuals from entering the mini fyke net and thus the mini fyke nets to select for smaller individuals than the fyke nets (Shoup et al. 2003), the size distribution of captured Shortnose Gar was similar between the two gears. The slender, cylindrical body of Shortnose Gars likely allowed most individuals to pass through the smaller throats of the mini fyke nets despite increasing total length, whereas more robust species may be limited by reduced throat sizes. Overall, Shortnose Gar less than 493 mm were not fully recruited to the gears I used, and I captured few Shortnose Gar less than 300 mm. Similarly, Shortnose Gar smaller than 330 mm were not captured in multi-gear surveys in Florida (Holloway 1954) and the smallest Shortnose Gar captured during DC EF surveys on the Wabash River was 498 mm (Sutton et al. 2009).

In addition to size-selective gear biases, the limited number of small Shortnose Gar I captured may have resulted from juveniles utilizing habitats I did not sample in this study. As juveniles of other gar species use floodplain areas for nursery habitats (Snedden et al. 1999), I expected to capture a higher proportion of small Shortnose Gar in the backwater habitat relative to main channel or side channel habitats. While I did not detect differences in size structure among the sampled habitat types, there are intermittently connected backwater habitats in the La Grange reach that I was unable to sample. These seasonally connected backwaters may provide more suitable nursery areas for juvenile Shortnose Gars, away from the threat of predation by adult gars (Robertson et al. 2008; VanMiddlesworth et al. 2016) or other piscivores. Alternatively, in highly modified river systems such as the Illinois River, tributaries may be increasingly important in providing ecological services to fish populations that mainstem rivers are not fulfilling (Pracheil et al. 2009). For example, other large river fishes such as Shovelnose Sturgeon (*Scaphirhynchus platorynchus*) and Lake Sturgeon (*Acipenser fulvescens*) use tributaries as spawning habitats (Fortin et al. 1993; Auer 1996; Rusak and Mosind 1997; Goodman et al. 2013). Tributaries are also important to the recruitment of young of year Paddlefish (*Polyodon spathula*; Pracheil et al. 2009). Future work should assess methods for capturing juvenile Shortnose Gar in order to provide a more robust picture of early life history traits, and examine the use of intermittently connected backwater habitats and tributaries as spawning and nursery areas.

Like other periodic life history strategists, Shortnose Gar likely experience variable or infrequent recruitment as evidenced by observed trends in size and age structure across years. Variation in recruitment may result in lagged effects on the age structure of populations (Gaillard et al. 2008), and dominant cohorts apparent in the age structure can be evidence of strong recruitment in the past (Doherty and Fowler 1994). In this study, a large cohort of age 5 Shortnose Gar was present in the 2015 age distribution and can be tracked in the 2016 and 2017 distributions, suggesting a strong recruitment year in 2010. Inter-annual variation in recruitment among large river fishes may be a response to evolving in habitats with somewhat predictable seasonal variation in hydrology (Winemiller and Rose 1992). The recruitment success of Alligator Gar in the middle Trinity River in Texas is significantly correlated with spawning habitat availability during the warmer months (May – July) and longer durations of flooding (30 and 90 days; Robertson et al. 2018). Spotted Gar showed positive correlations with increased connectivity to floodplain lakes in the Yazoo River Basin (Miyazono et al. 2010). Likewise, a slight increase in relative abundance of Shortnose Gars in 2014 coincided with a high magnitude flood that lasted 85 days in the La Grange reach and temporally aligned with the presumed spawning period, suggesting that these same environmental factors likely influence the recruitment of Shortnose Gars. Correspondingly, I observed a higher prevalence of age 2 Shortnose Gar in 2015, but I would not expect to see a clear signal of a strong cohort until 2018 when the individuals are fully recruited to the sampling gear at age 5. Although periodic production of offspring allows individuals to synchronize reproduction with favorable conditions (Armstrong and Shelton 1990; Scarnecchia et al. 2009), and longer life spans paired with an iteroparous reproduction strategy compensate for years of poor recruitment (Winemiller and Rose 1992); these same life history characteristics leave periodic life history strategists especially vulnerable to human disturbances (Ricker 1963; Adams 1980; Francis 1986; Reiman and Beamesderfer 1990; Ferrara 2001).

Length-weight relationships can be an indicator of nutritional status, prey abundance and habitat suitability. The parameters from my total length-weight regressions were similar to those from Shortnose Gar in the Wabash River (Sutton et al. 2009), suggesting that the length-weight relationship in Shortnose Gar may be conserved across populations in Illinois. As I employed a multi-gear approach and had a larger sample size, the regression more accurately reflects the true length weight relationship of Shortnose Gars as evidenced by an improved model fit (Sutton et al., 2009 $R^2 = 0.73$; this study $R^2 = 0.92$). Relative condition fluctuated around average condition ($K_n = 1$) over time, and in most years there were not size-specific differences in relative condition. Individuals at intermediate size ranges exhibited the widest ranges in relative condition, which may be the result of aggregating pre-spawning and post-spawning individuals of both sexes (Sutton et al. 2009). Due to low sample sizes in the main channel border and side channel border habitats ($N < 40$), I was unable to test for differences in relative condition among habitat types. Regardless, the results imply that there are ample prey resources available to Shortnose Gar in the La Grange reach overall and that Shortnose Gar of all sizes have the potential to resist nutritional stress (Pope and Kruse 2007). Furthermore, estimated $L_\infty$ was larger than the observed maximum total length in this study, suggesting that the La Grange reach has sufficient resources to support larger fish than what I observed. Future work should incorporate length-weight information from multiple populations of Shortnose Gar into a standard weight equation, so that relative weight can be compared throughout their wide-ranging distribution (Sutton et al. 2009).

Age estimates in this study indicate that Shortnose Gar reach older ages than previously reported. Sutton et al. (2009) observed Shortnose Gar up to age 12 from the Wabash River, while I observed Shortnose Gar up to age 18. Discrepancies in age estimation methods could be partially accountable for these differences as Sutton et al. (2009) used branchiostegal rays to estimate age whereas I used pectoral fin rays. Branchiostegal rays from old individuals become thick and opaque making it difficult to view annuli in these specimens (Ferrara 2001; King et al. 2018), suggesting that the ages from Sutton et al. (2009) may be underestimates. However, pectoral fin rays of Shortnose, Spotted and Longnose gars provide lower mean and maximum ages relative to branchiostegal rays (King et al 2018), and pectoral fin rays underestimate the age of Alligator Gar older than age 6 (Buckmeier et al. 2012). The two readers in this study were highly experienced with aging pectoral fin rays of gars, which may have benefitted the identification of older age classes despite the potential biases among structures (Buckmeier et al. 2018; King et al. 2018; Stein et al. 2018). The older age estimates in this study could also be a function of greater sampling efforts and larger sample sizes, as the probability of encountering individuals at longevity extremes likely increases with sampling effort and sample size (McGrath 2010). As such, I believe that the differences in maximum age I observed are likely a reflection of biology rather than choices in aging structure.

Growth rates of Shortnose Gar in this study appear to be typical of other gar species, but were slower compared to the only other study of SHG growth rates (Sutton et al. 2009). Generally, juvenile gars are reported to grow rapidly, exhibiting some of the fastest larval growth rates of all fish (see Netch &Witt 1962; Echelle & Riggs 1972; Simon & Wallus 1989; David

2012). By the end of the first growing season, Spotted Gar reach 300 mm TL and Longnose Gar reach 400 mm TL (Snedden et al. 1999; McGrath 2010). In this study, the 95% confidence interval of mean TL at age 1 predicted by the von Bertalannfy growth model was 339 – 369 mm, suggesting that young of year growth rates for Shortnose Gar are intermediate to that of Spotted and Longnose gars. For other gars, somatic growth slows after the first year, after which the majority of energy is allocated to reproduction following the onset of sexual maturity (Johnson and Noltie 1997; McGrath 2010; Sutton et al. 2009; Binion et al. 2015). The von Bertalannfy growth model in this study does not provide a conclusive age estimate for when asymptotic (post-maturation) growth begins. In a related ongoing study, however, dissections of Shortnose Gar from multiple watersheds throughout Illinois reveal that the frequency of immature gonads sharply declines around 450 mm and mean gonadal weight was increasing for both males and females by 500 mm (Sarah King, Illinois Natural History Survey, unpublished data). Based on predicted length at age from the growth model, this suggests Shortnose Gar reach sexual maturity from age 4 – 5, which agrees with previous findings from the Wabash River (4 years; Sutton et al. 2009). Overall, Shortnose Gar in the La Grange reach grew slower than Shortnose Gar in the Wabash River (Sutton et al. 2009), and Spotted Gar populations in Georgia and Lake Eerie (Ferrara 2001; David 2012). Growth rates exhibited by Spotted Gar in Louisiana (Smith 2006) and Longnose Gar in Alabama, Virginia and Texas (Ferrara 2001; McGrath 2010; Kelley 2012) were the most similar to Shortnose Gar in the La Grange Reach. Slow growth rates may indicate delayed sexual maturity and long generation times that result in lower intrinsic rates of population increase (Jennings et al. 1998; Musick 1999). Populations that exhibit these characteristics are highly susceptible to population decline due to anthropogenic factors such as habitat loss and overfishing (Parent and Schriml 1995; Boreman 1997; Jennings et al. 1998; Musick 1999; Ferrara 2001).

The instantaneous mortality rate of Shortnose Gar in the La Grange reach tended to be higher than in the Wabash River (Z = 0.28); however the mortality estimates from this study fell within the 95% CI reported by Sutton et al. (2009), indicating that differences in mortality rates between the two studies may not be statistically significant. The current study benefitted from a larger sample size and utilized catch-curve methodologies that are known to perform better (Dunn et al. 2002; Smith et al. 2012), thus this study's mortality estimates are more robust and may provide a stronger foundation for future management decisions that can be applied to other populations in the region. Shortnose Gar seemingly live longer in the Illinois River than the Wabash River, so I would expect that mortality rates would be lower in the Illinois River; however, I observed the opposite. The discordance in the relationship between longevity and mortality may be indicative of increasing fishing mortality of Shortnose Gars since the publication of Sutton et al. (2009). Tournament bow anglers exploit Shortnose Gar at low harvest rates in Illinois (Chapter 3), but it is unknown the extent or rate of harvest by rod-and-reel anglers and non-tournament bow anglers. As bow anglers enjoy targeting gars (Bennett et al. 2015; Schooley et al. 2019; Chapter 3), and bowfishing is growing in popularity (Johnson 2014; Lander 2014; Geiser 2016; Skurzewski 2017), fishing mortality of Shortnose Gars may be expected to increase. Furthermore, bow anglers typically harvest large gars from the population (Quinn 2010; Chapter 3) and are unlikely to harvest immature Shortnose Gars based on expected age at maturity. Long-lived, slow-growing fish are especially vulnerable to growth and recruitment overfishing (Ricker 1963; Adams 1980; Francis 1986; Rieman and Beamesdfer

1990; Ferarra 2001; Smith et al. 2018), so future studies should focus on determining current exploitation levels and the threshold for sustainable harvest of this emerging fishery.

Gars are sexually dimorphic with females living longer, exhibiting slower growth rates and reaching larger sizes than males (Holloway 1954, Johnson and Noltie 1997, Ferrara 2001, Love 2004, Smith 2006, Murie et al. 2009). However, determining the sex of gars requires inspection of the gonads, which was not possible in this study and consequently these analyses were pooled across sexes. For male Shortnose Gar, I likely overestimated the maximum length and age, and underestimated growth and mortality rates, whereas for female Shortnose Gar the opposite is likely true. Future studies should focus on sex-specific vital rates of Shortnose Gar and developing non-lethal, morphometrically-based methods for predicting sex similar to those available for other gar species (Love 2002; McGrath and Hilton 2012; McDonald et al. 2013; McDonald et al. 2018).

The long life span, slow growth rate and periodic spawning strategy exhibited by Shortnose Gar in the La Grange reach suggest that the population may be vulnerable to recruitment overfishing at low exploitation levels. Furthermore, the difficulty in aging Shortnose Gar may have resulted in the large variability in the length at age information, uncertainty in the age at maturity from the growth model and mortality rates higher than anticipated. Until these issues can be rectified, and the magnitude of recreational harvest and the size of Shortnose Gar populations can be estimated, a precautionary approach to management is advised. In addition to the future directions detailed above, current research is underway to develop estimates of fecundity in Shortnose Gar and to estimate population size in multiple watersheds throughout Illinois using mark recapture methods. In combination with the vital rates in this study, these future results can be incorporated into population growth models that examine population trends in response to different levels of exploitation and management scenarios. Altogether, this work will aid in the development of management scenarios that promote sustainable populations and provide quality recreational opportunities to anglers.

**Tables**

Table 2.1: Sampling effort in the La Grange reach from 2015 – 2018. The events column represents the number of sampling events, and the effort column is the total effort of the sampling events. Effort values for fish captured with DC EF, mini fyke nets and fyke nets, and bowfishing are estimated in minutes, net nights and angler hours respectively.

| Program | Gear | 2015 | | 2016 | | 2017 | | 2018 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Events | Effort | Events | Effort | Events | Effort | Events | Effort |
| LTRM | DC EF | 108 | 1,620 | 111 | 1,620 | 111 | 1,620 | 111 | 1,620 |
| | Mini fyke | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| | Fyke | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| LTEF | DC EF | - | - | 6 | 90 | 6 | 90 | 6 | 90 |
| Extra Sampling | DC EF | 5 | 75 | 10 | 150 | 1 | 15 | - | - |
| | Mini fyke | 1 | 1 | - | - | - | - | - | - |
| | Fyke | 29 | 29 | 57 | 57 | 34 | 34 | 50 | 50 |
| | Bowfishing Tournament | - | - | - | - | - | - | 1 | 94 |

Table 2.2: The high similarity between the model coefficients, residual sum of squares (RSS) and negative log-likelihoods (NLLH) among the von Bertalannfy growth models suggest that the analysis was robust to choices in algorithm and starting parameters. The original model fit is shown in bold.

| Algorithm | Starting parameters | | | Model coefficients | | | | |
|---|---|---|---|---|---|---|---|---|
| | $L_\infty$ | $K$ | $t_0$ | $L_\infty$ | $K$ | $t_0$ | RSS | NLLH |
| **Gauss-Newton** | **675** | **0.25** | **-1.5** | **821.7102** | **0.0917** | **-5.1458** | **1,343,251** | **-3,146.4** |
| Gauss-Newton | 800 | 0.25 | 0 | 821.7085 | 0.0917 | -5.1458 | 1,343,251 | -3,146.4 |
| Gauss-Newton | 500 | 0.35 | -1 | 821.7112 | 0.0917 | -5.1459 | 1,343,251 | -3,146.4 |
| Port | 675 | 0.25 | -1.5 | 821.7110 | 0.0917 | -5.1458 | 1,343,251 | -3,146.4 |
| Levenburg-Marquardt | 675 | 0.25 | -1.5 | 821.7110 | 0.0917 | -5.1458 | 1,343,251 | -3,146.4 |

Table 2.3: Parameters and 95% confidence intervals of the original von Bertalannfy growth model.

| Parameter | Coefficient | 95% Confidence interval | |
|---|---|---|---|
| | | lower | upper |
| $L_\infty$ | 821.71 | 747.33 | 964.38 |
| $K$ | 0.09 | 0.06 | 0.12 |
| $t_0$ | -5.15 | -6.82 | -3.90 |

**Figures**

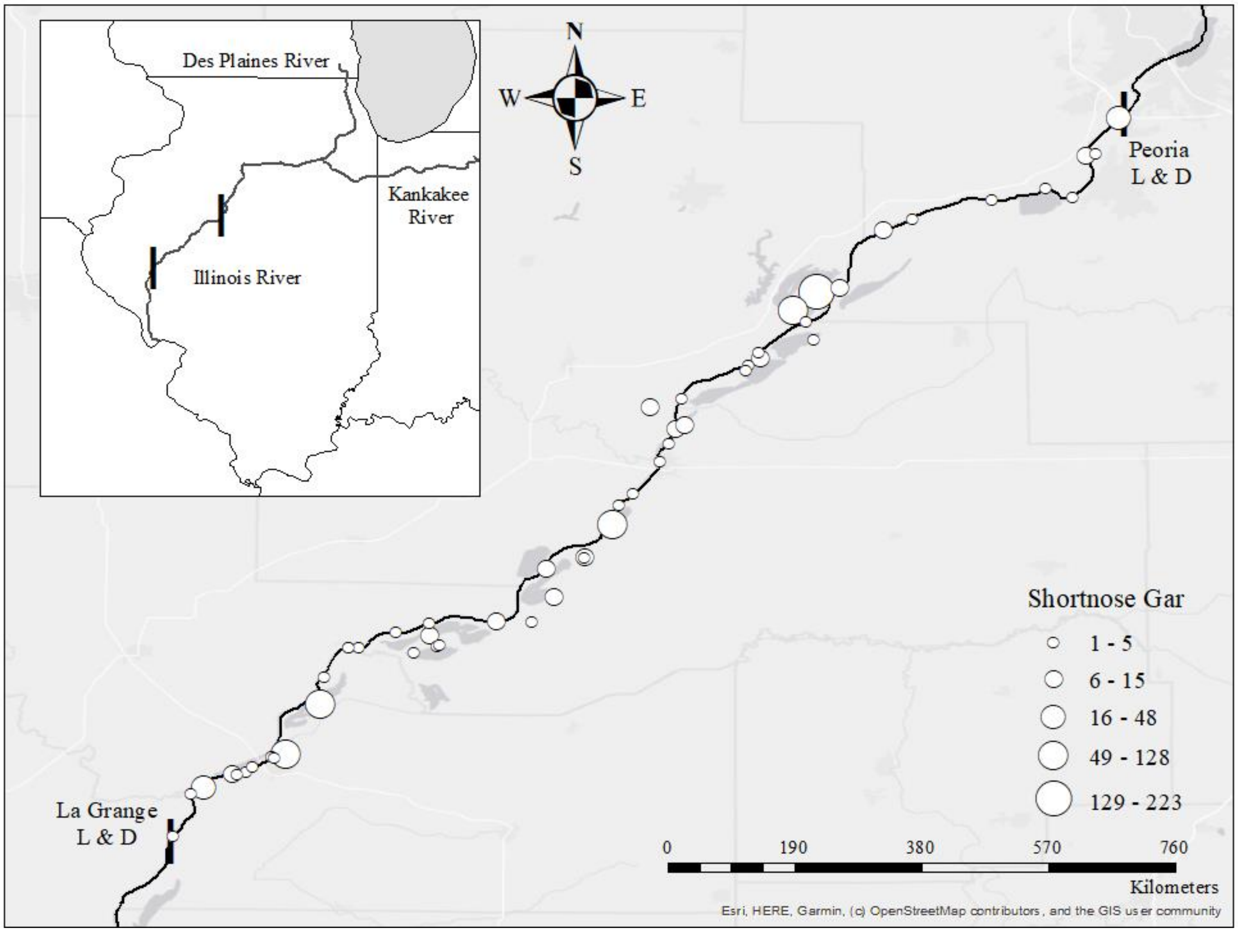


Figure 2.1: Shortnose Gar capture locations in the La Grange reach of the Illinois River from 2015 – 2018. The size of the circles is proportional to the number of Shortnose Gar captured. In both frames, the black lines represent the lock and dam complexes that border the La Grange reach.

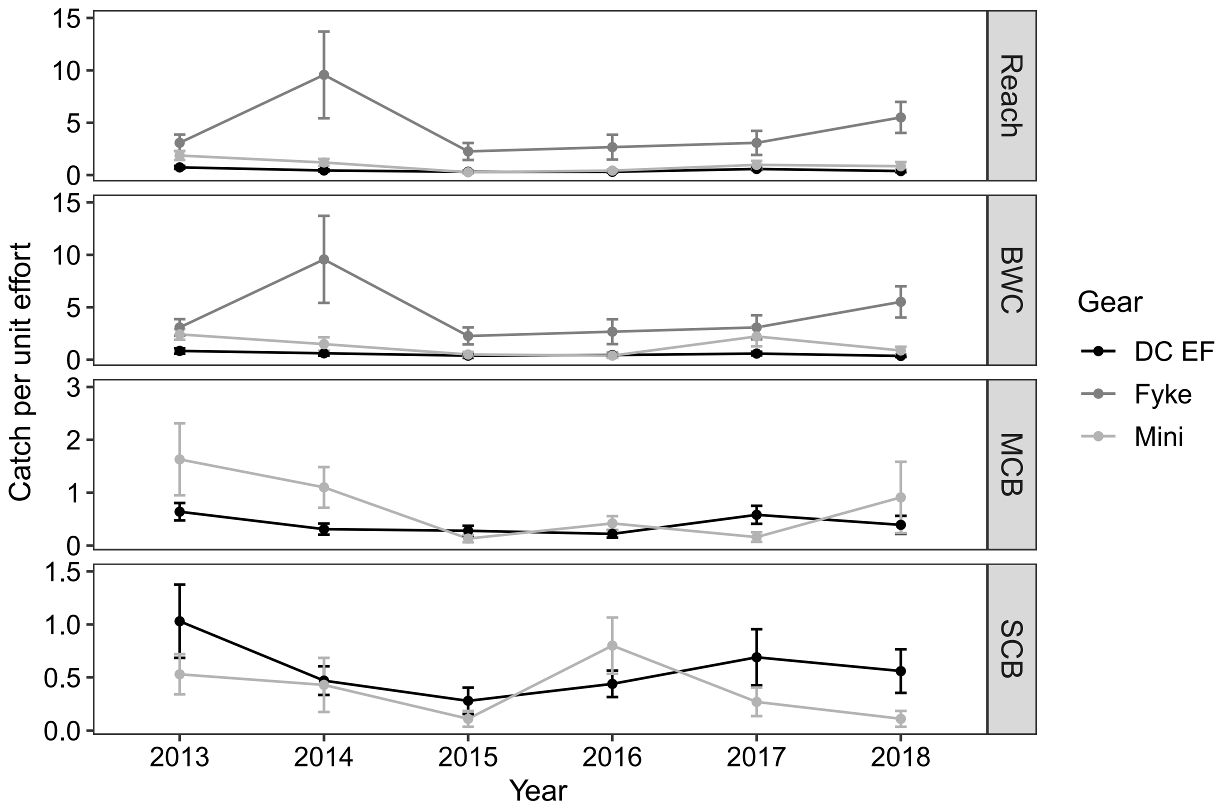


Figure 2.2: The relative abundance of Shortnose Gar in the La Grange reach captured in DC EF, fyke net (fyke) and mini fyke net (mini) LTRM sampling events from 2013 – 2018. The panels contain estimates for the connected back water (BWC), main channel border (MCB) and side channel border (SCB) habitats, and for the whole study reach. Note that the scale of the y-axis varies among the panels. The error bars represent the standard error of the estimate.

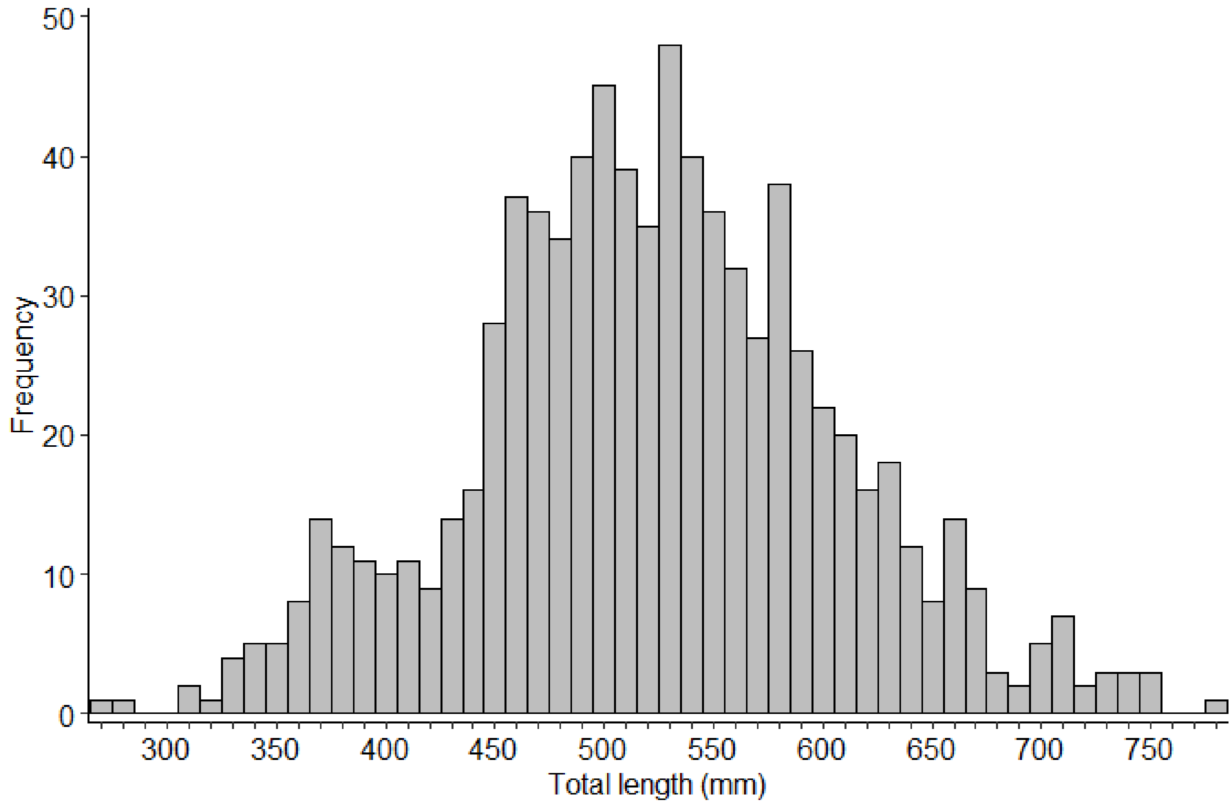


Figure 2.3: The length frequency distribution of all Shortnose Gar captured in the La Grange reach of the Illinois River from 2015 – 2018.

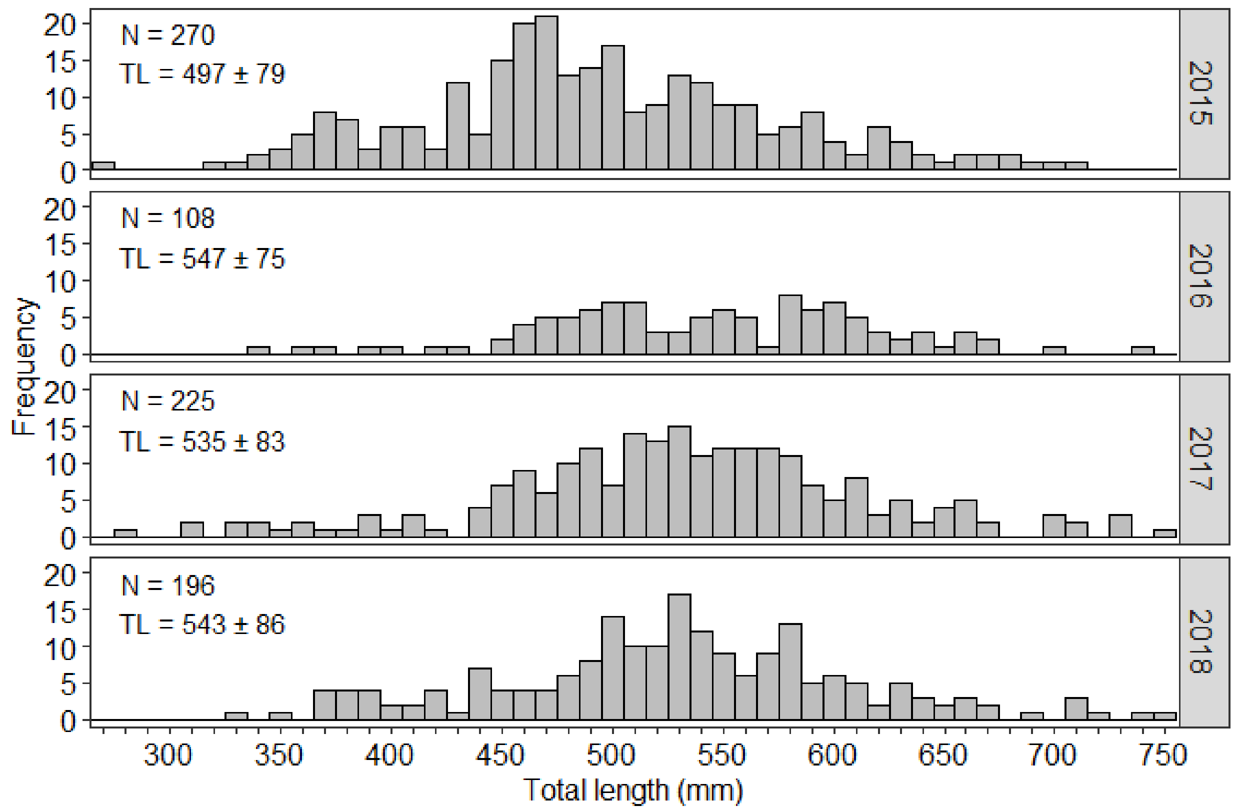


Figure 2.4: The length frequency distributions of Shortnose Gar captured in the La Grange reach of the Illinois River each year from 2015 – 2018. Shortnose Gar in 2015 were significantly smaller in TL than those in all other years ($P < 0.05$), and all other years were similar ($P > 0.05$). In each panel, the sample size (N) and mean TL ± SD are indicated.

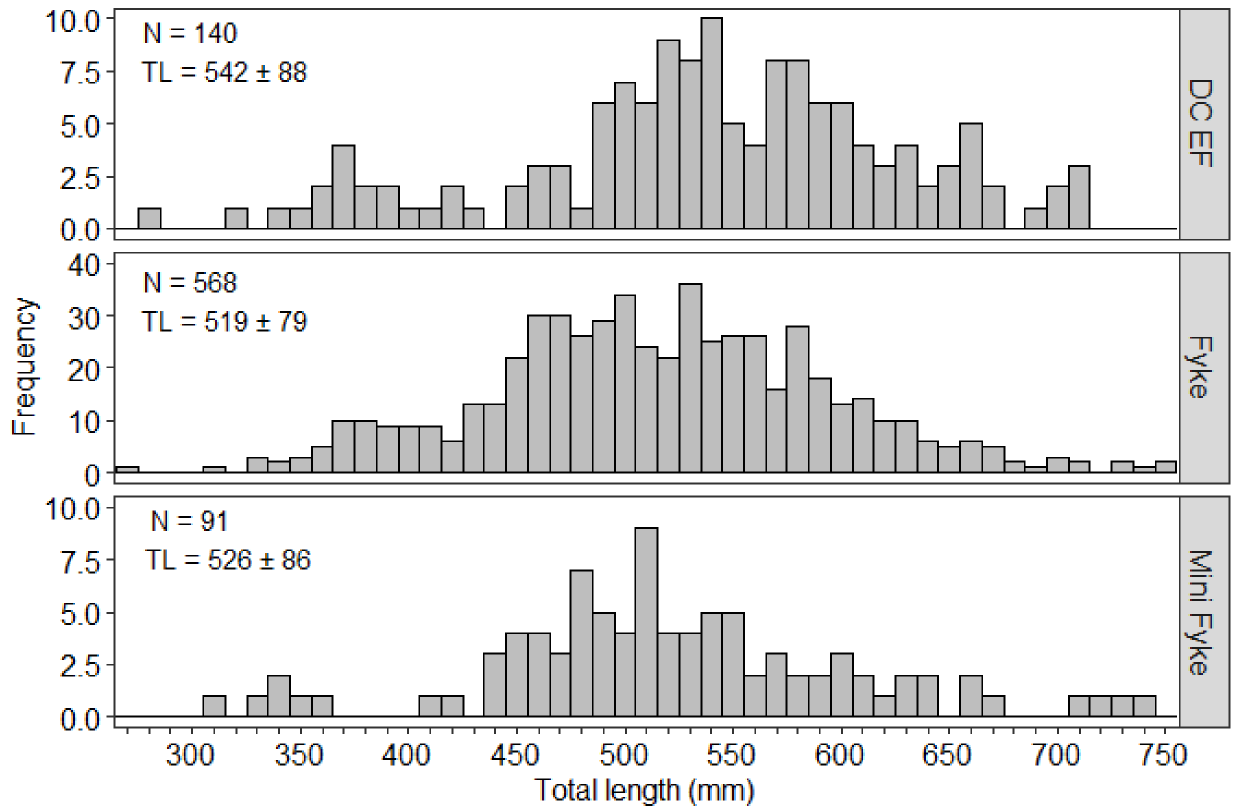


Figure 2.5: The length frequency distributions of Shortnose Gar captured in the La Grange reach of the Illinois River by each gear. Shortnose Gar captured by DC EF were greater in TL than those captured by fyke nets ($P < 0.05$), and all other gears were similar ($P > 0.05$). In each panel, the sample size and the mean total length ± SD are indicated. Notice that the y-axis differs among panels.

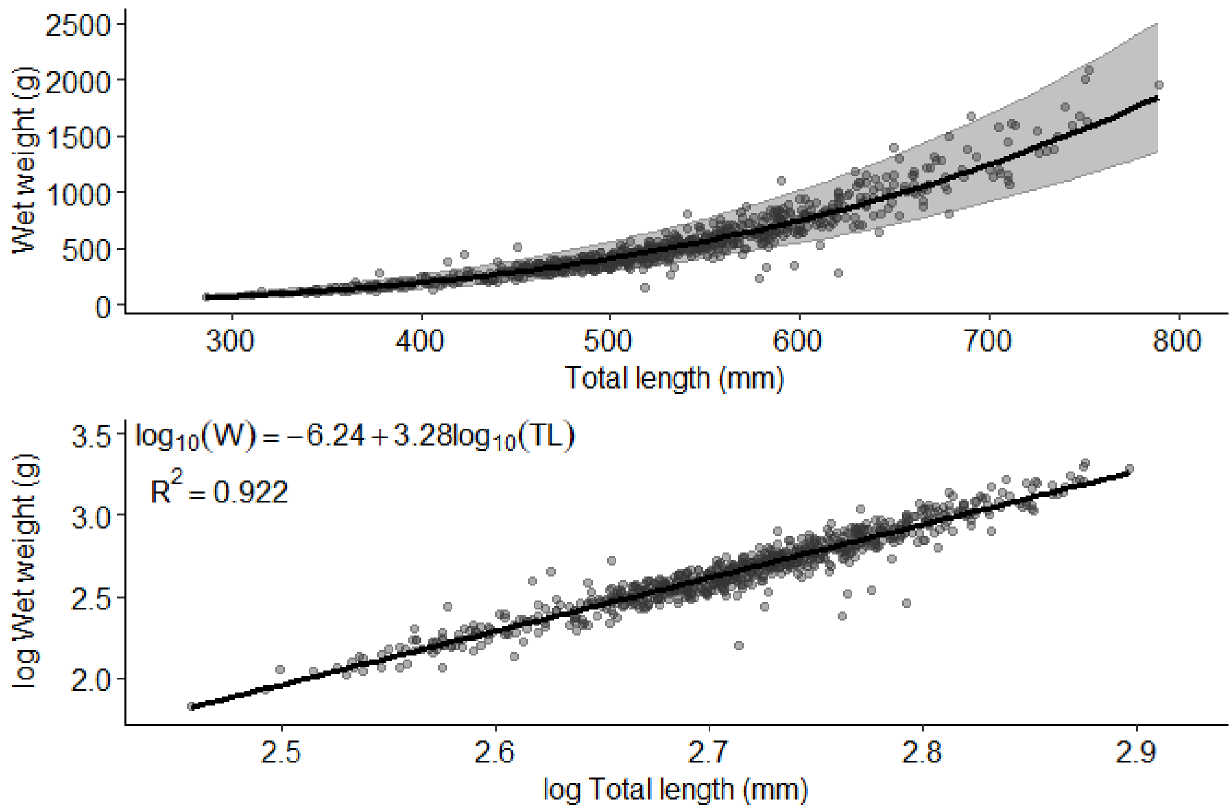


Figure 2.6: The W-TL relationship (top panel) and the $\log_{10}$ transformed W-TL relationship (bottom panel) for Shortnose Gar in the La Grange reach of the Illinois River. In both panels, grey circles represent individual fish. In the bottom panel, the solid line is the linear regression. In the top panel, the solid line is the allometric best-fit line back-transformed from the linear regression provided in the bottom panel, and the shaded area is the 95% confidence interval for predictions of individual fish.

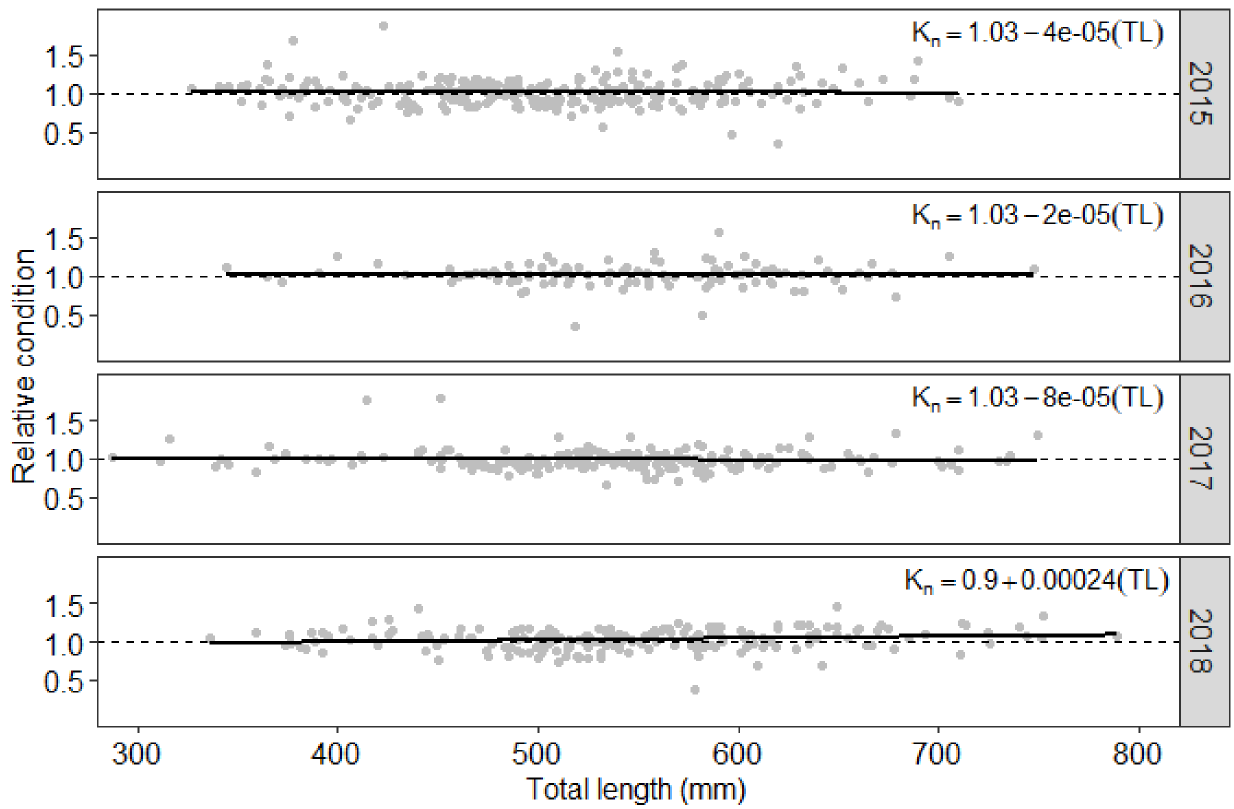


Figure 2.7: Relative condition ($K_n$) of Shortnose Gar captured from 2015 – 2018 in relation to TL. In 2015 – 2017, the linear regressions of $K_n$ and TL were not significant ($P > 0.05$) and poorly fit the data (all adjusted $R^2 < 0.01$). In 2018, the linear regression of $K_n$ and TL was significant ($P < 0.05$) but was a poor fit for the data (adjusted $R^2 = 0.02$). The grey circles represent individual fish and the dashed lines represent average fish condition ($K_n = 1$). The regression equation is given for each year and is represented by the solid black line in each panel.

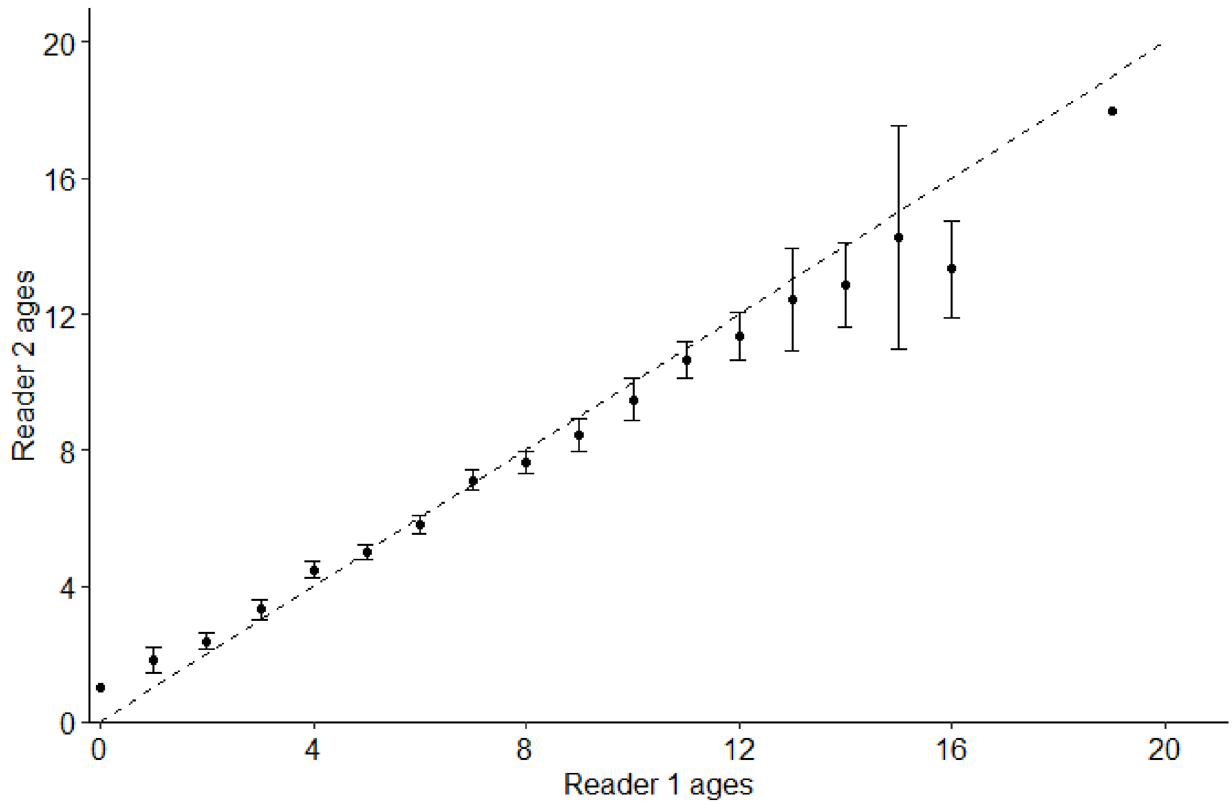


Figure 2.8: Differences in independently assigned ages between the two readers. The black circles are the mean age assignments of reader 2 given the assigned ages of reader 1, and the error bars represent the 95% confidence interval. Points without error bars represent samples sizes of 1.

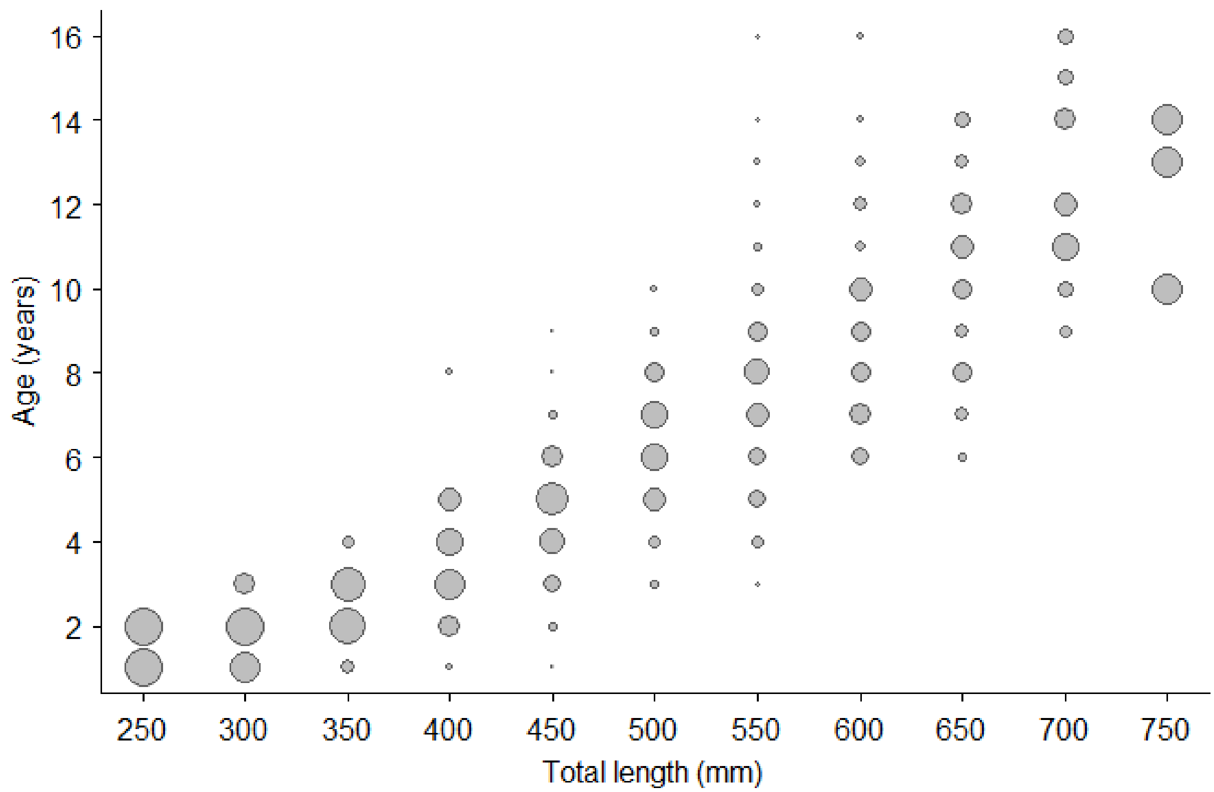


Figure 2.9: An observed age length key for Shortnose Gar captured from 2015 – 2018. Age class 18 was excluded due to low sample sizes (N = 1). The size of the circles is proportional to the proportion of individuals of each age class in each length interval.

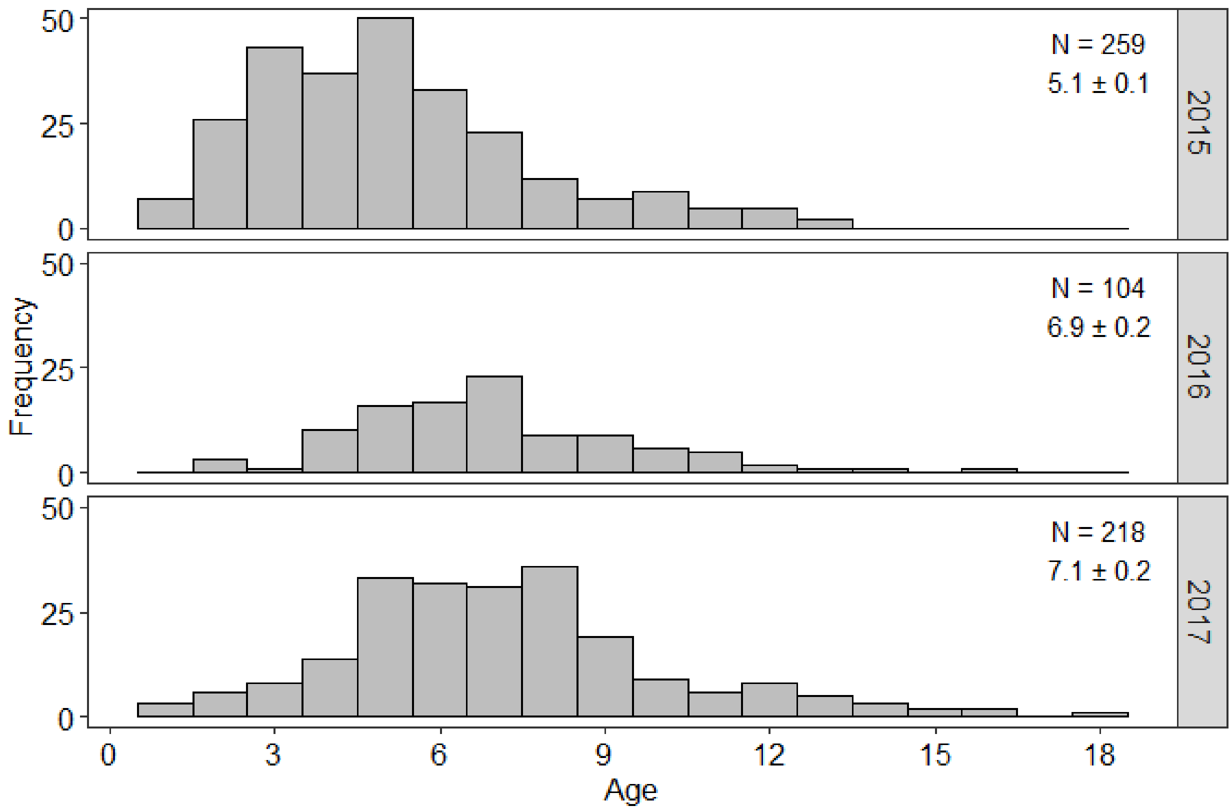


Figure 2.10: The age frequency distribution of Shortnose Gar captured in 2015 – 2017 in the La Grange reach of the Illinois River. The age frequency distribution in 2015 was significantly different from 2016 and 2017 ($P < 0.01$). The top number in each panel is the sample size, and the bottom numbers are the mean age ± SE.

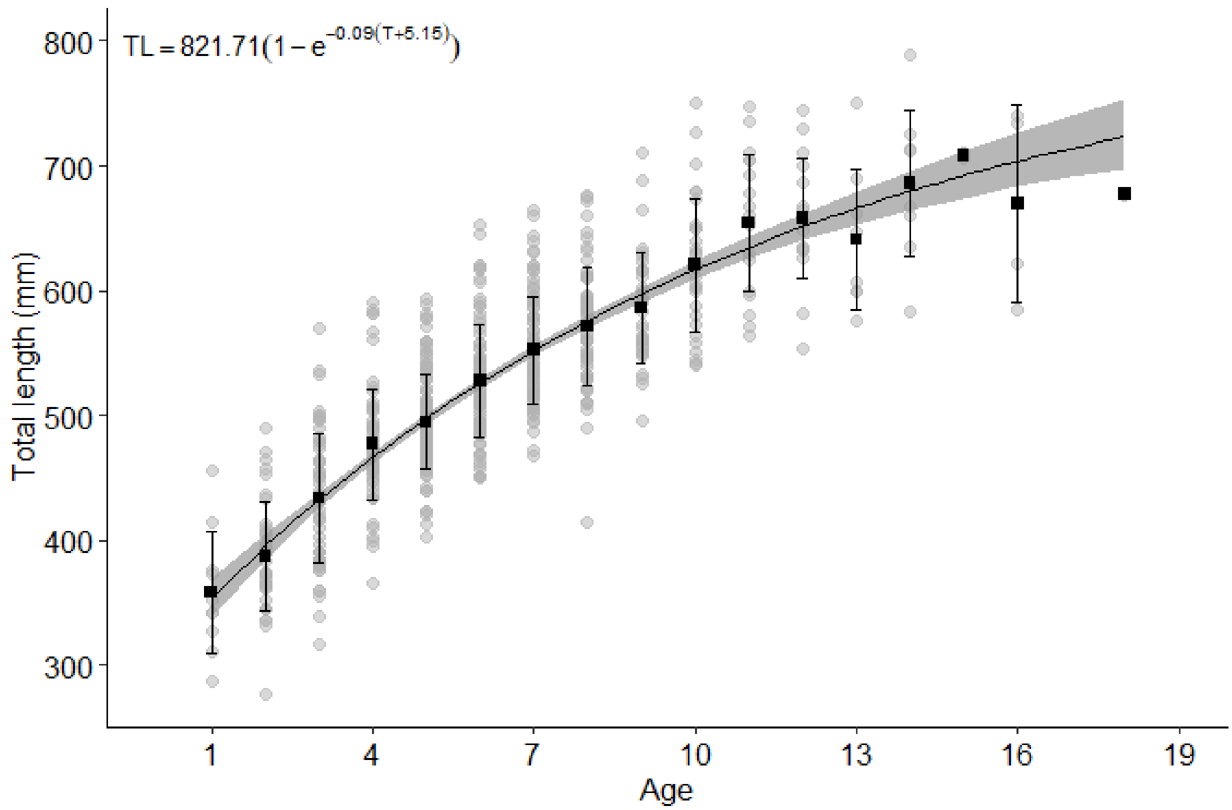


Figure 2.11: Mean length at age and the von Bertalannfy growth model for Shortnose Gar in the La Grange reach. The growth model was fit on ages 1 – 14, but older age classes were included for comparison. The grey circles represent individual fish. The black squares and error bars represent the observed mean length at age ± the standard deviation. The black line is the von Bertalannfy growth model, and the grey ribbon is the 95% confidence interval of mean length at age predicted by the von Bertalannfy growth model.

# CHAPTER 3: SHOOTING FOR AN ESTIMATE: BOWFISHING TOURNAMENT HARVEST AND BOW ANGLER HABITS IN ILLINOIS

## Introduction

Tournament fishing is a growing segment of recreational fishing as demonstrated by the estimated number of competitive angling events on inland waters of the United States increasing from 12,369 in 1978 to nearly 34,000 in 2005 (Shupp 1979; Schramm and Hunt 2007). Tournament anglers most commonly target black bass (*Micropterus spp.*) using rod-and-reel methods (Schramm and Hunt 2007); however, an apparent growth in the popularity of bowfishing (Johnson 2014; Lander 2014; Geiser 2016; Skurzewski 2017) has sparked the interest of management agencies as they seek to understand the particular habits of bow anglers and the species they target during bowfishing competitions (Bennett and Bonds 2012; Bennett et al. 2015; Binion et al. 2015; Lackmann et al. 2019; M. McClelland, Illinois Department of Natural Resources, personal communications). More broadly, the extent of bowfishing as a specific recreational angling method is largely unknown (Quinn 2010; Bennett and Bonds 2012; Bennett et al. 2015). Estimates of angler participation in bowfishing are generally not reported in federal surveys that describe the human dimensions and economic impact of fishing (e.g. USFWS 2016), although Kyle et al. (2013) reported that just 3% of freshwater anglers in Texas bowfish. Specialized recreational fishing segments such as bow anglers are inadequately sampled by traditional creel survey methods (Griffiths et al. 2010, Bennett and Bonds 2012) contributing to the limited understanding of their social and demographic characteristics and behavior.

The atypical fisheries that bow anglers commonly target coupled with the lethal nature of bowfishing presents a unique management challenge. In Illinois, bow anglers can legally harvest catfish (*Ictaluridae*) and a wide variety of rough fish species, including invasive carps

(*Cyprinidae*), gars (*Lepisosteidae*), suckers (*Catostomidae*), Bowfin (*Amia calva*), Freshwater Drum (*Aplodinotus grunniens*) and Gizzard Shad (*Dorosoma cepedianum*). Bowfishing likely represents the majority of fishing mortality for some of these species (Bennett et al. 2015), but some are commonly harvested by commercial fisheries (Klein et al. 2018) and other recreational fishing segments (USFWS 2016). Among these taxa, gars may be at greater risk of harvest due to their long life span and inconsistent recruitment (Ferrara 2001; Smith et al. 2018). The few published studies on bowfishing have shown that harvest rates can be higher than other recreational fishing methods (Quinn 2010; Bennett and Bonds 2012). Due to the lethal nature of bowfishing captures, catch and release regulations as a management tool would not be feasible at reducing the impact of bowfishing or bowfishing tournaments.

As managers consider the potential impacts of tournament bowfishing on emerging recreational fisheries, a better understanding of harvest and bow angler characteristics can help identify potential threats, angler preferences and inform the development of appropriate regulations if necessary (Bennett et al. 2015). To evaluate the scope and potential impact of bowfishing tournaments in Illinois, I utilized the Illinois Department of Natural Resources (IDNR) Online Tournament Permitting System, standard population assessments, and a point access creel survey of bowfishing tournaments. Fishery assessment and social information is often obtained from competitive fishing events (Schramm and Hunt 2007), and attending tournaments allowed us to survey a large number of bow anglers efficiently. The objectives of this study were to determine angler fishing effort, harvest composition and harvest rates at bowfishing tournaments, and to characterize bow angler favored target species and fishing habits. Results will provide novel information about tournament bowfishing and bow anglers in

Illinois and will guide the decision making of resource managers regarding future harvest regulations.

## Methods

### *Tournament Characteristics*

Bowfishing tournaments held in Illinois in 2017 and 2018 were identified using the Illinois Department of Natural Resources Online Tournament Permitting System and were included in an access-point creel survey. Fishing tournament registration is mandatory in Illinois; therefore, the identified tournaments were considered to be inclusive of all bowfishing tournaments occurring in the state. Participating teams were interviewed during the weigh-in at each tournament to obtain fishing effort and harvest information of the entire team (hereafter “team interview”), and information about the habits of a single, representative angler of the team (hereafter “angler interview”).

### *Effort and Harvest Characteristics*

During the team interviews, clerks recorded the number of anglers, the start and end times of tournament participation, the duration of extended breaks from fishing during the tournament (hereafter “break time”), whether all anglers actively fished for the entirety of the tournament, and the total catch by species for each team. When tournament weigh-in circumstances permitted, creel clerks measured total length (TL mm) and weight (g) of all harvested gars due to interest in understanding the exploitation of gars in bowfishing tournaments. Creel clerks also recorded the number of teams that participated in each tournament as reported by tournament officials. Due to time constraints and because some teams would leave a tournament prior to the start of the weigh-in, creel clerks were unable to survey a small number of participating teams across all tournaments. The number of interviewed teams was considered a representative subsample of the participating teams.

Fishing effort and total catch were calculated for each interviewed team. Fishing effort ($e$) is

$$e = [(t_s - t_0) - t_b] * a,$$

where $t_s$ is team stop time, $t_0$ is team start time, $t_b$ is team break time, and $a$ is the number of participating anglers on the team. During team interviews, two teams reported a range for the duration of break time spanning 5 minutes or less, so the maximum value was used to avoid overestimating fishing effort. During several team interviews, respondents noted that one angler always drove the boat and thus was not actively fishing for the duration of the tournament. For these teams, the calculation of $e$ was modified by substituting $(a - 1)$ for $a$. The total harvest ($c$) was determined by summing the fish counted during the team interview at three hierarchies: overall ("fish"), by taxonomic group, and by species. The taxonomic groups I examined are carps, suckers, gars, and an "other" group consisting of fishes from the *Amiidae*, *Clupeidae* and *Sciaenidae* families.

To account for teams not interviewed at each tournament, direct expansion methods were used to estimate the total number of participating anglers ($\hat{A}$), fishing effort ($\hat{E}$) and harvested fish ($\hat{C}$) (Pollock et al 1994). The equations used to expand the interview data for any given measure (z) and calculate the variances are as follows:

$\hat{z}_h = N_h \times \bar{z}_h$ (estimated total for tournament $h$),

$\bar{z}_H = \sum_{h=1}^{H} W_h \times \bar{z}_h$ (estimated population mean),

$var(\bar{z}_H) = \sum_{h=1}^{H} W_h^2 \left(\frac{s_h^2}{b_h}\right)\left(\frac{B_h - b_h}{B_h}\right)$ (estimated variance of the population mean),

$\hat{z}_H = \sum_{h=1}^{H} \hat{z}_h$ (estimated population total),

$var(\hat{z}_H) = B^2 \times var(\bar{z}_H)$ (estimated variance of the estimated population total),

$SE(\hat{z}_H) = \sqrt{var(\hat{z}_H)}$ (estimated standard error of the estimate population total),

where:

$h$ = the tournament being considered ($h$ = 1, … , $H$),

$H$ = the total number of tournaments,

$i$ = the teams within the tournament ($i$ = 1, … , $B_h$),

$B_h$ = the population size in tournament $h$,

$b_h$ = the sample size in tournament $h$,

$B = \sum_{h}^{H} B_h$ is the total population size,

$W_h = B_h/B$ is the stratum weight,

$z_{ih}$ = the value of the $i$th team in the $h$th tournament,

$\bar{z}_h$ = the sample mean for tournament $h$,

$s_h^2 = \left[\sum_{i=1}^{n_h}(z_{ih} - \bar{z}_h)^2\right] / (B_h - 1)$ is the sample variance for tournament $h$, and

$\left(B_h - b_h / B_h\right)$ = the finite population correction factor.

For each team, harvest rates ($r$) were calculated by dividing the total harvest by the team's total fishing effort. As with total harvest, team harvest rates ($r$) were calculated overall, by taxonomic group and by species. Tournament harvest rate ($\hat{R}$) is simply the mean of team harvest rate from $b_h$, and the global harvest rate is the mean of tournament means. To determine if native species and invasive species (i.e. carp) were harvested in similar numbers, the estimates of total harvest calculated by the direct expansion methods were summed for each group and compared using a Chi-squared test. Welch's ANOVAs were used to determine if there were differences in taxonomic group harvest rates among tournaments held on the same waterbody. Differences among tournaments were distinguished using Games-Howell post hoc tests from the 'userfriendlyscience' package (Peters 2018).

To characterize the length distribution of gars in populations exploited by bowfishing tournaments, I utilized sampling information on waterbodies where tournaments were held generated by the IDNR and Illinois Natural History Survey (INHS; Table 3.1). These length distributions were compared to length distributions of gars harvested during tournaments using one-sided Mann-Whitney U tests. Adequate sample sizes limited comparisons to size distributions of Longnose Gar harvested from the Kankakee & Des Plaines Rivers (four tournaments), and Shortnose Gar harvested from the Starved Rock and Peoria reaches of the Illinois River (four tournaments) and from the La Grange reach of the Illinois River (one tournament). In all groups, fish were assigned the lowest value of their respective 10 mm length bins. Additionally, the length of harvested gars from all tournaments was compared to size at maturity reported in the literature (Netsch and Witt 1962; Etnier and Starnes 1993; Pflieger 1997).

*Angler Habits*

The creel clerk interviewed one self-selected member from each interviewed team to collect data on angler habits. At the beginning of each angler interview, the creel clerk determined whether the team member had previously participated in an angler interview that year. When repeat participants were encountered, the creel clerk requested to interview a team member that had not previously participated in the angler interview. If all members of the team had previously participated in an angler interview, the angler interview was not completed for that team. Clerks were trained to use consistent phrasing of interview questions, and the questions were consistent across years except that a question about archery use (Question 6) was added prior to the start of the 2018 tournament season (Table 3.2).

Participants were asked questions about their bowfishing tournament participation (Question 2), monthly non-tournament bowfishing and rod-and-reel activity (Questions 3 and 4), their years of experience bowfishing (Question 5), and if they used archery for other outdoor recreation (Question 6). In cases where responses to Questions 2 – 5 were provided as a range the minimum values were used. Some participants responded to the monthly non-tournament bowfishing and rod-and-reel activity questions with answers such as “twice a year”, so all responses were multiplied by 12 to obtain a count for the number of annual trips using each fishing method. To assess whether tournament bow anglers take a similar proportion of annual bowfishing and rod-and-reel angling trips, the counts from all angler responses were summed for each method and compared using a Chi-squared test. Using the responses to the questions about monthly bowfishing, monthly angling and archery use (Questions 3, 4 and 6 respectively; Table 3.2) from the 2018 interviews, I aggregated participants into four mutually exclusive methodology groups: participants who only bowfish, participants who bowfish and rod-and-reel angle, participants who bowfish and use archery for other outdoor recreation, and participants who use all three methods. The percent of anglers in each methodology group were then described.

Travel distance to tournament was calculated as the linear distance from the geographic centroid of angler-reported home zip codes acquired from the publicly available USA ZIP Code

Areas data layer (ESRI 2017) to location of tournament weigh-in locations. Travel distances (m) were calculated in the USA Contiguous Lambert Conformal Conic projection using the "Generate Near Table" tool in ArcMap 10.6.1 (ESRI, Redlands, California). A one-way ANOVA was performed to assess whether travel distance varied among tournaments. Travel distance was log transformed to meet the assumption of normality and model fit was assessed graphically. Differences among tournaments were determined by a Tukey post hoc test.

To quantify how tournament characteristics and angler engagement in fishing activity influence angler travel distance to bowfishing tournaments, I built five competing general linear models. The tournament characteristics model included number of offered contests, tournament type (day or night), and the number of participating boats as fixed factors. The activity engagement model included yearly tournament participation (one tournament or more than one), monthly non-tournament bowfishing trips, and monthly non-tournament rod-and-reel angling trips as fixed factors. The third model, referred to as the "combined" model, included all factors in the tournament characteristic and activity engagement models. The fourth model, referred to as the "full" model, included all factors of the tournament characteristic and angler activity engagement models plus one interaction term (yearly tournament participation x tournament type). A null model where the dependent variables have no influence on the independent variable was also included. All independent variables were assessed for linear correlation using Pearson's correlations and were removed from models where appropriate. Log transformed travel distance was used as the dependent variable in all models. Akaike's Information Criterion adjusted for small sample sizes ($AIC_C$) was calculated using the 'MuMIn' package (Barton 2018). Models where $\Delta AIC_C \leq 7$ were considered plausible and models where $\Delta AIC_C \leq 2$ were chosen as the top models (Burnham and Anderson 2001; Burnham et al. 2011).

I described target species favorability and assessed how favorability compared to harvest outcomes. Interview participants could provide up to three favored target species in response to Question 7, and all responses were pooled together by taxonomic group. Descriptive comparisons were made among taxonomic groups, and patterns in favored target species were examined within the groups. To compare target species favorability to catch outcomes among the taxonomic groups, a matrix was created detailing if an angler favored targeting carps, suckers, gars and the other species group, and if that angler's team harvested at least one fish from each of the taxonomic groups during the tournament. A count of anglers who favored targeting and whose team harvested at least one fish from the four taxonomic groups were then generated from the matrix. A Fisher's Exact Test was used to compare the probability of bow anglers favoring a taxonomic group to the probability of bow anglers catching fish from that taxonomic group. All tests were conducted using R 3.5.2 (R Core Team 2018), and results were considered significant at the 95% confidence level ($\alpha = 0.05$).

**Results**

*Tournament Characteristics*

Creel surveys were conducted at 16 of the 19 tournaments identified on the IDNR Online Tournament Permitting System in 2017 and 2018. I could not conduct creel surveys at three tournaments in 2017 due to scheduling conflicts. The tournaments were held throughout the state (Figure 3.1), with three tournaments hosted on lakes and 12 on rivers, six tournaments held during the day and 10 held at night (Table 3.3). Fishable water rules varied between tournaments, but most often teams could fish public waters that were reachable by boat from the designated launch point or were given a range within which trailering to public boat ramps was allowed. The Illinois Open allowed teams to bowfish on any publicly accessible water body throughout

Illinois, including rivers and lakes. Voluntary species harvest restrictions occurred at three tournaments, with Tournament 12 prohibiting all gars at the weigh-in, and Tournaments 13 and 16 prohibiting Paddlefish at the weigh-in. Additionally, all tournaments prohibited the harvest of catfishes (*Ictaluridae*).

The number of tournament contests ranged from 2 – 14 ($\bar{x}$ = 3.8 ± 3.4 SD; Table 3.3). Most often, contests followed the Big "X" format, where contests winners were determined by the largest batch weight of "X" number of fish of a specified assortment of species. Other contests included total number of fish, big fish (weight or length of individual), small fish (weight or length of individual), point-based scoring systems, and separate contests for shore bowfishing and female participants.

*Effort and Harvest Characteristics*

Across both years, 147 teams were interviewed representing over 75% of total participating teams, which varied across tournaments ranging from 40 – 100% ($\bar{x}$ = 80% ± 6% SD). Clerks were unable to collect accurate harvest information at Tournament 8 because most teams had placed their harvested fish in a large dumpster before creel clerks arrived, so all team interviews from that tournament were excluded from analysis. Two incomplete team interviews from other tournaments were also removed, resulting in 137 interviews for use in the effort and harvest analyses. Tournament size ranged from 6 – 30 participating teams ($\bar{x}$ = 11.9 ± 6.8 SD), and team size ranged from 1 – 5 anglers per team ($\bar{x}$ = 3.1 ± 0.0 SE; Table 3.4). An estimated 576 anglers participated across all surveyed tournaments, ranging from 14 – 95 anglers per tournament ($\bar{x}$ = 38± 6 SE, Table 3.4). Estimated fishing effort at surveyed tournaments totaled 4,312.2 angler hours and ranged from 94.0 – 767.8 angler hours per tournament ($\bar{x}$ = 287.5 ± 51.0 SE; Table 3.4).

The estimated total harvest was 5,927 fish, ranging from 87 – 1,346 fish per tournament ($\bar{x}$ = 395.11 ± 0.11 SE), and overall harvest rates ranged from 0.74 – 9.24 fish per angler hour ($\bar{x}$ = 1.73 ± 0.41 SE; Table 3.4). In total, 18 species were harvested representing six families, and the number of species harvested per tournament ranged from 1 – 11 ($\bar{x}$ = 7± 3 SD). Carps accounted for 84% of all harvested fish, suckers for 11%, gars for 4%, and other species for 1% (Table 3.5). The top five species accounted for 93% of harvested fish: Silver Carp (54%), Common Carp (17%), Smallmouth Buffalo (9%), Bighead Carp (9%) and Grass Carp (4%; Table 3.5). Overall, invasive species were harvested in higher numbers than native species ($\chi^2$ = 2,703.6, df = 1, $p < 0.01$). Based on the estimated number of anglers, estimated angling effort, and estimated fish harvested at 16 of 19 permitted tournaments (84.2% of all tournaments), I estimate that 684 anglers fished 5,121 angler hours and harvested 7,039 fish at bowfishing tournaments in Illinois during the study period.

Comparisons of harvest rates by taxonomic group indicated that for carps team harvest rates were similar among tournaments held on the Fox River Chain O'Lakes (F = 0.05; df = 1, 14.05; p = 0.82), on the Upper Illinois River (F = 1.32; df = 3, 10.67; p = 0.32), and on the Ohio River (F = 0.47; df = 1, 17.20; p = 0.50). However, team harvest rates for carps were different among tournaments held on the Kankakee & Des Plaines Rivers (F = 6.64; df = 3, 10.48; $p < 0.01$; Figure 3.2). For suckers, team harvest rates were similar among the tournaments held on the Upper Illinois River (F = 1.87; df = 3, 10.52; p = 0.20); whereas team harvest rates were different among tournaments held on the Kankakee & Des Plaines Rivers (F = 6.78; df = 3, 9.41, $p < 0.05$; Figure 3.3). Suckers were not harvested at either tournament held on the Fox River

Chain O'Lakes nor at one of the two tournaments held on the Ohio River, so Welch's ANOVA could not be performed for this group at these locations.

For gars, team harvest rates were similar among tournaments held on the Kankakee and Des Plaines Rivers ($F = 0.99$; df = 3, 9.92; $p = 0.43$), and on the Upper Illinois River ($F = 1.72$; df = 3, 10.67; $p = 0.22$), but were varied among tournaments held on the Ohio River ($F = 5.70$; df = 1, 8.27; $p < 0.05$, Figure 3.4). Gar were not harvested at tournaments held on the Fox River Chain O'Lakes, so Welch's ANOVA could not be performed for this group. +Welch's ANOVA could not be performed on team harvest rates for tournaments held on the Fox River Chain O'Lakes, Upper Illinois River or the Ohio River because too few fish in the other species group were harvested.

Creel clerks recorded measurements from a representative subsample of all harvested gars. Only four Spotted Gar were measured, so they were omitted from the length frequency analyses. For both Shortnose and Longnose gars, IDNR and INHS sampling events collected fish with smaller minimum TL than bowfishing tournaments held on the same waterbody. In the La Grange reach of the Illinois River, Shortnose Gar harvested at bowfishing tournaments (N = 23; $\bar{x}$ = 627 ± 17 SE) were larger than those captured during standard sampling (N = 422; $\bar{x}$ = 531 ± 4 SE; U = 7,770; $p < 0.01$; Figure 3.5). However, in the Starved Rock and Peoria reaches of the Illinois River Shortnose Gar harvested at bowfishing tournaments (N = 24; $\bar{x}$ = 580 ± 12 SE) were similar in length to those captured during standard sampling (N = 50; $\bar{x}$ = 538 ± 16 SE; U = 738; $p = 0.06$; Figure 3.6). Longnose Gar harvested at bowfishing tournaments (N = 42; $\bar{x}$ = 821 ± 31 SE) were considerably larger than Longnose Gars captured during standard sampling (N = 113; $\bar{x}$ = 567 ± 20 SE) in the Kankakee and Des Plaines rivers (U = 3,828; $p < 0.01$; Figure 3.7). Statewide, harvested Shortnose Gar ranged in TL from 406 – 882 mm (N = 87, $\bar{x}$ = 658 ± 11

SE), and all exceeded the size at maturity (330 mm) reported in Etnier and Starnes (1993) and Pflieger (1997). Longnose Gar ranged in TL from 322 – 1600 mm (N = 61, $\bar{x}$ = 844 ± 31 SE). Twenty-one percent and 37% of fish were below the minimum size at maturity for male (635 mm) and female (762 mm) Longnose Gar respectively (Netsch and Witt 1962), although sex was not determined for harvested fish in this study.

*Angler Habits*

Across all tournaments, creel clerks conducted 118 angler interviews of the estimated 578 total participating anglers (25%). Two partial angler interviews were excluded, resulting in 116 unique angler interviews for use in all angler habits analyses. Ninety-five percent of interviewed participants were male. While 74% of participants reported 10 or less years of bowfishing experience, 10% reported 20 or more years ($\bar{x}$ = 9 ± 0.7 SE; Figure 3.8). Thirty-one percent of participants only planned to attend the tournament at which they were interviewed, whereas 24% planned to attend more than five tournaments that season. On an annual basis, participants take a higher proportion of bowfishing than rod-and-reel angling trips ($\chi^2$ = 1,058.7, df = 1, $p < 0.01$). On a monthly basis, participants reported a mean of 7.0 ± 0.6 SE bowfishing trips as compared to a mean of 4.1 ± 0.6 SE rod-and-reel angling trips. Responses to Question 6 indicated that 65 of 79 participants (82%) reported using archery equipment for other outdoor recreation. When examining the mutually exclusive methodology groups: 6% of anglers only bowfish, 11% bowfish and rod-and-reel angle, 25% bowfish and use archery equipment for other outdoor recreation, and 57% use all three methods.

The majority of surveyed anglers were Illinois residents (69%). However, out of state anglers attended seven tournaments, and came from Kentucky (9%), Wisconsin (6%), Iowa (5%), Missouri (5%), Indiana (4%) and Alabama (< 1%). Travel distance from angler residence to a tournament site ranged from 5 – 497 km ($\bar{x}$ =112.97 ± 9.97 SE; Figure 3.10) and varied between tournaments ($F = 3.131$; $df = 14, 99$; $p < 0.001$) based on log-transformed travel distance. Participants traveled shorter distances to night tournaments on the Kankakee and Des Plaines Rivers that offered a small number of contests (tournaments 2, 7 and 9) compared to day tournaments held on the Illinois River (tournaments 3 and 14) that offered a large number of contests (adjusted $p < 0.05$; Figure 3.11).

The number of boats was dropped from all general linear regression models as it was positively correlated with the number of contests ($r = 0.83$, $p < 0.001$). The $AIC_C$ analysis selected the full model as the only top model (Table 3.6), suggesting that tournament characteristics, angler engagement in activity and the interaction between those factors are important to travel distance to bowfishing tournaments. The number of contests and yearly tournament participation positively influenced travel distance, while monthly rod-and-reel angling trips and the interaction between tournament type and yearly tournament participation negatively influenced travel distance (Table 3.7). Tournament participants who anticipated attending a single tournament during the year traveled similar distances to both day and night tournaments, while tournament participants who anticipated attending more than one tournament traveled longer distances for day tournaments than for night tournaments (Figure 3.12).

When asked about their three favorite bowfishing target species (Question 6), participants reported 22 unique responses (N = 312 total responses). Aggregating all responses, participants reported carps (55%), suckers (17%), gars (21%), other species (3%) and “anything” (3%) as favorite targets. Within family groups, carps had the highest diversity of responses whereby anglers specified a particular species, whereas most anglers who favored targeting suckers and gars generalized their responses to the taxonomic common names above species (Table 3.8).

More participants harvested carp (99%) than favored targeting them (91%; $p < 0.01$), whereas fewer participants harvested gars (41%) than favored targeting them (58%; $p < 0.01$). No significant differences were found between target species favorability and harvest outcomes for suckers (favor = 44%; harvest = 38%; $p = 0.70$) or the other species group (favor = 8%; harvest = 12%; $p = 0.40$; Figure 3.13).

**Discussion**

Tournament bowfishing and bowfishing in general, appear to be growing in popularity among recreational anglers (Johnson 2014; Lander 2014; Geiser 2016; Skurzewski 2017), however little is known about the potential impacts of bowfishing harvest or the need for active management of these emerging recreational fisheries. Using tournaments as a sampling frame, I found that bowfishing harvest composition is dominated by invasive carp spp. in Illinois, while native species comprise a much smaller percentage of total harvest than anticipated (Quinn 2010, Bennett and Bonds 2012). Harvest rates at bowfishing tournaments are higher than rod-and-reel tournaments in Illinois, so the potential impact of each tournament on fisheries is greater despite being a rather small segment of overall competitive fishing in the state. Although the magnitude of increased popularity of bowfishing remains unclear, a portion of competitive bow anglers might be emigrating to the method from bow hunting and other fishing activities. As management agencies attempt to reverse declining trends in participation in fishing and hunting activities (Poudyal et al. 2011; Kyle et al. 2013; White et al. 2016), bowfishing may help recruit and retain new anglers. Given the small number of highly active participants in bowfishing tournaments and that invasive species are the dominant component of tournament harvest, the need for immediate management actions seems low. Yet, further study in necessary to understand the population dynamics of and harvest pressures faced by native species that may be at risk of overexploitation, so that management strategies can be developed to support sustainable recreational fisheries.

Tournament bowfishing is a very small component of competitive fishing in Illinois, but like rod and reel tournaments, competitive contests appear to be a relevant factor attracting participants to the tournaments. In 2017 – 2018 there were over 200 times more rod-and-reel tournaments (N = 4,058) held in Illinois than bowfishing tournaments (N = 19), with rod-and-reel tournaments typically attracting more participating teams than bowfishing tournaments. Compared to bowfishing tournaments in Illinois, those in Arkansas typically had fewer participating teams (Quinn 2010), while those in Texas (Bennett and Bonds 2012) and Oklahoma (Schooley et al. 2019) typically had more participating teams. The chance to engage in competition (i.e. winning contests), and the perceived financial benefit of attending tournaments (i.e. the monetary value of the contest prizes) likely influence the popularity and attendance of bowfishing tournaments. In a meta-analysis between saltwater tournament anglers and saltwater anglers in general, Falk et al. (1989) found that tournament anglers ranked “sport/challenge” among their top fishing motives, whereas non-tournament anglers seldom did so. Tournament black bass anglers also placed greater emphasis on “winning a trophy or prize” than non-tournament black bass anglers (Wilde et al. 1998). It comes as no surprise that nearly 200 teams traveled from 13 states to attend the 2018 U.S. Bowfishing Championship (Schooley et al. 2019) that offered national notoriety and a $25,000 prize (Bowhunting World Staff 2018). While I did not directly measure angler motivations for attending bowfishing tournaments, participants traveled farther to attend tournaments that offered many contests, and the number of contests positively correlated with the number of participating teams. Similar to other forms of competitive fishing, bowfishing tournaments appear to attract participants through competition involving prizes.

Generally speaking, per capita harvest at a bowfishing tournament will be greater than a rod-and-reel tournament. For species like Common Carp and Smallmouth Buffalo, per capita harvest at bowfishing tournaments appears to be 1.3-1.6 times higher than rod-and-reel tournaments held in Illinois during the study period (Stein, unpublished data). Silver carp are a notable exception, where tournament bow anglers captured invasive Silver carp at a rate over 40 times greater than rod-and-reel tournament anglers. Smallmouth Buffalo are native to Illinois and are an important component of commercial fisheries (Klein et al. 2018), so increased harvest at bowfishing tournaments could lead to potential conflicts with other resource uses. Invasive carps have wide-ranging impacts to the native fish community (e.g. Irons et al. 2007; Wolfe et al. 2009; Solomon et al. 2016), and the ecosystem (e.g. Weber and Brown 2009; Sass et al. 2014), so increased harvest of Silver Carp and Common Carp at bowfishing tournaments may contribute to the current management strategies for these species. In comparison to other regions, the intensity of harvest at Illinois bowfishing tournaments appears to be moderate – harvest rates were higher than in Oklahoma (Schooley et al. 2019), but lower than in Arkansas (Quinn 2010) and Texas (Bennett and Bonds 2012).

The popularity of certain species among competitive bow anglers is likely influenced by fish body morphology as well as the community composition and the relative abundance of populations within the watershed where bowfishing activities occurs. For instance, large bodied species, such as carps and suckers, may be valued for their weight in the context of tournament contests that reward biomass measures of harvest. Indeed, carps dominated harvest composition at bowfishing tournaments in Illinois (84%), and 91% of tournament bow anglers reported carp among their three favorite bowfishing targets. Specifically, Silver Carp accounted for just over half of all harvest. Silver Carp are highly abundant in areas with established populations (e.g. Sass et al. 2010), exhibit strong schooling behaviors and frequently jump out of the water when frightened by noise, which may make them especially vulnerable to bowfishing. Carp were less prominently harvested at tournaments in Oklahoma (17%; Schooley et al. 2019) and Arkansas (18%; Quinn 2010), and fewer bow anglers reported them as favorite target species in Texas or Oklahoma (Bennett et al. 2015, Schooley et al. 2019).  Invasive carp species are less abundant in these locations, therefore suckers accounted for a higher percentage of total harvest (Arkansas: 27%; Quinn 2010; Oklahoma: 57%; Schooley et al. 2019), than in Illinois (11%). Harvest composition also varied among bowfishing tournaments in Illinois, presumably due to fish community composition and relative abundance. For example, *Moxostoma* spp. were only harvested from the Kankakee & Des Plaines Rivers, which provides higher quality habitat to support *Moxostoma* spp. (Butler and Wahl 2017, J. Parker, INHS, personal communications) than other watersheds in this study. Quinn (2010) also suggested that the distribution of fishes in Arkansas influenced bowfishing tournament harvest composition.

Slender-bodied species, such as gar, may be valued by competitive bow anglers for the skill required to accurately shoot and harvest a smaller target. While gars represented less than 5% of total bowfishing tournament harvest in Illinois, 58% of bow anglers reported them among their three favorite bowfishing target species, suggesting there is substantial interest for a gar fishery in the state. Shortnose and Longnose Gars accounted for approximately 2% of harvest each with Shortnose Gars harvested at slightly higher rates. I may have underestimated the small number of Spotted Gar that were harvested, because I could not collect accurate harvest information at Tournament 8 where anglers anecdotally captured a large number of Spotted Gar.

When comparing the length of Shortnose and Longnose gars harvested at bowfishing tournaments to the broader population, I found that competitive bow anglers harvest the larger individuals within a population. Although Shortnose Gar harvested at tournaments in the Starved rock and Peoria reaches were not significantly different from those captured during population assessments, I had low samples sizes and may not have had adequate statistical power to detect the true difference between the groups. Kelley (2012) also suggested that bowfishing captures can be biased toward larger Longnose Gar, and between 89% – 100% of gars harvested at bowfishing tournaments in Arkansas exceeded the size at maturity (Quinn 2010). Female gars tend to reach sexual maturity later than and grow larger than males (Holloway 1954; Netsch and Witt 1962; Suttkus 1963; Ferrara 2001; Love 2004, Murie et al. 2009; Binion et al. 2015) and fecundity typically increases with size (Johnson and Noltie 1997; Ferrara 2001), so competitive bow anglers may disproportionately remove fecund females from the population. Furthermore, the periodic life history strategy of gar spp., characterized by a large adult body size, long life span, late age at maturity, high fecundity and sporadic recruitment (Winemiller and Rose 1992), make them susceptible to overfishing (Johnson and Noltie 1997; Ferrara 2001; Smith et al. 2018). Models developed by Smith et al. (2018) demonstrated that exploitation rates of just 7% caused the mean population size of Alligator Gar to decline by 50%, and the risk of recruitment overfishing at relatively low exploitation rates has been shown for other long-lived fishes, such as sturgeons (family *Acipenseridae*), (e.g. Rieman and Beamesdfer 1990; Boreman 1997; Quist et al. 2002). Thus, bowfishing tournaments may have substantial impacts on gar populations despite relatively low harvest rates in comparison to rod-and-reel fisheries (see examples in Lewin et al. 2006), particularly if tournament bow anglers target gars when they assemble into large, temporally and spatially predictable spawning aggregations (van Overzee and Rijnsdorp

2015; de Mitcheson 2016; Hall et al. 2018). Considering the deficit of knowledge about gar reproduction in Illinois and their long-lived, slow-growing life history, a precautionary approach to managing gars may be warranted to prevent overharvest (de Mitcheson 2016).

Understanding the species that bow anglers enjoy targeting will help managers focus their efforts on the species that are most likely to be harvested by bowfishing. I found that bow anglers preferentially targeted certain taxonomic groups or species, and rarely reported “anything” as a favorite target species. Interestingly, anglers more frequently referred to carp by species name, whereas they primarily referred to gars and suckers using high-level taxonomic common names. Bow anglers simply may not care what species they target below the family level for native species or bow anglers may not be knowledgeable enough to distinguish among native gars and suckers. Anecdotally, I observed that some bow anglers could not distinguish between closely related species or simply lacked knowledge about the native species, which is similar to reports from the 2018 U.S. Bowfishing Championship (Schooley et al. 2019). Education campaigns about aquatic invasive species and the prevalence of Asian Carp stories in the news may contribute to bow anglers’ familiarity with carps.

Examining the relationship between target species favorability and harvest outcomes can provide insights into bow angler behavior. I found that carps were harvested at a higher frequency than they were reported as a favorite target species, and the opposite pattern was true for gars. Bow anglers are likely harvesting carp in Illinois because they are readily available, whereas bow anglers may enjoy targeting gars for the skill required to successfully capture a slender-bodied fish, but have fewer opportunities to harvest them because of their relatively lower abundance. Similar comparisons of species favorability and harvest at the 2018 U.S. Bowfishing Championship in Oklahoma revealed a similar result, where more anglers favored gar than harvested them, and fewer anglers favored suckers than harvested them (Schooley et al. 2019). The discrepancies between stated and realized bowfishing targets and the results of the travel distance model selection suggest that factors other than angler preferences influence harvest composition at competitive bowfishing events. I acknowledge, however, that this study has some limitations in its ability to inform the understanding of target species preferences in competitive bowfishing. First, I asked participants to indicate their favorite bowfishing target species generally, rather than specifically in the context of tournament bowfishing. Bow angler motivations during competitive fishing events likely differ from general bowfishing activity, and this may have modulated the harvest outcome from the expected result based on their favorite target species. For example, a bow angler could favor targeting gar while bowfishing in general, but chose to harvest carp to win tournament contests based on aggregate weight harvested. Second, the favorability metric represents the responses from individual anglers during the angler interview, while the harvest outcome is a result of the team's collective fishing effort. The team members that were not interviewed were equally likely to influence the harvest outcome during the tournament as the angler on the team who was interviewed, potentially leading to differences between the stated and realized outcomes. Finally, the abundance of fishes in tournament waterbodies, weather events and tournament characteristics could have prevented the harvest of the favored target species, leading to mismatches with the stated favorite targets.

When fishing opportunities do not meet their expectation of quality angling, recreational anglers may substitute locations (Hunt 2005; Hunt et al. 2007), target species (Fisher and Ditton 1993; Ditton and Sutton 2004; Sutton and Ditton 2005), or fishing methods. Growth in popularity in specialized recreational fisheries, such as bowfishing, may be the result of such a diversification. It has also been proposed that bow hunters are being recruited to bowfishing as a way to prepare for the bow hunting season (Bennett et al. 2015). Eighty-two percent of the surveyed bow anglers in this study reported using archery for outdoor recreation other than bowfishing (primarily to hunt deer), and 31% reported they do not rod-and-reel angle, suggesting that some bow anglers represent a new segment of anglers who otherwise would not purchase fishing licenses. Management agencies have used competitive fishing to grow interest in fishing previously (Schramm and Hunt 2007), likewise bowfishing tournaments may be a pathway for recruiting, retaining and reactivating new anglers and hunters.

Tournament bow anglers participate in a variety of fishing and hunting activities, and appear to represent a spectrum of specialization. For example, the bow anglers that frequently engaged in rod-and-reel angling (i.e. the more generalist anglers) tended to travel shorter distances to attend bowfishing tournaments than those specialized anglers who seldomly engaged in rod-and-reel angling. This agrees with previous findings that more-specialized anglers are willing to travel further to access fishing opportunities relative to less-specialized anglers (Arlinghaus and Mehner 2004). While competitive anglers are highly specialized in general (Schramm et al. 1991; Fisher et al. 1997), there are likely segments within competitive anglers who show increasing levels of specialization reflected by the characteristics of tournaments they participate in, and the frequency of their participation (Wilde et al. 1998). I found that presumably casual bow anglers who attend only one tournament per season traveled shorter distances to tournaments than more avid participants attending more than one tournament, supporting the idea that participation can be used to differentiate segments of tournament bow anglers. As specialized segments of recreational fishing may exhibit differing motivations for fishing (Chipman and Helfrich 1988; Wilde et al. 1998; Falk et al. 1989; Fisher et al. 1997), measures of satisfaction (Beardmore et al. 2015) and attitudes about management interventions

(Fisher et al. 1997; Edison et al. 2006; Oh et al. 2007), understanding the differences between segments of bow anglers will be critical to achieve the biological and social objectives of management plans.

Due to the extremely small footprint of competitive bowfishing in Illinois, there is likely room for sustainable growth of tournaments in the state and minimal need to regulate harvest, but with some caveats. First, despite being a small proportion of competitive angling events, the magnitude and rate of harvest at bowfishing tournaments is relatively large. For invasive carps this may be beneficial, but for long-lived or commercially harvested native species this may require management interventions. Second, high-profile competitive fishing events surely have the potential to attract hundreds of anglers and harvest thousands of fish at a single event. Continuing to monitor the size, timing and location of bowfishing tournaments will be valuable to protect spawning aggregations and other vulnerable life stages of native species. Furthermore, as harvest rates within broad taxonomic groups were relatively consistent among tournaments held on the same waterbody, the baseline harvest data provided in this study may be useful in predicting the potential impact of future bowfishing tournaments on exploited populations and can inform the development of tournament guidelines that promote and protect sustainable fisheries. Finally, the results of this study should not be extrapolated to non-tournament bow anglers as they may have different preferences, fishing habits and harvest characteristics (Quinn 2010). Future research should focus on the fishing effort and habits of non-tournament bow anglers, monitor the participation rates of competitive and non-tournament bowfishing, and evaluate the impacts of bowfishing on poorly studied rough fish populations.

## Tables

Table 3.1: Description of sampling data used to create length frequency distributions of gars in each waterbody for comparison with gars harvested at bowfishing tournaments.

| Species | Waterbody | Source | Year | Gears | Effort | Count |
|---|---|---|---|---|---|---|
| Shortnose Gar | La Grange reach, | INHS | 2017 – 2018 | Electrofishing | 1,290 min | 86 |
| *Lepisosteus* | Illinois River | | | Mini fyke net | 60 net nights | 65 |
| *platostomus* | | | | Fyke net | 248 net nights | 271 |
| | Starved Rock & Peoria | IDNR | 2013 – 2015 | Electrofishing | 744 min | 33 |
| | reaches, Illinois River | INHS | 2016 – 2017 | Electrofishing | 180 min | 17 |
| Longnose Gar | Kankakee & | IDNR | 2013 – 2015 | Electrofishing | 3,250 min | 105 |
| *L. osseus* | Des Plaines Rivers | INHS | 2016 | Electrofishing | 15 min | 8 |

Table 3.2**:** The questions asked during angler interviews at bowfishing tournaments. Question 7 was introduced at the start of the 2018 tournament season.

| | |
|---|---|
| Q1. | I am trying to determine how far people are willing to travel to attend tournaments, do you mind giving me a home zip code? |
| Q2. | How many bowfishing tournaments do you anticipate attending this year, including ones you have already participated in? |
| Q3. | On average, how many times a month do you bowfish (not at a tournament)? |
| Q4. | On average, how many times a month do you use rod and reel (not at a tournament)? |
| Q5. | How many years have you been bowfishing? |
| Q6. | Do you use archery equipment for other outdoor recreation? If yes, for what? |
| Q7. | What are your three favorite bowfishing target species? |

Table 3.3: Based on chronological order, tournaments were assigned an identification number (ID) that is used to reference the tournaments throughout this paper. Abbreviations in the host organization column stand for: Bowfishing Association of Illinois (BAI), Kaskaskia State Fish and Wildlife Area (KSFWA), Southeastern Illinois College (SIC) and Rosiclare, IL Fire Department (RFD). The hours column contain the official start and stop times of each tournament (military hours). The contests column indicates the number of contests offered at each tournament.

| ID | Tournament | Host organization | Start date | Hours | Water body | Contests |
|---|---|---|---|---|---|---|
| T1 | Grass Lake Championship | BAI | 06/01/2017 | 06:00 – 12:00 | Fox Chain O' Lakes | 2 |
| T2 | Three Rivers Championship | BAI | 07/01/2017 | 20:00 – 04:00 | Kankakee & Des Plaines Rivers | 2 |
| T3 | State Championship – Day | BAI | 07/15/2017 | 05:00 – 14:00 | Illinois River[1] | 14 |
| T4 | State Championship – Night | BAI | 07/15/2017 | 20:00 – 05:00 | Illinois River[1] | 2 |
| T5 | Illinois Open | BAI | 08/04/2017 | 19:00 – 05:00 | All public waters in Illinois | 2 |
| T6 | Conservation Shoot | BAI | 09/16/2017 | 19:00 – 06:00 | Kankakee & Des Plaines Rivers | 2 |
| T7 | Spring Kickoff | BAI | 04/21/2018 | 18:00 – 02:00 | Kankakee & Des Plaines Rivers | 3 |
| T8 | Rend Lake Open | BAI | 05/05/2018 | 19:00 – 07:00 | Rend Lake | 3 |
| T9 | Conservation Shoot | BAI | 05/19/2018 | 20:00 – 02:00 | Kankakee & Des Plaines Rivers | 2 |
| T10 | Grass Lake Championship | BAI | 06/09/2018 | 07:00 – 14:00 | Fox Chain O' Lakes | 3 |
| T11 | Bighead Birthday Bash | BAI | 07/14/2018 | 07:00 – 14:30 | Illinois River[2] | 2 |
| T12 | Rough Fish Roundup | KSFWA | 07/21/2018 | 08:00 – 16:00 | Kaskaskia River[3] | 6 |
| T13 | Big 20 Bowfishing | SIC | 07/21/2018 | 19:00 – 07:00 | Ohio River | 2 |
| T14 | State Championship – Day | BAI | 07/28/2018 | 05:00 – 14:00 | Illinois River[1] | 10 |
| T15 | State Championship – Night | BAI | 07/28/2018 | 20:00 – 05:00 | Illinois River[1] | 3 |
| T16 | Fire Department Big 15 | RFD | 08/11/2018 | 19:00 – 07:00 | Ohio River | 3 |

[1] Restricted to the Peoria and Starved Rock reaches.
[2] Restricted to the La Grange reach.
[3] Restricted to the area downstream from Fayetteville, IL to the lock and dam complex near the confluence with the Mississippi River.

Table 3.4: Participation, effort and harvest information from sixteen bowfishing tournaments in Illinois. Creel clerks were unable to collect accurate harvest information at T8, so this tournament was excluded. Columns in the table are as follows: the number of participating teams ($B_h$), the number of teams interviewed in the creel survey ($b_h$), the mean number of anglers per team ($\bar{a}$), the estimated number of anglers per tournament ($\hat{A}$), the mean team fishing effort in angler hours ($\bar{e}$), the estimated total fishing effort in angler hours ($\hat{E}$), the mean number of harvested fish per team ($\bar{c}$), the estimated number of harvested fish ($\hat{C}$) and the estimated harvest rate (fish per angler hour ; $\hat{R}$).

| ID | $B_h$ | $b_h$ | $\bar{a} \pm SE$ | $\hat{A}$ | $\bar{e} \pm SE$ | $\hat{E}$ | $\bar{c} \pm SE$ | $\hat{C}$ | $\hat{R} \pm SE$ |
|---|---|---|---|---|---|---|---|---|---|
| T1 | 15 | 14 | 2.6 ± 0.2 | 40 | 14.9 ± 1.5 | 223.2 | 16.4 ± 2.3 | 245 | 1.24 ± 0.20 |
| T2 | 10 | 5 | 3.0 ± 0.3 | 30 | 24.0 ± 2.5 | 240.0 | 17.0 ± 8.8 | 170 | 0.74 ± 0.37 |
| T3 | 30 | 12 | 3.2 ± 0.3 | 95 | 22.9 ± 2.2 | 687.7 | 21.3 ± 3.5 | 638 | 0.95 ± 0.15 |
| T4 | 9 | 4 | 4.0 ± 0.4 | 36 | 28.8 ± 4.8 | 258.8 | 60.5 ± 27.8 | 545 | 1.93 ± 0.59 |
| T5 | 7 | 4 | 3.3 ± 0.5 | 23 | 25.5 ± 5.5 | 178.5 | 15.0 ± 2.3 | 105 | 0.75 ± 0.29 |
| T6 | 9 | 6 | 3.0 ± 0.3 | 27 | 29.8 ± 2.6 | 268.1 | 47.7 ± 6.5 | 429 | 1.66 ± 0.25 |
| T7 | 9 | 7 | 3.0 ± 0.4 | 27 | 17.5 ± 3.4 | 157.8 | 29.7 ± 6.4 | 267 | 1.81 ± 0.30 |
| T9 | 6 | 6 | 3.5 ± 0.4 | 21 | 17.3 ± 1.6 | 104.1 | 27.3 ± 7.2 | 164 | 1.59 ± 0.45 |
| T10 | 7 | 7 | 2.9 ± 0.3 | 20 | 19.8 ± 2.9 | 138.5 | 19.7 ± 3.5 | 138 | 1.17 ± 0.24 |
| T11 | 7 | 7 | 2.0 ± 0.3 | 14 | 13.4 ± 2.3 | 94.0 | 12.4 ± 1.6 | 87 | 1.15 ± 0.28 |
| T12 | 15 | 15 | 3.3 ± 0.2 | 49 | 22.0 ± 1.3 | 330.1 | 23.5 ± 5.7 | 353 | 1.06 ± 0.24 |
| T13 | 8 | 8 | 3.4 ± 0.2 | 27 | 32.7 ± 2.2 | 261.5 | 28.0 ± 4.3 | 224 | 0.91 ± 0.17 |
| T14 | 20 | 17 | 2.9 ± 0.2 | 58 | 20.5 ± 1.8 | 410.2 | 23.9 ± 3.1 | 479 | 1.36 ± 0.24 |
| T15 | 9 | 9 | 3.3 ± 0.2 | 30 | 21.3 ± 1.9 | 192.0 | 149.6 ± 86.6 | 1,346 | 9.24 ± 5.88 |
| T16 | 22 | 16 | 3.6 ± 0.2 | 80 | 34.9 ± 1.4 | 767.8 | 33.5 ± 5.0 | 737 | 1.00 ± 0.17 |
| **Total** | 183 | 137 | 3.1 ± 0.0 | 576 ± 9 | 23.56 ± 0.40 | 4,312.2 ± 78.3 | 32.4 ± 1.2 | 5,927 ± 226 | 1.73 ± 0.41 |

Table 3.5: Summary of harvest by species and family group across 15 bowfishing tournaments. $\hat{C}$ is the estimated total harvest at all tournaments, and $\hat{R}$ is the mean harvest rate (fish per angler hour) of all tournaments.

| | $\hat{C}$ ± SE | Percent of $\hat{C}$ | $\hat{R} \pm SE$[1] | Hours to catch 1 fish |
|---|---|---|---|---|
| Carp | 4,965 ± 211 | 84 | 1.5185 ± 0.4103 | < 1 |
| Silver Carp *Hypophthalmichthys molitrix* | 3,175 ± 207 | 54 | 0.9837 ± 0.4144 | > 1 |
| Common Carp *Cyprinus carpio* | 1,003 ± 36 | 17 | 0.3680 ± 0.0566 | > 2 |
| Bighead Carp *H. nobilis* | 522 ± 59 | 9 | 0.0917 ± 0.0278 | > 10 |
| Grass Carp *Ctenopharyngodon idella* | 263 ± 39 | 4 | 0.0747 ± 0.0170 | > 13 |
| Goldfish *Carassius auratus* | 1 ± 0 | < 1 | 0.0004 | > 2,363 |
| Suckers | 651 ± 44 | 11 | 0.1344 ± 0.0240 | > 7 |
| Smallmouth Buffalo *Ictiobus bubalus* | 561 ± 44 | 9 | 0.1161 ± 0.0223 | > 8 |
| Silver Redhorse *Moxostoma anisurum* | 29 ± 10 | < 1 | 0.0051 ± 0.0030 | > 197 |
| River Carpsucker *Carpiodes carpio* | 19 ± 4 | < 1 | 0.0035 ± 0.0013 | > 283 |
| Golden Redhorse *M. erythrurum* | 14 ± 4 | < 1 | 0.0029 ± 0.0015 | > 339 |
| Bigmouth Buffalo *I. cyprinellus* | 13 ± 2 | < 1 | 0.0040 ± 0.0014 | > 250 |
| Quillback *Carpiodes cyprinus* | 13 ± 5 | < 1 | 0.0025 ± 0.0012 | > 399 |
| Shorthead Redhorse *M. macrolepidotum* | 2 ± 1 | < 1 | 0.0002 | > 4,110 |
| Gar | 259 ± 22 | 4 | 0.0671 ± 0.0162 | > 14 |
| Shortnose Gar *Lepisosteus platostomus* | 148 ± 12 | 2 | 0.0410 ± 0.0130 | > 24 |
| Longnose Gar *L. osseus* | 107 ± 16 | 2 | 0.0231 ± 0.0055 | > 43 |
| Spotted Gar *L. oculatus* | 4 ± 0 | < 1 | 0.0030 ± 0.0022 | > 333 |
| Other species | 52 ± 9 | 1 | 0.0110 ± 0.0034 | > 90 |
| Freshwater Drum *Aplodinotus grunniens* | 41 ± 8 | 1 | 0.0086 ± 0.0032 | > 116 |
| Gizzard Shad *Dorosoma cepedianum* | 8 ± 4 | < 1 | 0.0012 ± 0.0008 | > 825 |
| Bowfin *Amia calva* | 3 ± 1 | < 1 | 0.0012 ± 0.0007 | > 832 |

[1] For species without reported variance, only one fish was counted in the creel surveys and so variance could not be computed.

Table 3.6: Results of the $AIC_C$ analysis comparing the alternative travel distance models. Models were considered plausible if $\Delta AIC_C \leq 7$ and were chose as top models if $\Delta AIC_C \leq 2$. The top model is shown in bold.

| Model | $AIC_C$ | $\Delta AIC_C$ | – 2 log likelihood | $W_i$ |
|---|---|---|---|---|
| **Full** | **104.74** | **0** | **-43.68** | **0.97** |
| Combined | 111.85 | 7.11 | -48.40 | 0.03 |
| Tournament characteristics | 116.13 | 11.40 | -53.88 | < 0.01 |
| Activity engagement | 127.88 | 23.15 | -58.66 | < 0.01 |
| Null | 133.93 | 29.19 | -64.91 | < 0.01 |

Table 3.7: The lower and upper 95% confidence intervals (LCI and UCI respectively) of the coefficient estimates and *P* values for the top travel distance general linear model. Terms in bold represent significant parameters.

| Model | Parameter | LCI | UCI | *P* |
|---|---|---|---|---|
| Full | **Intercept** | **1.50** | **2.04** | **< 0.001** |
| | Type–night | -0.14 | 0.46 | 0.28 |
| | **Number of contests** | **0.01** | **0.06** | **< 0.05** |
| | **Tournament participation–more than 1** | **0.01** | **0.43** | **< 0.05** |
| | Monthly bowfishing frequency | -0.02 | 0.01 | 0.45 |
| | **Monthly angling frequency** | **-0.03** | **-0.01** | **< 0.01** |
| | **Type–night x Tournament participation–more than 1** | **-0.78** | **-0.16** | **< 0.01** |

Table 3.8: Participant responses to the question about their favorite bowfishing target species (N = 312). The “percent in group” column represents the percent of the response within the corresponding taxonomic group. The “percent overall” column represents the percent of the response among all the responses.

| Taxonomic Group | Response | Percent in group | Percent overall |
|---|---|---|---|
| Carp | Carp | 10 | 5 |
| | Grass Carp | 34 | 19 |
| | Bighead Carp | 23 | 13 |
| | Common Carp | 23 | 13 |
| | Silver Carp | 10 | 5 |
| | Goldfish | 1 | < 1 |
| Sucker | Buffalo *Ictobus spp*. | 94 | 16 |
| | Bigmouth Buffalo | 4 | 1 |
| | Quillback | 2 | < 1 |
| Gar | Gar | 85 | 18 |
| | Longnose Gar | 9 | 2 |
| | Alligator Gar *Atractosteus spatula* | 4 | 1 |
| | Shortnose Gar | 1 | < 1 |
| Other | Any | 50 | 3 |
| | Bowfin | 25 | 2 |
| | Freshwater Drum | 15 | 1 |
| | Flathead Catfish *Pylodictis olivaris* | 5 | < 1 |
| | Paddlefish *Polyodon spathula* | 5 | < 1 |

**Figures**


Figure 3.1: Locations of surveyed bowfishing tournaments held throughout Illinois.

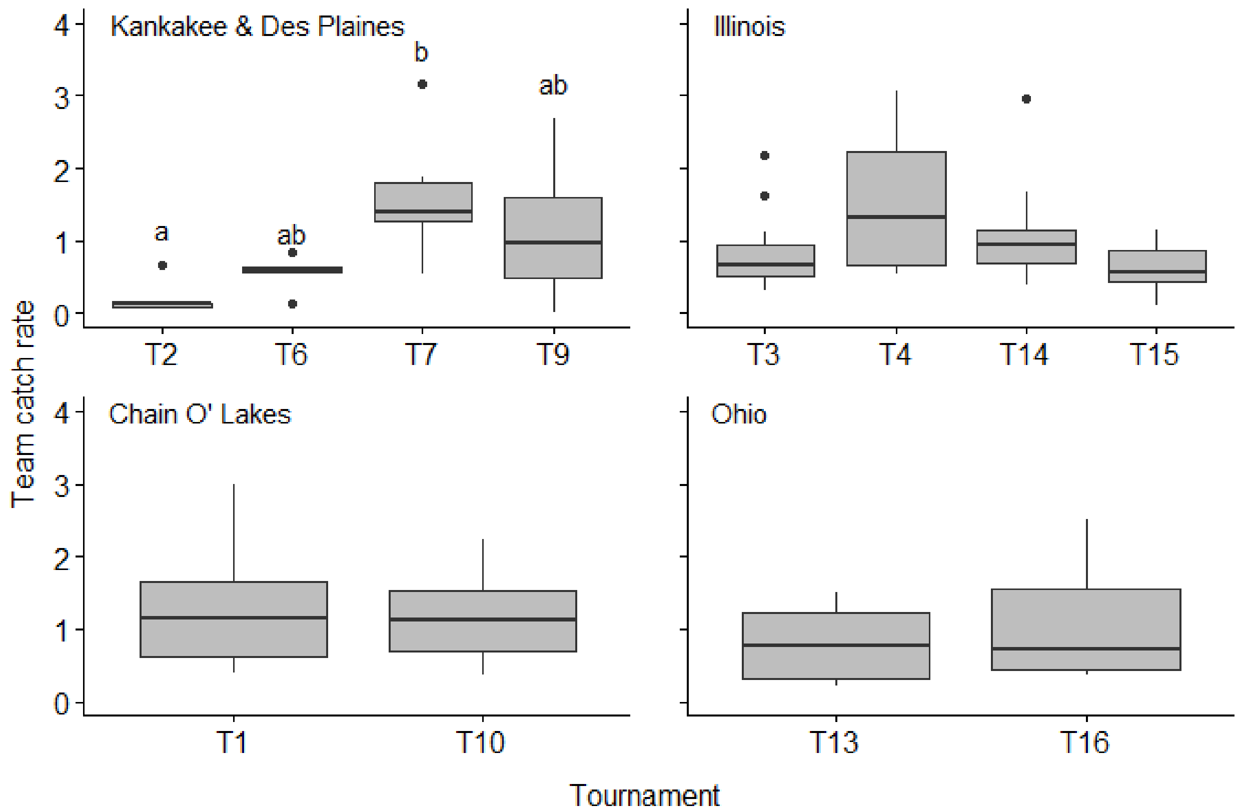


Figure 3.2: The variation in team catch rate (fish per angler hour) for carps harvested at tournaments held on the same waterbodies. Each panel is a waterbody where multiple tournaments were held. In panels where letters are present Welchs' ANOVA was significant at α = 0.05, and Games-Howell post hoc tests were performed. Tournaments not sharing letters represent significant differences at α = 0.05. Horizontal bars in the boxplots represent the median harvest rate, and the 75% and 25% quartiles. Whiskers represent ± 1.5 times the interquartile range, and outliers are indicated as dots.

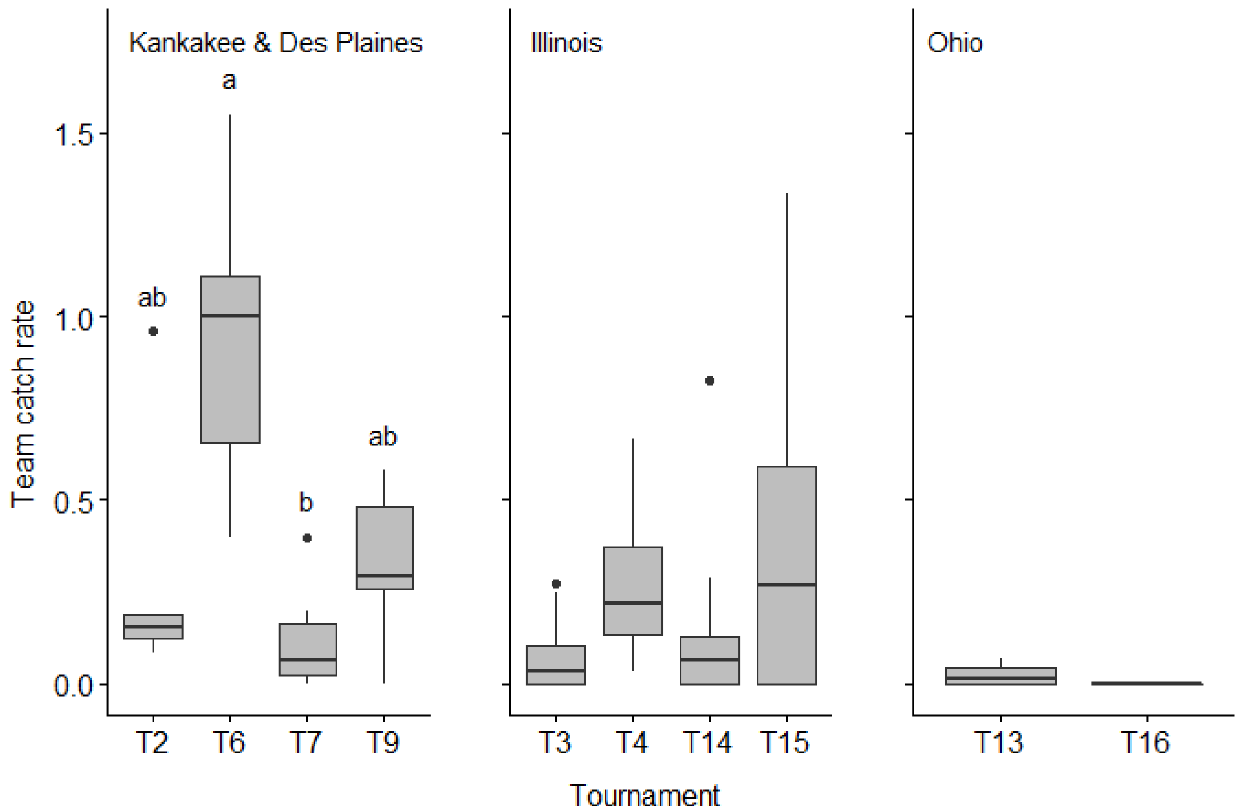


Figure 3.3**:** The variation in team catch rate (fish per angler hour) for suckers harvested at tournaments held on the same waterbodies. Welch's ANOVA was not performed for the Ohio River tournaments, but this panel is shown for comparison. For description of figure layout, refer to Figure 3.2.

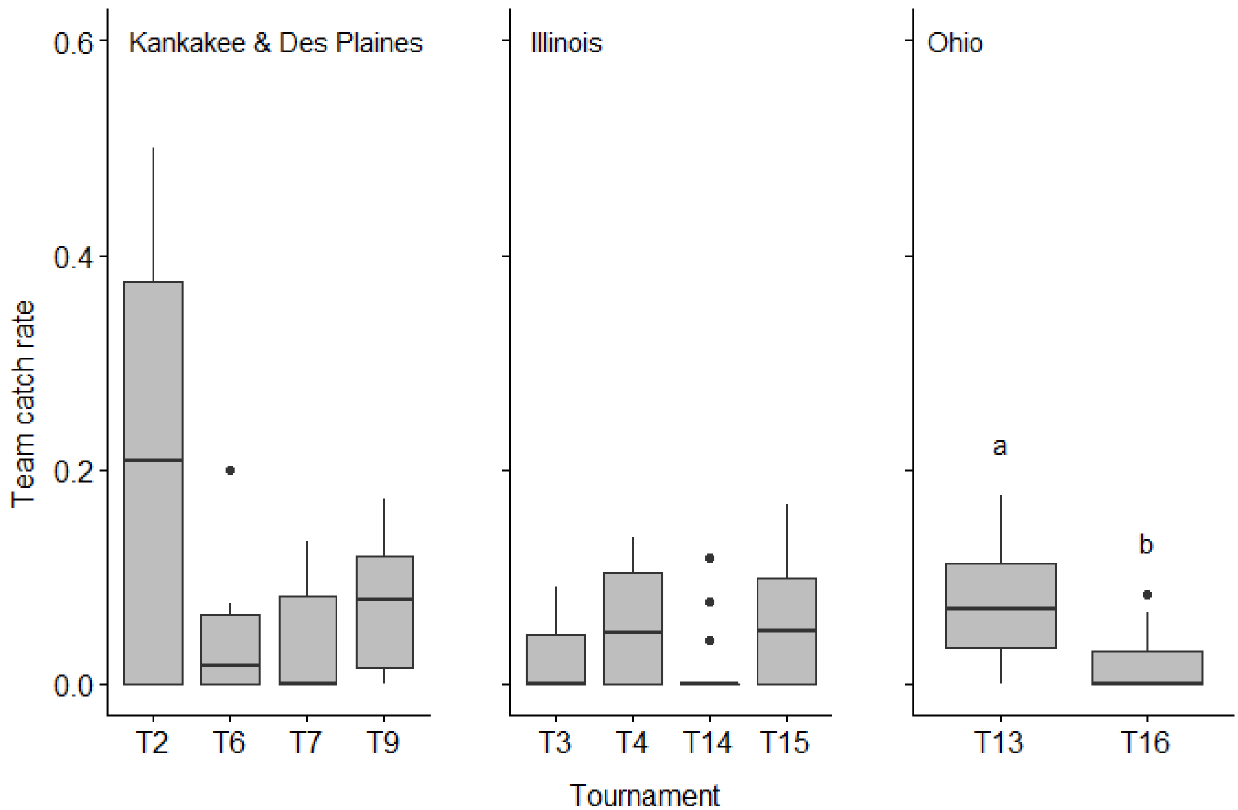


Figure 3.4: The variation in team catch rate (fish per angler hour) for gars harvested at tournaments held on the same waterbodies. For description of figure layout, refer to Figure 3.2.

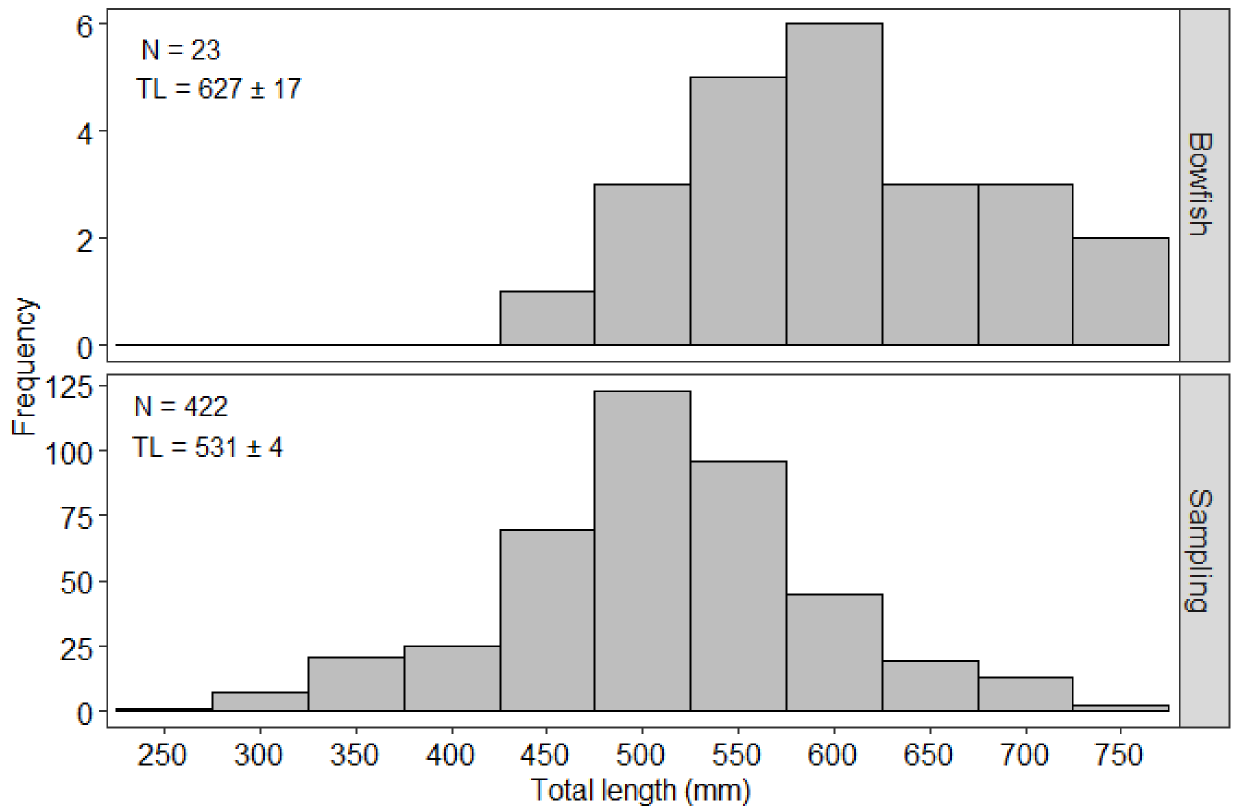


Figure 3.5: In the La Grange reach of the Illinois River, Shortnose Gar captured at bowfishing tournaments were larger than those captured during sampling events ($U = 7{,}770$; $p < 0.01$). In each panel, the sample size and the mean TL ± SE are given. The bins are left inclusive and right exclusive, and bin labels represent the lower limit. Note that the y-axes differ among panels.

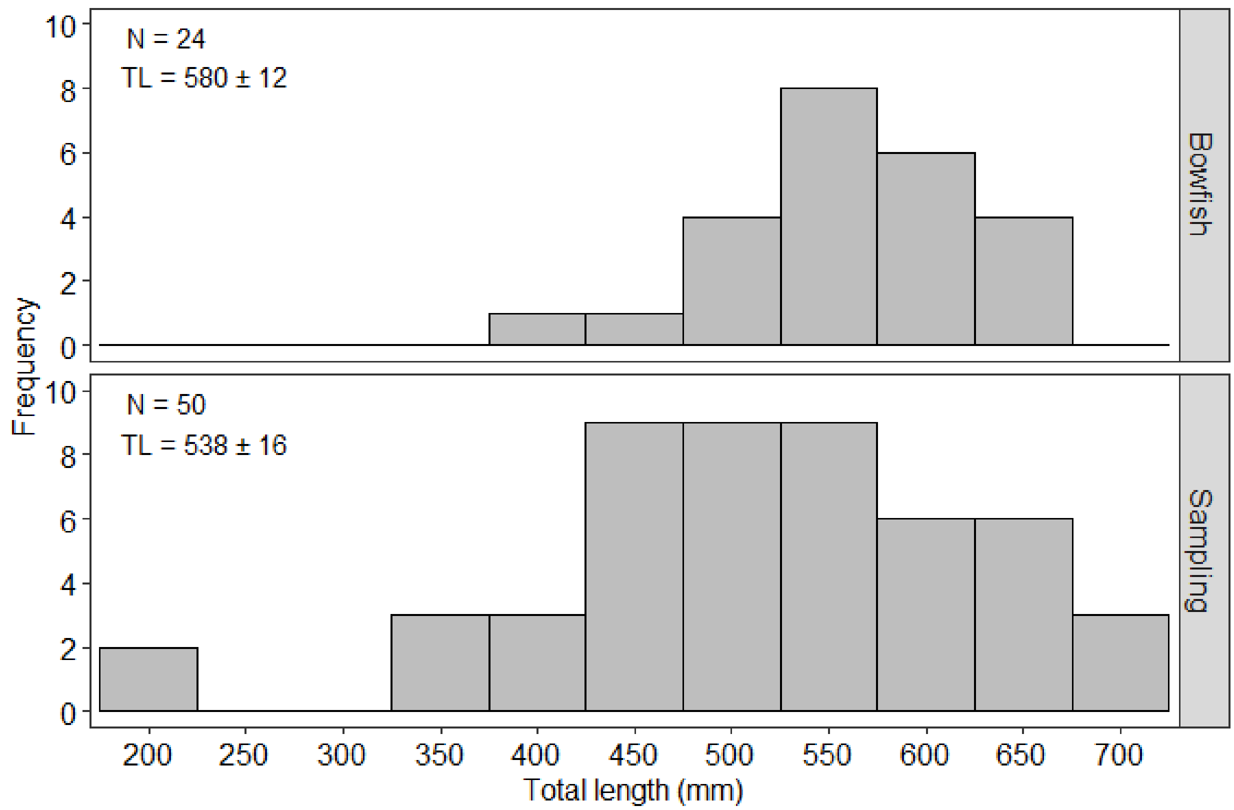


Figure 3.6: The length distributions of Shortnose Gar were similar for those captured at bowfishing tournaments and during sampling events in the Starved Rock and Peoria Reaches of the Illinois River (U = 738; p = 0.06). In each panel, the sample size and the mean TL ± SE are given. The bins are left inclusive and right exclusive, and bin labels represent the lower limit.

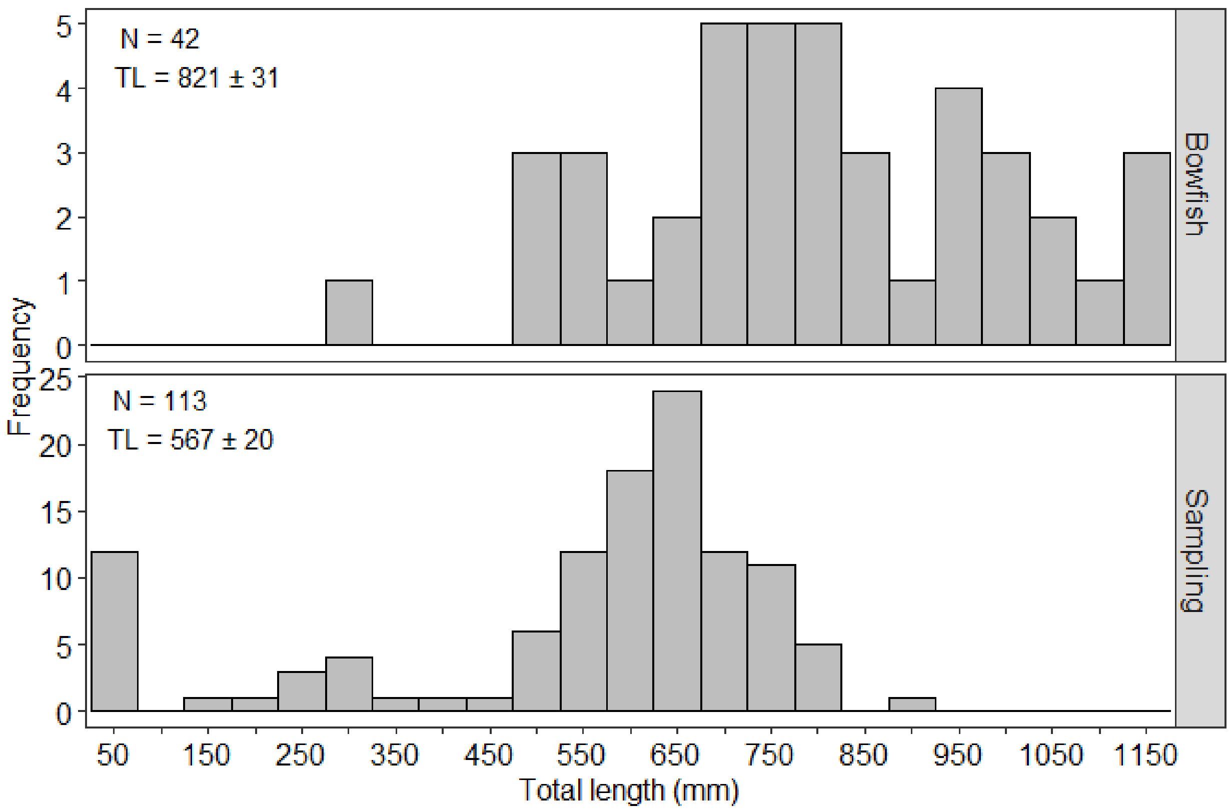


Figure 3.7: In the Kankakee and Des Plaines Rivers, Longnose Gar captured at bowfishing tournaments were larger than those captured during sampling events (U = 3,828; $p < 0.01$). In each panel, the sample size and the mean TL ± SE are given. The bins are left inclusive and right exclusive, and bin labels represent the lower limit. Note that the y-axes differ among panels.

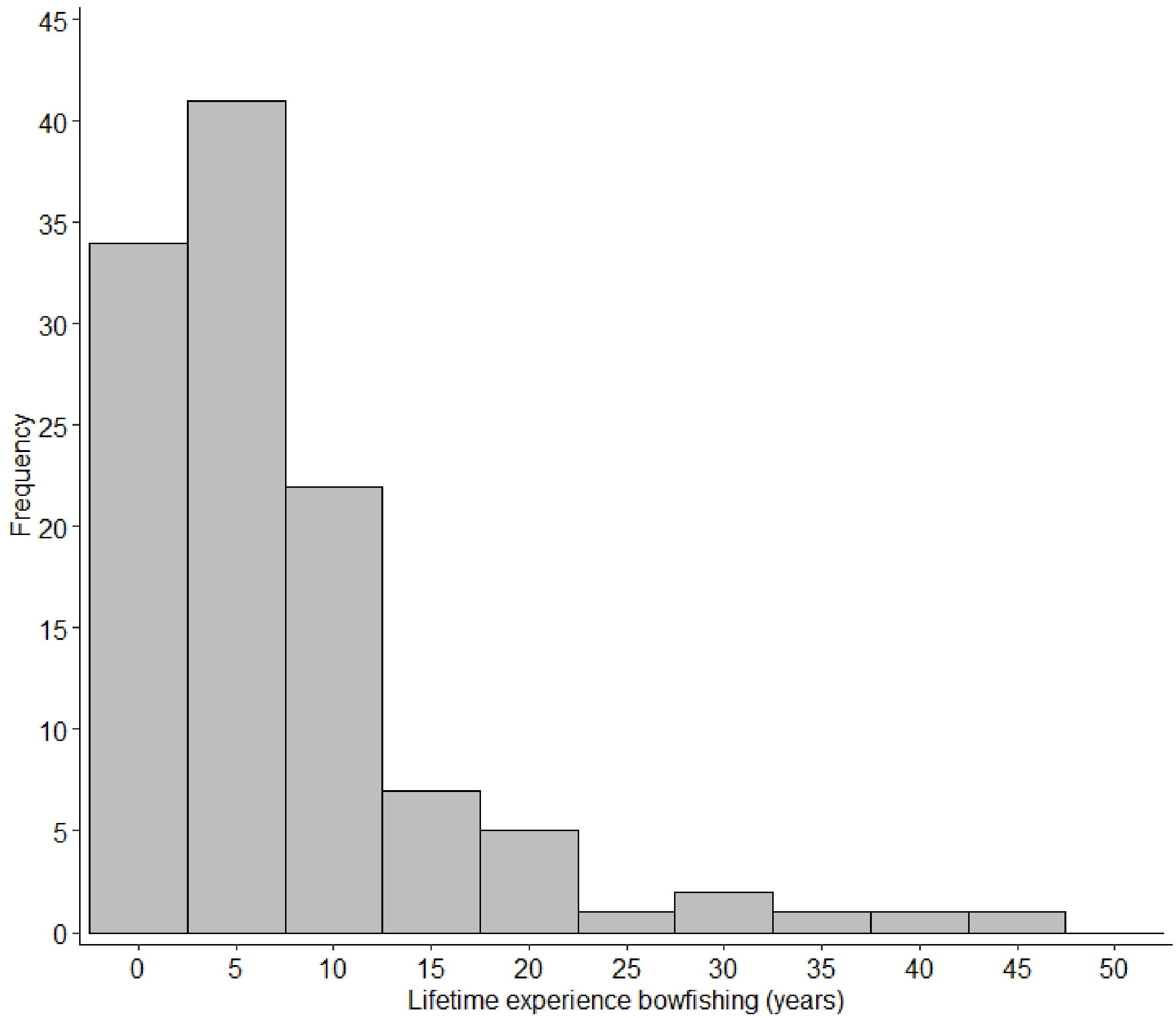


Figure 3.8: The distribution of tournament of reported lifetime experience bowfishing (years). Mean experience is 8.9 ± 0.7 SE, and median experience is 7.0 years. The bins are left inclusive and right exclusive, and bin labels represent the lower limit.

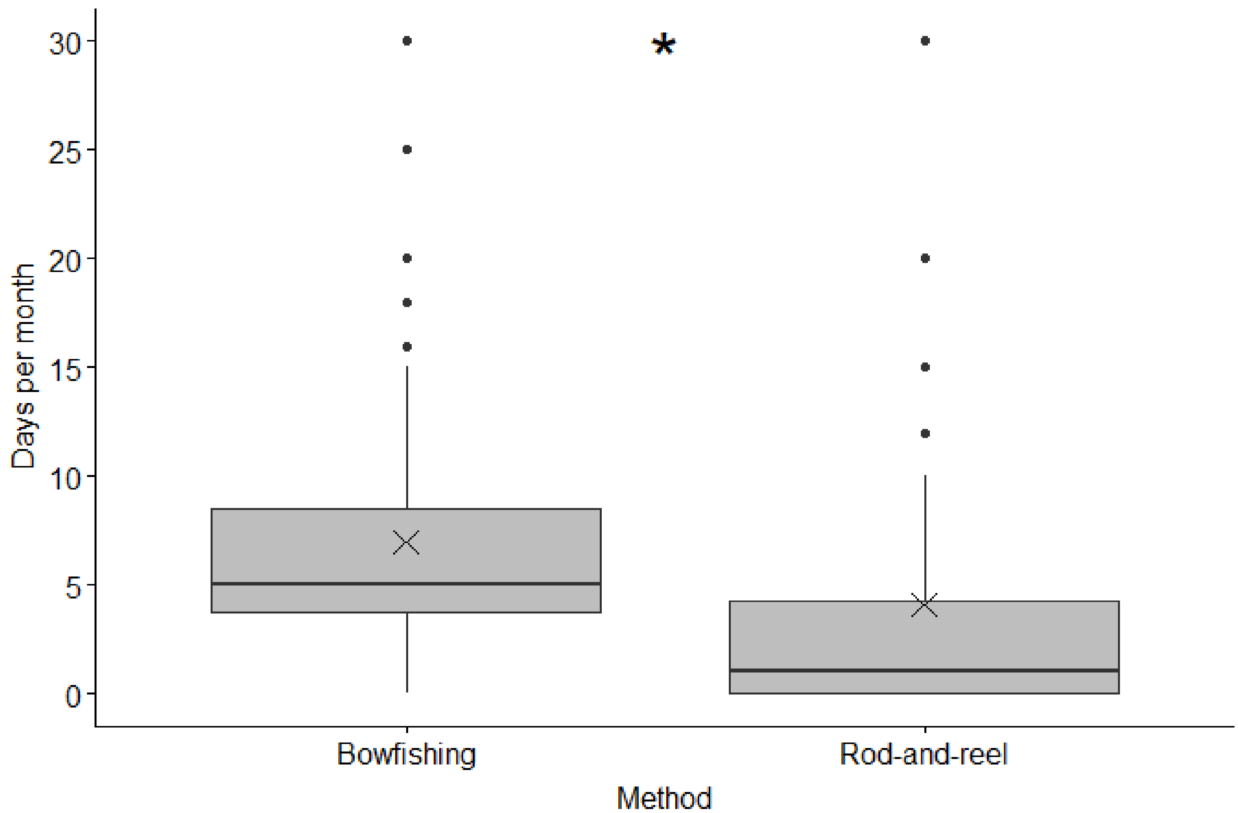


Figure 3.9: Tournament bow anglers spent more days per month engaged in non-tournament bowfishing ($\bar{x}$ = 7.0 ± 0.6 SE) than rod and reel angling ($\bar{x}$ = 4.1 ± 0.6 SE). The asterisk indicates a significant difference found from a Wilcoxin Signed Rank test at $\alpha = 0.05$. Horizontal bars in the boxplots represent the median days per month, and the 75% and 25% quartiles. Whiskers represent ± 1.5 times the interquartile range, and outliers are indicated as dots. The "x" represents mean days per month engaged in non-tournament activity for each method.

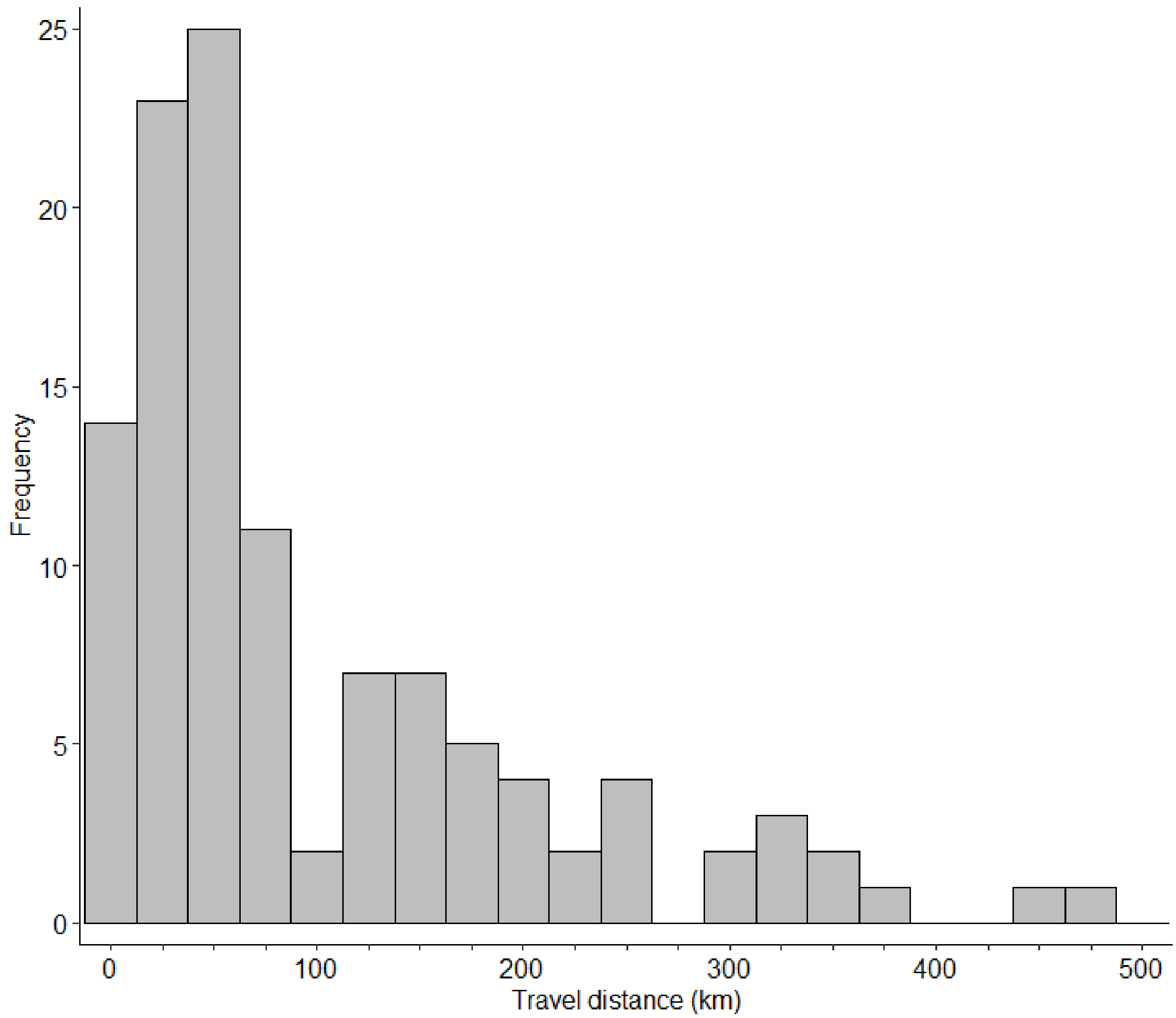


Figure 3.10: The distribution of travel distance to tournament. Travel distance to tournament is the linear distance between the angler reported home zip code centroid and the GPS location of the tournament weigh in. Mean travel distance is 112.97 ± 9.97 SE, and median travel distance is 67.51 km. The bins are left inclusive and right exclusive, and bin labels represent the lower limit.

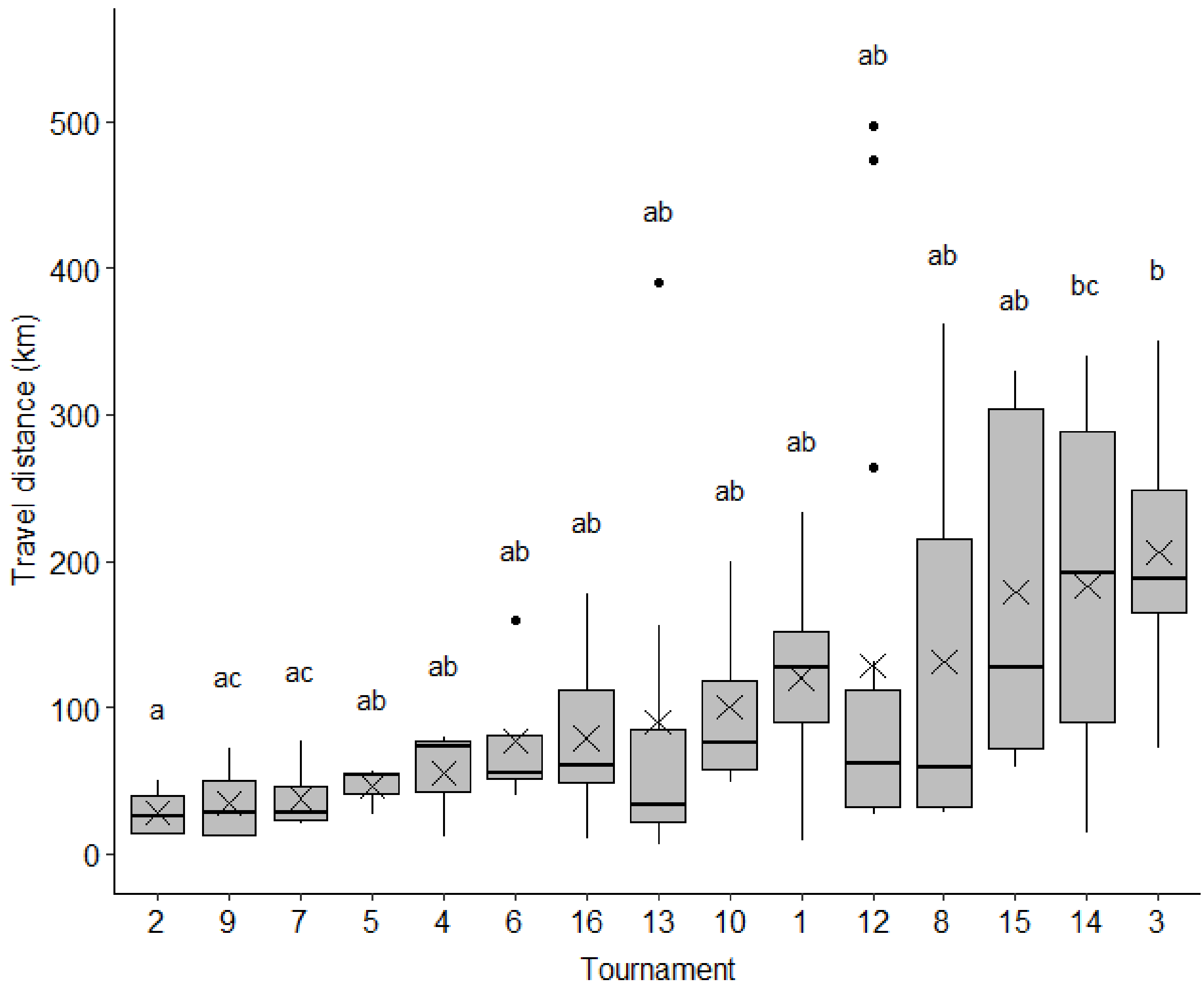


Figure 3.11: The variation in angler travel distance to tournament (km) among tournaments. A one way ANOVA found significant differences among log-transformed travel distance between tournaments at the 95% confidence interval. Box plots that do not share a letter represent tournaments found to have significantly different travel distances by a Tukey post hoc test. Travel distance was back-transformed for ease of interpretation in the figure. Horizontal bars in the boxplots represent the median travel distance, and the 75% and 25% quartiles. Whiskers represent ± 1.5 times the interquartile range, and outliers are indicated as dots. The “x” represents the mean travel distance of each tournament.

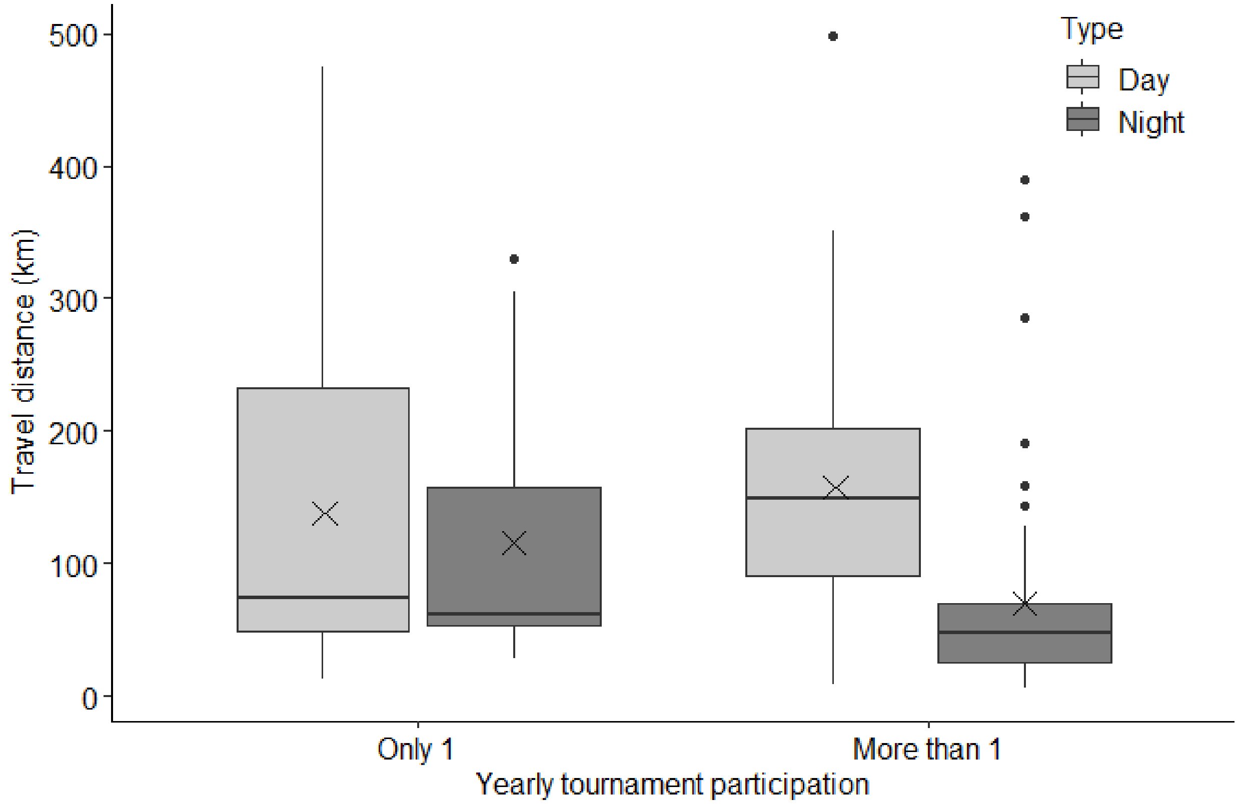


Figure 3.12: The relationship between yearly tournament participation and tournament type. This interaction had a significant, negative influence on log-transformed travel distance in the top general linear model. Horizontal bars in the boxplots represent the median travel distance, and the 75% and 25% quartiles. Whiskers represent ± 1.5 times the interquartile range, and outliers are indicated as dots. The “x” represents the mean travel distance of each group.

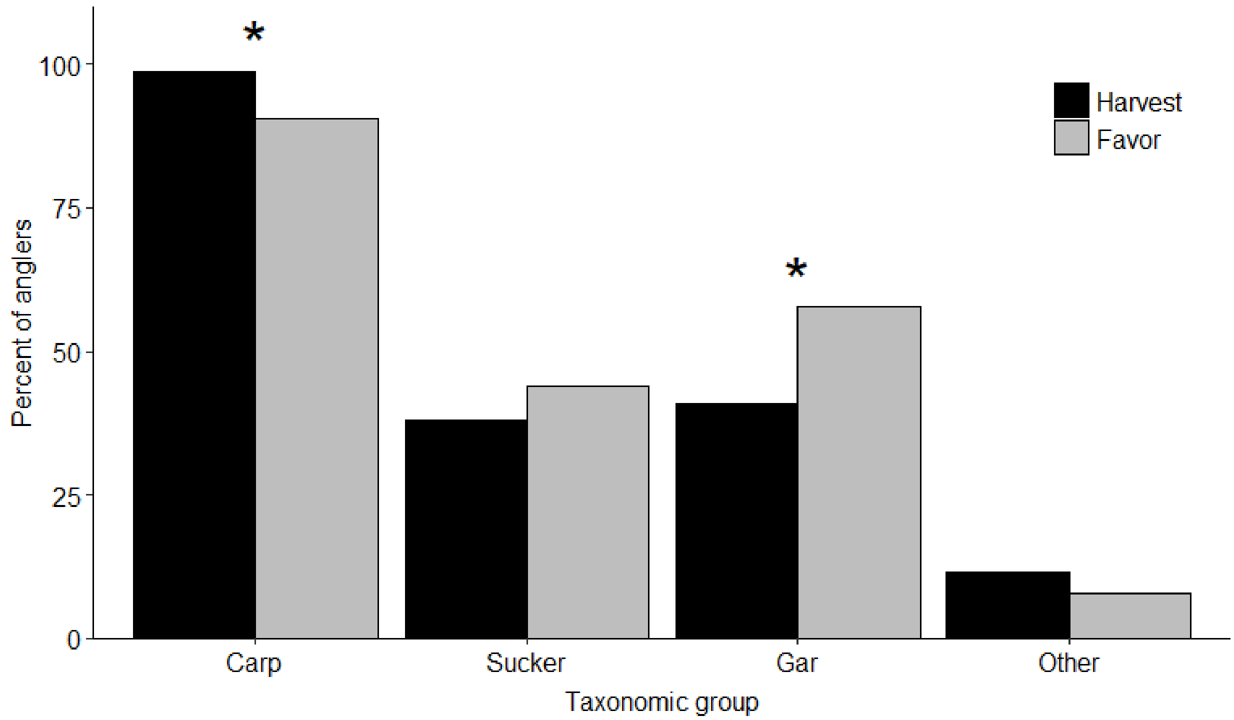


Figure 3.13: The percentage of tournament bow anglers who favored targeting and whose team harvested at least one fish from the taxonomic groups. The asterisk indicates a Fisher's exact test found significant differences between the favorability and harvest outcome at $\alpha = 0.05$.

# CHAPTER 4: SUMMARY AND BROADER CONTEXT

Despite a storied history regarded as "trash" fish, gars contribute to the diversity of the fish assemblage and stabilize the food web through predation in their native habitats. The emerging recreational importance of gars and the deficit of knowledge regarding Shortnose Gar population dynamics creates a critical need to evaluate the status of populations in Illinois. The apparent growth in bowfishing and the lethality of the method necessitates a better understanding of bowfishing harvest characteristics, including species composition, harvest rates and potential size selectivity. Furthermore, knowledge of the fishing habits and preferences of anglers will help achieve the biological and social objectives of management plans. To facilitate a better understanding of this knowledge gap, I conducted two complementary studies.

In chapter 2, I estimated the relative abundance, stock structure and vital rates of Shortnose Gar in the lower Illinois River. I found that Shortnose Gar primarily utilize permanently connected backwater habitats, but that main channel habitats are likely important to their movement between spawning and feeding habitats in tributaries and intermittently connected floodplain habitats. The observed trends in the size and age structures across years indicate that Shortnose Gar exhibit infrequent spawning or variable recruitment and that temporally predictable flood pulses are likely relevant to successful reproduction. The length at age information was highly variable, likely due to the differential growth of individuals over long life spans and the inability to distinguish among sexes. The von Bertalanffy growth model was inconclusive on age at sexual maturity; however, it predicted that Shortnose Gar in the La Grange reach have the potential to reach larger maximum lengths than observed and exhibit slow growth rates. Finally, the mortality estimates are likely evidence of increased fishing mortality for gars in Illinois. Overall, the periodic life history strategy of Shortnose Gar – characterized by large body size, slow growth rates, delayed sexual maturity, variable recruitment and a long lifespan – suggest that this population may be vulnerable to recruitment overfishing.

In chapter 3, I characterized participation and harvest of Illinois bowfishing tournaments, and described bow angler favored target species and fishing habits. While invasive carp species dominate harvest composition at Illinois bowfishing tournaments, bow anglers favor targeting gars and selectively remove large individuals from the population. Harvest rates at bowfishing tournaments may be higher than other recreational fishing methods; however, there is likely room for sustainable growth of tournaments in Illinois. Due to the extremely small footprint of competitive bowfishing events, there appears to be minimal need for more restrictive regulations regarding tournament bowfishing harvest. However, the results should not be extrapolated to non-tournament bow anglers, and future work should focus on determining non-tournament bowfishing harvest.

Collectively this work will aid in the development of appropriate management strategies that promote sustainable populations and provide quality recreational opportunities to anglers. For example, harvest characteristics from Chapter 3 may be useful in predicting the potential impact of future bowfishing tournaments on exploited populations and can inform the development of tournament guidelines. Integration of the results from Chapter 2 into a population growth model can estimate Shortnose Gar sensitivity to varying exploitation rates and harvest regulations. Ongoing studies examining the movement ecology, fecundity and population sizes of Shortnose Gar will likely resolve many of the questions resulting from this work; however, until then a precautionary management approach is advisable to prevent overharvest.

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