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STURGEON PAPER

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Monitoring demographics of a commercially exploited population of shovelnose sturgeon in the Wabash River, Illinois/Indiana, USA

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Abstract

Shovelnose sturgeon (*Scaphirhynchus platorynchus*, Rafinesque, 1820) in the Wabash River, Illinois/Indiana, USA, provide an important recreational sport and commercial caviar fishery. In fact, it is one of the last commercially viable populations for sturgeon roe harvest. Due to increased demand in the caviar trade and endangered species legislation that protect shovelnose sturgeon in only a portion of their range, efforts of the roe harvest market may continue to divert toward unprotected populations like the shovelnose sturgeon in the Wabash River. Previous studies have shown that increased harvest pressure in this species can affect the age-at-maturation and result in recruitment overfishing. Therefore, it is important to closely and continuously monitor commercially exploited populations. Over the past decade (2007–2016), 13,170 shovelnose sturgeon were sampled with boat electroshocking, hoop nets, drift nets, trotlines, and benthic electrified trawls. Captured fish ranged from 61 to 910 mm fork length (FL; mean = 668 mm), with very few fish less than 550 mm FL. Although fish were found to be in a healthy condition (mean relative weight = 87), there was a decrease in the mean condition over time. In addition, we saw declines in mean FL, weight of roe-per-fish, and size-at-maturity for female fish directly impacted by harvest. The decline of these population parameters, coupled with an increase in total annual mortality and a truncated age frequency distribution, suggest that harvest is negatively impacting the demographics and recruitment of shovelnose sturgeon in the Wabash River. Considering the downward trajectory of population dynamics and high estimates of mortality, their resiliency to continued harvest and environmental changes will be limited.

1 | INTRODUCTION

Shovelnose sturgeon (*Scaphirhynchus platorynchus*, Rafinesque, 1820) are widely distributed in the Missouri and Mississippi River basins of North America. They are the most abundant sturgeon species inhabiting this area, and some of these populations are subject to substantial commercial fishing pressure (Bailey & Cross, 1954; Keenlyne, 1997). Shovelnose sturgeon are slow to mature, reproduce infrequently, and experience low rates of natural mortality. These life history traits, shared by all sturgeon species, make them very susceptible to over-harvest (Billard & Lecointre, 2001; Pikitch, Doukakis, Lauck, Chakrabarty, & Erickson, 2005). However, shovelnose sturgeon are believed to be one of the last commercially viable options for roe harvest because they are small-bodied and fast-growing relative to other sturgeon species. Females typically reach sexual maturity at 7 to 9 years of age and spawn once every 2 to 3 years. Males are likely to reach reproductive maturity between ages 5 and 8 years (Colombo, Garvey, & Wills, 2007; Keenlyne, 1997; Tripp, Phelps, et al., 2009). Historically, their small size has made them undesirable to the commercial caviar market. However, in light of the closure of several marine sturgeon fisheries and the decline of lake sturgeon (*Acipenser fluvescens*) populations in North America, shovelnose sturgeon are now a popular commercial species (Colombo, Garvey, Jackson, et al., 2007; Hintz & Garvey, 2012; Quist, Guy, & Pegg, 2002).

The Wabash River is the largest tributary to the Ohio River, and hosts a significant population of shovelnose sturgeon. While most large rivers in the United States have been modified for reasons of flood control or navigation, the Wabash River has remained largely unaltered. Featuring 661 km of unimpounded river, it is the longest free-flowing stretch of river east of the Mississippi. The lower 322 km of the Wabash River divides the southern half of Illinois and Indiana and hosts a commercial caviar fishery under the joint jurisdiction of the Illinois Department of Natural Resources (IL-DNR) and the Indiana Department of Natural Resources (IN-DNR).

There are several regulations in place that affect and help protect this population. In 2010, the United States Fish and Wildlife Service (USFWS) listed shovelnose sturgeon as a threatened species under the “Similarity of Appearances” (SOA) provisions of the Endangered Species Act (USFWS, 2010). This regulation closed the sturgeon fishery in areas where the shovelnose sturgeon range overlaps with the morphometrically similar and endangered pallid sturgeon (*Scaphirhynchus albus*). In response, the Wabash River population may receive diverted efforts of the shovelnose sturgeon roe market (Hintz & Garvey, 2012). In 2007 a 635 mm (25 in) minimum length limit was established with no bag limit for the Wabash River shovelnose sturgeon fishery. The roe harvest season begins October 1 and ends May 31 with a cap of 35 commercial roe permits per state (IL and IN). Two weeks prior to the 2014 harvest season, IL-DNR and IN-DNR introduced a ban on the use of “leads” for commercial hoop net fishing. This was in response to reports of commercial fishermen misusing hoop net leads as entanglement gear, which is also banned for use on the Wabash River.

Previous research on heavily harvested populations has shown that increased harvest pressure can affect age-at-maturation and lead to recruitment overfishing (Colombo, Garvey, Jackson, et al., 2007; Tripp, Colombo, & Garvey, 2009; Trippel, 1995). Therefore, close and continuous monitoring are good practice for sound management of an exploited sturgeon fishery. We assessed size structure and condition trends, quantified age structure, estimated growth and mortality, and defined sex-specific demographics. We also compared changes in these characteristics to the commercial harvest reports and regulation changes that have occurred in the history of the Wabash River roe fishery. A population that reflects a stable size structure and maintains condition and growth patterns would suggest that the population is resistant to variable environmental factors and commercial harvest pressure. On the other hand, changes in size and age structure, condition, growth, and mortality may be compounded by commercial harvest and environmental variation to affect population dynamics.

2 | METHODS

2.1 | Sampling

Shovelnose sturgeon sampling was conducted on the entirety of the Wabash River. Since 2000, the IL-DNR has conducted a mark-recapture study of shovelnose sturgeon on the Lower Wabash River (LWR). The IN-DNR began monitoring the Upper Wabash River (UWR) in 2005. The IN-DNR has focused their springtime sampling primarily around the spawning portion of the population at a probable spawning area near Lafayette, Indiana (Kennedy, Sutton, & Fisher, 2006). For this study, we have combined these data sets and focused on the past decade (2007–2016). The LWR includes all portions of the river that share a border between Illinois and Indiana. The UWR includes the upstream reach of the river only bound by Indiana. An electrified benthic trawl was used to sample shovelnose sturgeon by the Fisheries and Aquatic Research Team at Eastern Illinois University (power output = 3,500–4,500 watts). DC electrofishing and drifting gill nets (drift nets) were used by both the IL-DNR and IN-DNR. In addition, the IL-DNR used AC electrofishing, trotlines, and stationary gill nets. Electrofishing conducted by the IL-DNR consisted of either three-phase AC electrofishing with an unbalanced array or as DC electrofishing (output = 5 A; 60 pulses/s; 20%–50% range) in midchannel habitat of the LWR. Effort was set at 10 min per site with two netters. DC electrofishing was conducted by the IN-DNR across all years of the study and consisted of three 20-min transects (i.e., ¼, ½, and ¾ stream width) in fixed index stations of the UWR. IL-DNR used monofilament gill nets (30.5 m long; 1.2 or 2.4 m deep; with four 7.6- m panels of 3.8-, 5.1-, 7.6- and 10.2- cm bar mesh) for both stationary and drifting sets. Drift nets were floated perpendicular to the river current for approximately 15 min. IN-DNR began use of drift nets in 2008 with multifilament experimental gill nets (36.5 m long; 1.8 m deep; with 1.3–6.3 cm bar mesh) at the same effort as previously described.

2.2 | Population and sex-specific demographics

All captured shovelnose sturgeon were measured to the nearest millimeter fork length (FL). IN-DNR utilized a linear spring scale to determine wet weight, measuring with 50 g precision. Shovelnose sturgeon captured by all other agencies were weighed to the nearest gram. All fish were tagged with unique identifying Floy© tags. In 2013 the IN-DNR sacrificed several fish for internal assessment of sex and maturity. Fish were classified using the gonadal development guide for shovelnose sturgeon as described in Colombo, Garvey, & Wills, 2007. Additionally, all shovelnose sturgeon were visually inspected for sex during the spring spawning months. Males were identified as mature by expression of milt. Females were determined by visually inspecting the ventral surface for a red vent and a soft/swollen or loose/stretched abdomen. Suspected gravid females were confirmed by checking for the presence of eggs with a 10-gauge needle.

2.3 | Age, growth, and mortality

For age estimation, a 25 mm section was removed from the anteriormost pectoral fin ray. Fin rays were placed in scale envelopes and set out to air dry for several weeks. In the lab, three 0.6 mm cross-sections were cut from the distal end using a Buehler Isomet low-speed saw with a diamond cutting blade. Cross sections were placed in emersion oil and viewed under a stereomicroscope (≤80 × magnification) and photographed with a mounted 3.1-megapixel digital camera. Age estimations were made by two independent readers and any discrepancies were resolved with a concert read.

Two hundred fifty fish (44% of the total catch) from the 2016 sampling season captured via drift nets were subsampled for age analysis by using a length-stratified (30 fish/25 mm FL) random sampling approach. The coefficient of variation (CV; 100·*SD*/mean) for age estimations was calculated for each subsampled FL-group (575–725 mm FL; range = 3.8%–10.9%, mean = 8.0%). The age distribution of the subsample was extrapolated to the entire catch (N = 559) using direct proportions.

2.4 | Commercial harvest

We reviewed historical data for total weight (g) of roe, average price for caviar, and total number of shovelnose sturgeon harvested in the Wabash River by Illinois and Indiana commercial permit holders. Permit holders in Illinois and Indiana report total weight of roe differently. Illinois permit holders report the weight of roe as the entire ovary weight, including eggs and ovary tissue, while Indiana permit holders report total weight of roe as egg weight only. Upon sacrificing several FIV females in the 2013 sampling season, IN-DNR reported entire ovary weight, which was used to compare to commercial harvest reports. The data was compiled from the harvest season beginning in 2007 through 2016. We were limited by the assessments we could perform because requirements in reporting commercial fishing data have changed over time. In addition, we have no estimate of effort put forth by the commercial fishery. Therefore, we are limited in our ability to determine whether increase in catch was due to increased effort or increased catchability. Indiana commercial data is only available for the 2011–2015 harvest seasons.

2.5 | Data analysis

All statistical analyses were performed in R version 3.4.3 (R Development Core Team., 2017). For the analyses, we pooled data from all agencies and sampling locations within the Wabash River. We calculated the proportion of total catch contributed by each gear type and compared the mean FL of fish using a Kruskal-Wallis rank-sum test. Relative abundance was calculated as number of fish per hour (CPUE). CPUE was quantified for DC electrofishing and drift nets separately. These methods were chosen because they made up the largest proportion of the catch. DC electofishing was used consistently across all years of the study (2007–2016). Drift nets were not used until 2008 but were continuously used by IN-DNR for the remainder of the study.

The size structure for shovelnose sturgeon in the Wabash River was assessed for the years 2008–2016 using length frequency histograms. The length frequency histograms were created from fish captured with DC electrofishing and drift nets because these gears were used consistently throughout the study. Additionally, we calculated size distribution indices for fish captured with all gear types, and calculated the yearly size structure of shovelnose sturgeon (Anderson & Neumann, 1996; Guy, Neumann, Willis, & Anderson, 2007). The proportional size distribution (PSD) was calculated as

$$\mathrm{PSD} = \frac{\text{number of fish} \geq 380\,\text{mm}}{\text{number of fish} \geq 250\,\text{mm}} \times 100,$$

and the relative size distribution was calculated as

$$\mathrm{PSD}-\mathrm{X.} = \frac{\text{number of fish} \geq \text{specified length}}{\text{number of fish} \geq 250\,\text{mm}} \times 100,$$

with a preferred FL of 510 mm, a memorable FL of 640 mm, and a trophy FL of 810 mm (Quist, Guy, & Braaten, 1998). We used a linear regression to determine any changes in overall FL over time, and further assessed the changes by separating gender.

As an index of somatic condition, we calculated the mean relative weight (W_r; Anderson & Neumann, 1996) of individuals sampled each year: $W_r = (W/W_s) \times 100$, where W is the observed wet weight and W_s is the length-specific standard weight for the species. The W_s of shovelnose sturgeon was estimated based on the equation given by Quist et al. (1998):

$$\log_{10}(W_s) = -6.287 + 3.330 \times \log_{10}(\mathrm{FL})$$

We used a linear regression for mean W_r by year to determine any trends in overall condition, and further assessed by separating genders.

We plotted length-at-age for all age-classes; the average percent error and the CV ($100 \times [\mathrm{SD}/\mathrm{mean}]$) were calculated to assess the between-reader precision of fin ray age estimates. Growth was assessed for two different sampling years (2013 and 2016) by the von Bertalanffy growth function:

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

where L_t = fish length at time t; L_∞ = theoretical maximum length; K = Brody growth coefficient (the rate at which fish length approaches L_∞); and t_0 = theoretical age at a length of zero. A fixed-effect nonlinear regression model was used to compare the most recent growth parameters (2016) to those reported for the shovelnose sturgeon population in the LWR in 2013 (Nepal KC, Colombo, & Frankland, 2015). The most parsimonious model was selected based on Bayesian Information Criteria (BIC, Schwarz, 1978).

Mortality rates were calculated using two methods. First, the Chapman-Robson method (Robson & Chapman, 1961) was used to estimate annual mortality ($1-\hat{S}$) based on all fish that were older than the modal age:

$$A=1-\hat{S}=\frac{\sum T}{\sum N+T-1}$$

where T = years since the fish had fully recruited to the sampling gear; and N = total number of fully recruited fish in the sample. The mortality estimate was corrected for overdispersion and bias, as suggested by Smith et al. (2012). Second, total instantaneous mortality (Z) was estimated by a weighted catch curve analysis (Ricker, 1975; Smith et al., 2012). The frequency of fish captured in each age-class was plotted against age to detect the age at which shovelnose sturgeon were fully recruited to the sampling gear. Age-classes not fully recruited to the gear were excluded from the analysis. All ages after full recruitment were used in the analysis with no right truncation as suggested by Smith et al. (2012). Annual survival (S) and total annual mortality (A) rates were derived from the total instantaneous mortality rate (Z).

We calculated the reproductive output of female shovelnose sturgeon as the average weight (g) of roe-per-fish reported from the Wabash River by Illinois and Indiana commercial roe harvest permit holders. This was calculated as:

$$\text{roe}-\text{per}-\text{fish}=\frac{\text{total weight of roe(g)}}{\text{total number of fish}}.$$

We used a linear regression to show the changes in roe-per-fish over time. We also included the average weight of roe-per-fish found in the 2013 sampling season when IN-DNR sacrificed several FIV females. We assessed harvest trends from 2007–2013 before a new regulation was put in place banning the use of leads on hoop net fishing. It was compared to trends in harvest after the ban (2014–2016). We also compared the roe-per-fish calculations from Illinois commercial data with female relative weight by using Pearson's product correlation.

3 | RESULTS

A total of 13,170 shovelnose sturgeon were captured from the entirety of the Wabash River between 18 April 2007 and 30 November 2016. DC boat electrofishing was used across all years, employed mostly during August and September (range = April–December), and accounted for most of the captures with a total of 7,175 individuals (54.4% of the total catch; Table 1). Drift nets were utilized in all years except 2007 and were used mostly in April through June (range = January-December), capturing a total of 5,160 individuals (39.2% of total catch; Table 1). Stationary gillnets were used irregularly from 2009 to 2014 and captured 454 individuals (3.4% of total catch; Table 1). The overall catch of shovelnose sturgeon was highest in August (26.6% of the total catch) and May (21.8% of the total catch). The mean CPUE for shovelnose sturgeon captured by DC electrofishing was 93.8 fish/hour (SE = 7.25) and 76.5 fish/hour (SE = 5.6) for drift nets. There were no patterns of decline in relative abundance (CPUE) across the years for either gear type.

3.1 | Population and sex-specific demographics

Shovelnose sturgeon ranged from 61 to 910 mm FL. Overall, the mean FL was 668 mm (SE = 0.6). Different gear types captured fish of different lengths (Kruskal-Wallis test: χ^2 = 340.64, df = 6, p < 0.0001; Table 1). On average, AC electrofishing selected for the largest fish (mean = 681 mm FL, SE = 13.1), followed by drift nets (mean = 675 mm FL, SE = 0.9), and the benthic electrified trawl selected for the smallest fish (mean = 549 mm, SE = 29; Table 1). Overall, the size structure was negatively skewed (Figure 1). The overall size structure indices were 100 for quality-size fish (PSD; ≥380 mm FL), 98 for preferred-size fish (PSD-P; ≥510 mm FL), 71 for memorable-size fish (PSD-M; ≥640 mm FL), and 1 for trophy-size fish (PSD-T; ≥810 mm FL). There was a significant decrease in both the PSD-M (range = 65–76; $F_{1,8}$ = 5.64, R^2 = 0.41, p = 0.045) and mean FL over time (range = 650.3–675.4 mm; $F_{1,8}$ = 8.0, R^2 = 0.5, p = 0.02; Figure 2). However, there were no significant trends in PSD or PSD-P over time. The mean overall wet weight of Shovelnose Sturgeon was 1,193 g (SE = 3.4). The mean and median W_r of shovelnose sturgeon was 87 (SE = 0.1) and 86, respectively. We also saw a linear decrease in the overall W_r over time (W_r range = 80–91; $F_{1,8}$ = 55.16, R^2 = 0.86, p < 0.001).

TABLE 1 Gear-specific catch of shovelnose sturgeon in the Wabash River, Illinois, 2007–2016. Catch does not represent true efficiency because some gears were used more often than others. Mean FLs without a letter in common are significantly different (ANOVA, p < 0.05)

Gear	Number of fish	Percentage of total catch	Average FL (mm)
AC electrofishing	19	0.14	680.74 a
Drifting gill net	5,160	39.18	675.16 a
Hoop net	292	2.22	672.38 a
DC electrofishing	7,175	54.48	665.94 a
Trotline	27	0.21	640.85 ab
Gill net	454	3.45	621.76 b
Benthic Trawl	43	0.33	532.84 c

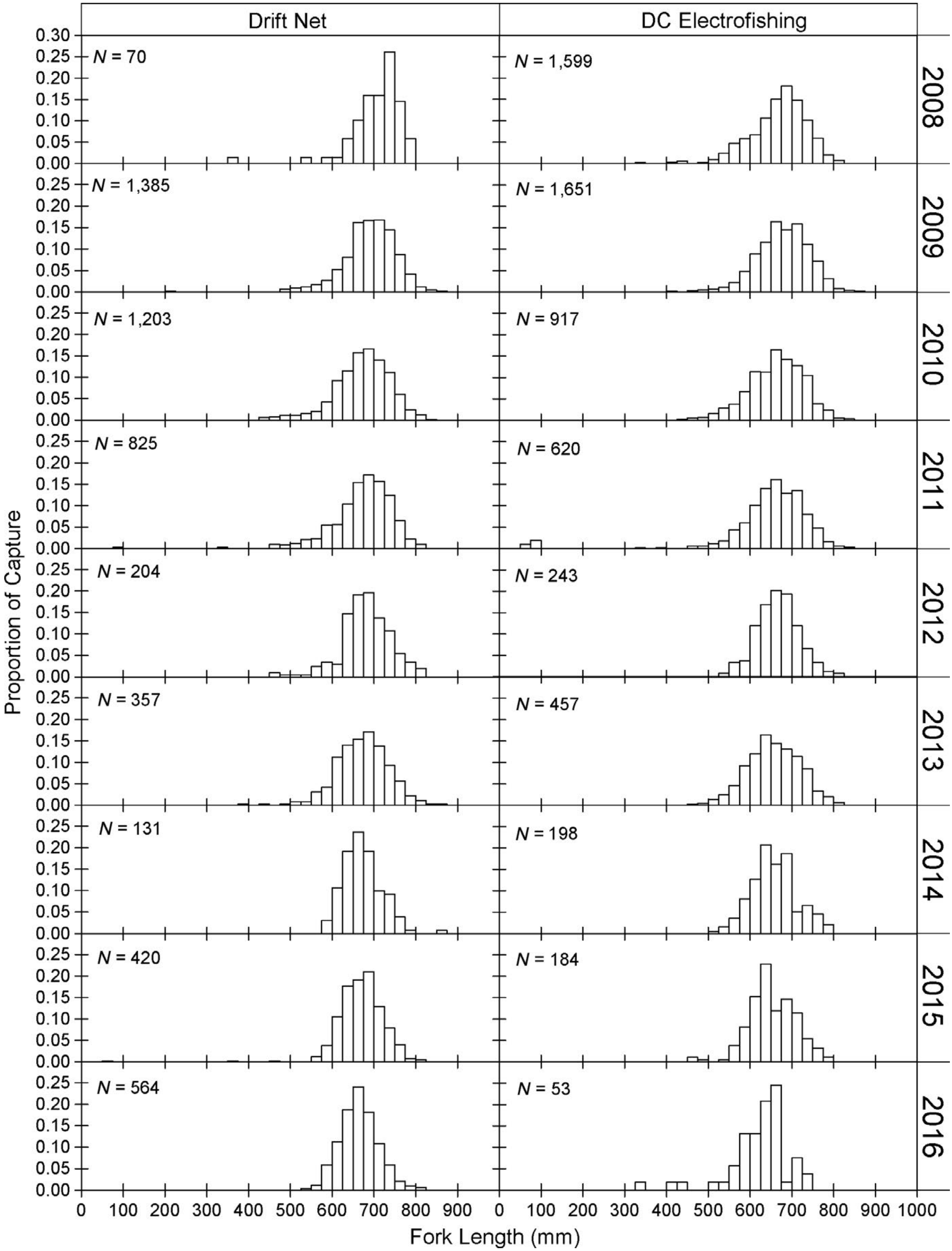

FIGURE 1 Length frequency histograms (FL, mm) of shovelnose sturgeon sampled by drift nets and DC electrofishing in the Wabash River, 2008–2016 (*N* = number of fish)

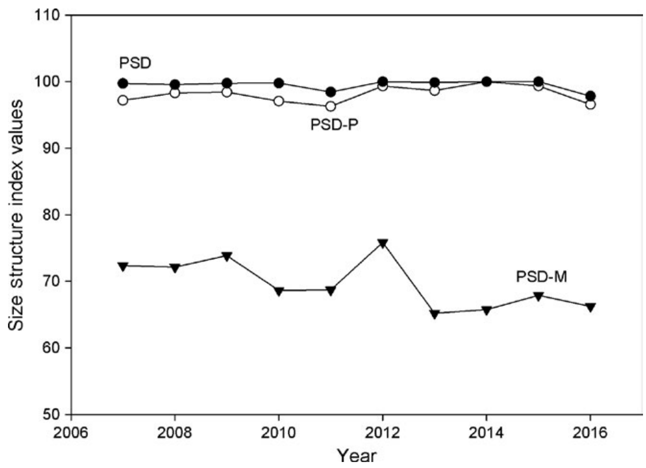

FIGURE 2 Size structure index values for shovelnose sturgeon in the Wabash River, 2007–2016 (PSD = proportional size distribution, percentage of fish ≥ 380 mm; PSD-P = percentage of preferred-length fish [≥510 mm]; PSD-*M* = percentage of memorable-length fish [≥640 mm]). There was a significant decrease in PSD-M over time ($F_{1,8}$ = 5.64, R^2 = 0.41, *p* = 0.045)

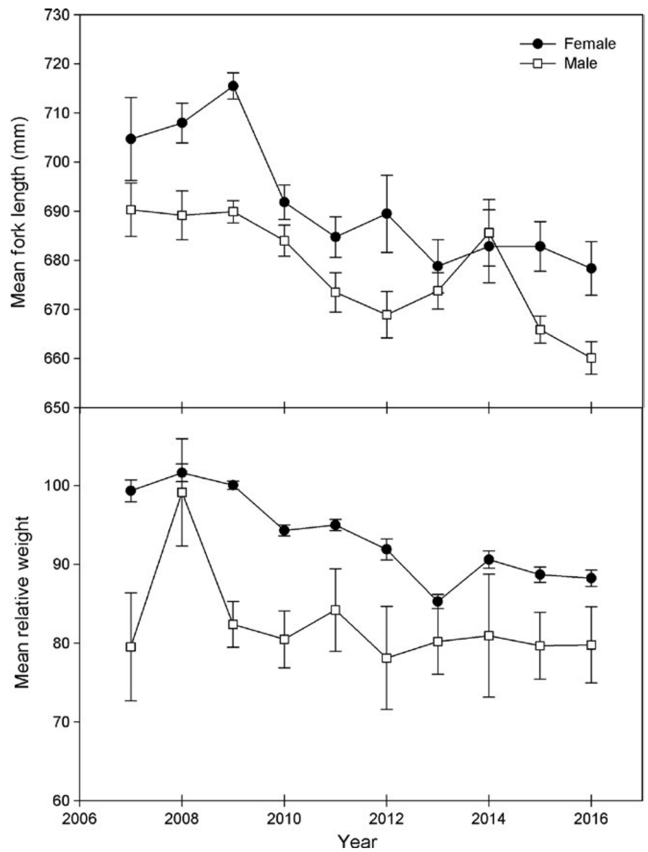

FIGURE 3 Mean FL (± SE) and relative weight (W_r ± SE) of male and female shovelnose sturgeon in the Wabash River, 2007–2016. There was a significant decrease in mean FL for both males and females (Male, $F_{1,8}$ = 16.0, R^2 = 0.62, *p* = 0.004; Female, $F_{1,8}$ = 22.3, R^2 = 0.68, *p* = 0.001) and a significant decrease in W_r for females in the population (Female W_r: $F_{1,8}$ = 21.31, R^2 = 0.69, *p* = 0.002)

Upon defining sex-specific demographics, we found that the mean FL declined in both males and females over time (Male, $F_{1,8}$ = 16.0, R^2 = 0.62, *p* = 0.004; Female, $F_{1,8}$ = 22.3, R^2 = 0.68, *p* = 0.001; Figure 3). We also saw a significant decline in the mean W_r of females, but not in males (Female W_r: $F_{1,8}$ = 21.31, R^2 = 0.69, *p* = 0.002; Figure 3). Mature, gravid females (FIV) ranged from 525 mm FL to 868 mm FL with a mean FL of 697 mm. FIV females in the 25th percentile for FL represents the size-at-maturity for females within the Wabash River; when plotted across the past decade, we saw a significant decline in the average size-at-maturity ($F_{1,8}$ = 25.79, *p* < 0.001); Figure 4).

3.2 | Age, growth, and mortality

The precision of age estimates for shovelnose sturgeon across each subsampled 25 mm FL group (575–725 mm FL) was variable (CV range = 3.8%–10.9%, mean = 8.0%). Overall, exact agreement between readers was 45.6%. Further, agreement between readers within 1 year was 70% and within 2 years was 82.4%. Average percent error in age estimates between readers was 5.4%, with an overall CV of 7.7%. The age structure of shovelnose sturgeon in 2016 was based on drift net sampling and was comprised of fish from 19 age-classes ranging from age 3 to age 26. Ages 5 and 22–25 were not represented (Figure 5). The frequency of fish in each age-class increased through age 13, suggesting that shovelnose sturgeon did not fully recruit to the sampling gear until this age. The age structure for shovelnose sturgeon in 2013 was based on DC electrofishing. It comprised of 23 age classes between 0 and 25 years old and had a modal age of 10 (Figure 5). The mean age (13) was the same for both years, but the age frequency distributions are significantly different with a narrowing of the distribution in 2016 (KS-test: *D* = 0.125, *p* = 0.004; 2013: Kurtosis = 0.39, Skewness = 0.17; 2016: Kurtosis = 1.9, Skewness = 0.465).

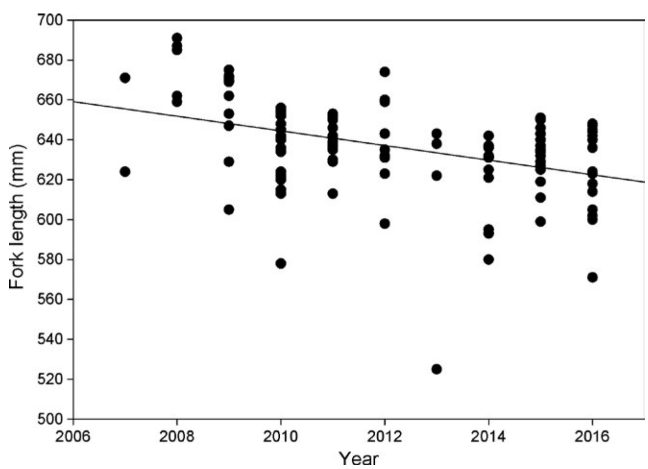

FIGURE 4 Gravid, FIV female shovelnose sturgeon in the 25th percentile of fork length ranges for each year (2007–2016), in the Wabash River. The 25th percentile of FLs for gravid FIV females represents the average size-at-maturity. There was a significant linear decrease in size-at-maturity for females over time ($F_{1,8}$ = 25.79, *p* < 0.001).

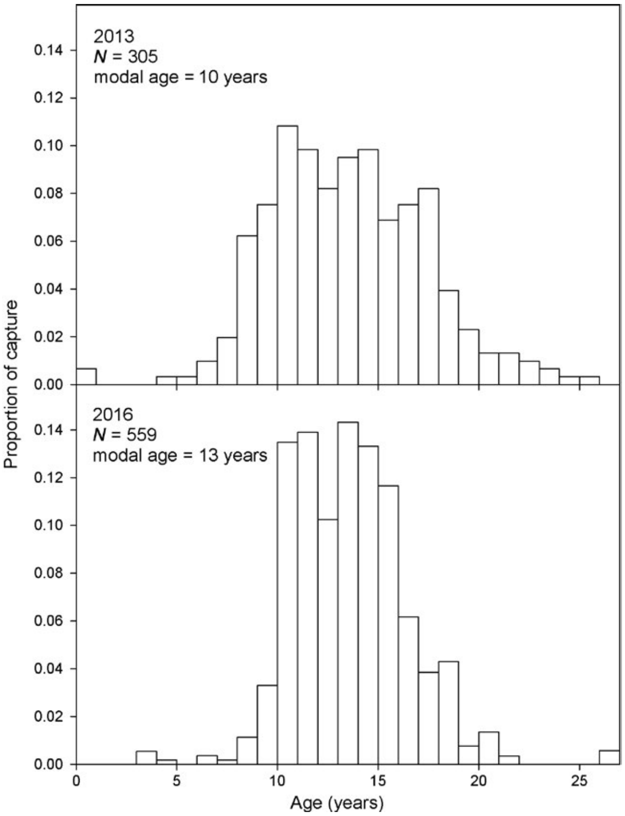

FIGURE 5 Age frequency diagrams of shovelnose sturgeon sampled from the LWR in 2013 with DC electrofishing and from the UWR in 2016 with drift nets. Age estimates were extrapolated from a length-stratified subsample (2013: N = 305, modal age = 10 years; 2016: N = 559, modal age = 13 years). The age frequency distributions were significantly different (KS-test: D = 0.125, p = 0.004)

The von Bertalanffy growth model was predicted for two sampling years to determine if any changes in growth had occurred. The 2013 sampling season predicted that fish grew at a rate of 53.4 mm/year up to age 8, at a rate of 17.5 mm/year from ages 9 to 16, and reached an L_∞ of 771 mm FL (Figure 6). Individuals greater than age 17 experienced average growth rates of 5.3 mm/year. The von Bertalanffy growth function for the 2016 sampling year was based on all gears. It predicted that shovelnose sturgeon grew at a rate of 64.6 mm/year up through age 8, at a rate of 15.0 mm/year from ages 9 to age 16, and reached an L_∞ of 732 mm (Figure 6). Older individuals (>17 years) grew at a rate of 3.0 mm/year. Although the parameters differed between the two sampling years, there was no statistical difference in the two growth models. The most parsimonious model was selected based on BIC value and was a combined model with no difference in parameters (combined model of best fit: $L_t = 752 * [1\text{-}e^{-0.16\ (t+0.88)}]$). The total instantaneous mortality rates calculated from the 2016 sampling season was 0.42 (95% confidence interval [CI] = 0.31–0.53) and 0.40 (95% CI = 0.33–0.47) for the catch curve analysis and Chapman-Robson method, respectively. The total annual mortality rate (A) estimated for 2016 was similar between methods at 0.34 (95% CI = 0.27–0.41) for weighted

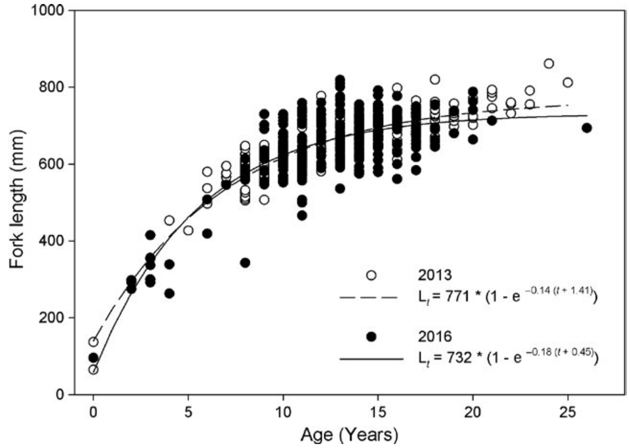

FIGURE 6 Fork length at age of shovelnose sturgeon sampled in the 2013 season in the lower Wabash River and sampled in the 2016 season in the entire Wabash River. The two lines and equations represent the fitted von Bertalanffy growth functions for each sampling year with no statistical difference found between years (L_t = FL at age t)

linear regression of the catch curve and 0.33 (95% CI = 0.28–0.38) for Chapman-Robson method.

3.3 | Commercial harvest

From 2007 to 2016, approximately 16,403 kg of shovelnose sturgeon roe from 57,449 fish was harvested from the Wabash River as reported by Illinois commercial roe harvest permit holders, with an average of 275.6 g of roe-per-fish. Reports from Indiana roe harvesters were much lower with 649 kg of roe harvested from 3,120 fish in the 2011–2015 harvest seasons, an average of 182.8 g of roe-per-fish. The difference in average roe-per-fish between states is likely due to differences in requirements for reporting. Indiana fishermen report egg weight only, while Illinois fishermen report the entire ovary weight, which includes fat and tissue weight. In 2013, the IN-DNR reported an average of 237 g of roe-per-fish when they sacrificed several FIV females and weighed the entire ovary of the fish. The average roe-per-fish reported in both states declined similarly across the years (IL: $F_{1,8}$ = 21.71, R^2 = 0.70, p = 0.002; IN: $F_{1,3}$ = 60.63, R^2 = 0.94, p = 0.004; Figure 7). We found that female relative weight was strongly correlated with roe-per-fish (Pearson's r = 0.921, N = 10, p < 0.001).

Two major commercial harvest regulation changes occurred between 2007 and 2016, including the SOA in 2010 and the 2014 ban on hoop net leads in the Wabash River. Although the greatest commercial catch was reported in 2007 and 2008, there was an 85% increase in the number of fish harvested in 2010 when SOA took effect, compared to 2009. In addition, there was a 53% increase in the price per pound of caviar between 2009 and 2010. Following the 2014 ban on leads, we saw a reduced number of Illinois commercial roe harvest permits being sold, from 35 permits sold in each of the 2007–2014 harvest seasons, then down to 21 permits sold in 2015 and 20 permits in 2016. On average, the total weight of roe reported

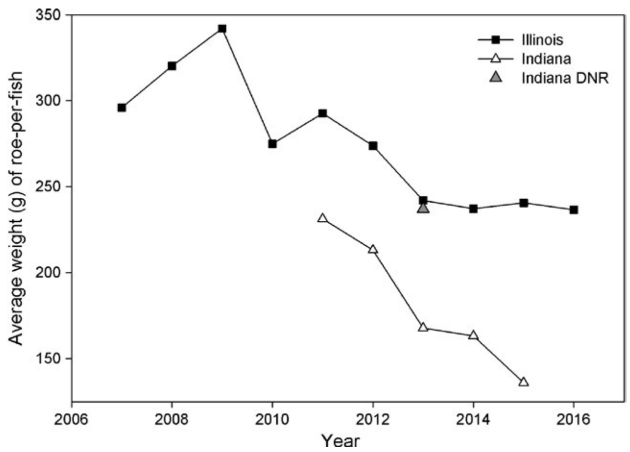

FIGURE 7 Average weight (g) of roe-per-fish for shovelnose sturgeon harvested in the Wabash River as reported by Illinois roe harvesters (2007–2016), Indiana roe harvesters (2011–2015), and from sacrificed FIV females collected by Indiana Department of Natural Resources (IN-DNR) in the 2013 sampling season. Illinois roe harvest and Indiana DNR averages include entire ovary weight. Indiana roe harvest average includes egg weight only. Linear decline in roe-per-fish was significant (IL: $F_{1,8}$ = 21.71, R^2 = 0.70, p = 0.002; IN: $F_{1,3}$ = 60.63, R^2 = 0.94, p = 0.004)

in Illinois before the lead ban (2007–2013) was 2,091 kg per year, and that was significantly reduced to 588.8 kg per year following the ban (2014–2016; $F_{1,8}$ = 10.5, p = 0.01).

4 | DISCUSSION

The shovelnose sturgeon in the Wabash River has several characteristics of a healthy population; however, many of the dynamics have shown a downward trend, indicating instability in the population. In our study, the size distribution was skewed toward large fish (i.e., PSD = 97, PSD-M = 71). This is not unique to our study, as most shovelnose sturgeon populations are found to be predominated by large fish (Kennedy, Daugherty, Sutton, & Fisher, 2007; Koch, Quist, Pierce, Hansen, & Steuck, 2009; Nepal KC et al., 2015; Quist et al., 1998; Roseman, Boase, Kennedy, Craig, & Soper, 2011). The lack of small fish in our sample could be explained by low recruitment over the past several years, though it is more likely a result of size-selection associated with sampling gears. The mean FL (668 mm), maximum FL (910 mm), and L_∞ (732 mm) values reported in this study are within the ranges reported for populations in other systems (maximum FL = 693–996 mm; L_∞ = 660–858 mm FL; (Everett, Scarnecchia, Power, & Williams, 2003; Koch et al., 2009; Morrow, Kirk, Killgore, & George, 1998; Quist et al., 2002; Tripp, Colombo, et al., 2009). The L_∞ reported in this study was lower than what was previously estimated in the Wabash River (LWR L_∞ = 771, UWR L_∞ = 825; Kennedy et al., 2007; Nepal KC et al., 2015). Additionally, shovelnose sturgeon showed good condition with the overall mean W_r (87), falling within the target range (80–90) suggested by Quist et al. (1998). Longevity, reported as the maximum age (age 26), was also within the range previously reported in literature (maximum age = 16–43; Everett et al., 2003; Kennedy et al., 2007; Morrow et al., 1998; Nepal KC et al., 2015; Tripp, Phelps, et al., 2009). There were very few individuals captured over age 20.

Monitoring of populations across time is important for the management and conservation of this species (Phelps et al., 2016). Over the past decade, the commercial harvest of shovelnose sturgeon flesh has increased sharply in the Wabash River (Nepal KC et al., 2015). We observed decline in mean FL and W_r when calculating sex-specific demographics. We found that both males and females show declines in mean FL over time; however, only females show a decline of relative weight condition over time. A decline in condition for females could be the result of fishing pressure placed on large females by the commercial market. Due to the coupling of declines in condition for females and mean fork length for all fish over the past decade, we suspect that slower-growing fish are being selected for in the population as an effect of the harvest pressure that is placed on large females. In addition, we also consider that this decline in condition could be caused by declining reproductive output. Fecundity is known to be strongly related to both wet weight and FL (Kennedy et al., 2006).

We used the FL of FIV females in the 25th percentile as an estimate of size-at-maturity. In doing this, we could report the changes that have occurred in our study over time. We found that the size-at-maturity has decreased over the past decade. This might suggest that females are becoming mature earlier in life. We also see evidence of size-selectivity for early maturation in the decreasing FL and relative weight of females over time. In heavily exploited populations, few large, late-maturing fish are likely to persist, whereas, small, early maturing fish are likely to participate in breeding before they become vulnerable to the fishing gear. The results of this size-selectivity for early maturation could lead to reduced reproductive traits like egg size and length of spawning season (Trippel, 1995). In fact, our data supports evidence of a reduction in egg size, as indicated by a significant decline in weight of roe-per-fish reported by roe harvest permit holders. We believe that size-selectivity for early maturation is occurring for shovelnose sturgeon in the Wabash River, as evident by decreased body size, decreased size-at-maturation, and declines in average weight of roe-per-fish. Because body size affects fecundity and reproductive success, we might expect that future recruitment will also be affected by this size-selection.

The kurtosis of the age frequency distribution for shovelnose sturgeon has notably changed over time. The age structure found in 2016 is truncated when compared to the more diverse age distribution found in 2013. The presence of fewer old age classes may have negative effects on the recruitment of shovelnose sturgeon in the Wabash River, as has been demonstrated for several fish species (Secor, 2000; Shelton et al., 2015). Such loss of age class diversity, particularly the loss of larger, older individuals, is likely induced by increased harvest in recent years. A possibility exists that the truncation in age distribution may be a result of different selectivities of the two sampling gears used to collect fish in 2013 versus 2016. However, drift nets (used in 2016) captured larger individuals on average than DC electrofishing (used in 2013). In addition, both gears showed similar declines in the average size of fish collected across time, suggesting that the observed trends are not gear-dependent.

Although we are unable to tease apart the contribution of harvest to our estimated annual mortality rates, it is very concerning from a management perspective that the observed mortality rates in this population have risen so dramatically after just three years of monitoring. Our observed annual mortality rate (33%–34%) in 2016 was much higher than rates previously estimated for the LWR, at 21% in 2013 (Nepal KC et al., 2015), and at 22% in the UWR (Kennedy et al., 2007). The total annual mortality for shovelnose sturgeon in the Wabash River is at the high end of estimated values found in other commercially exploited populations (e.g., lower Mississippi River, 20%: Morrow et al., 1998; lower Missouri River, 20%: Quist et al., 2002; upper Mississippi River, 37%: Colombo, Garvey, & Wills, 2007). Mortality rates are often influenced by anthropogenic forces like harvest and waterway regulation (Hamel et al., 2015; Quist et al., 2002). The Wabash River is largely unaltered. Considering this, we might expect lower rates of natural mortality in the Wabash River, and attribute the increase in total annual mortality to harvest.

For shovelnose sturgeon in the Wabash River many parameters are still within a healthy range, yet we are concerned with the declines in these features over time. When coupled with increased mortality estimates and a truncated age distribution, it is unlikely that this population will be resilient to increased harvest efforts or environmental disturbances. Considering the popularity and high price of caviar, commercial pressure will likely persist in the Wabash River. Managers need to take into consideration the implications of this study and continue proper monitoring techniques to ensure that shovelnose sturgeon harvest remains sustainable in the Wabash River.

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