2018

Evaluation and demographic response of the shovelnose sturgeon commercial caviar fishery in the Wabash River

Jessica L. Thornton
Eastern Illinois University

The Graduate School
EASTERN ILLINOIS UNIVERSITY

Thesis Maintenance and Reproduction Certificate

FOR: Graduate Candidates Completing Theses in Partial Fulfillment of the Degree
Graduate Faculty Advisors Directing the Theses

RE: Preservation, Reproduction, and Distribution of Thesis Research

Preserving, reproducing, and distributing thesis research is an important part of Booth Library's responsibility to provide access to scholarship. In order to further this goal, Booth Library makes all graduate theses completed as part of a degree program at Eastern Illinois University available for personal study, research, and other not-for-profit educational purposes. Under 17 U.S.C. § 108, the library may reproduce and distribute a copy without infringing on copyright; however, professional courtesy dictates that permission be requested from the author before doing so.

Your signatures affirm the following:

- The graduate candidate is the author of this thesis.

- The graduate candidate retains the copyright and intellectual property rights associated with the original research, creative activity, and intellectual or artistic content of the thesis.

- The graduate candidate certifies her/his compliance with federal copyright law (Title 17 of the U. S. Code) and her/his right to authorize reproduction and distribution of all copyrighted materials included in this thesis.

- The graduate candidate in consultation with the faculty advisor grants Booth Library the nonexclusive, perpetual right to make copies of the thesis freely and publicly available without restriction, by means of any current or successive technology, including but not limited to photocopying, microfilm, digitization, or internet.

- The graduate candidate acknowledges that by depositing her/his thesis with Booth Library, her/his work is available for viewing by the public and may be borrowed through the library's circulation and interlibrary loan departments, or accessed electronically. The graduate candidate acknowledges this policy by indicating in the following manner:

__X__ Yes, I wish to make accessible this thesis for viewing by the public

______ No, I wish to quarantine the thesis temporarily and have included the ***Thesis Withholding Request Form***

- The graduate candidate waives the confidentiality provisions of the Family Educational Rights and Privacy Act (FERPA) (20 U. S. C. § 1232g; 34 CFR Part 99) with respect to the contents of the thesis and with respect to information concerning authorship of the thesis, including name and status as a student at Eastern Illinois University. I have conferred with my graduate faculty advisor. My signature below indicates that I have read and agree with the above statements, and hereby give my permission to allow Booth Library to reproduce and distribute my adviser's signature indicates concurrence to

Jessica L Thornton
Printed Name

Biological Sciences
Graduate Degree Program

Robert Colombo
Printed Name

07/8/18
Date

Please submit in duplicate.

Evaluation and demographic response of the shovelnose sturgeon commercial caviar fishery in the Wabash River

(TITLE)

BY

Jessica L. Thornton

THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

Master of Science

IN THE GRADUATE SCHOOL, EASTERN ILLINOIS UNIVERSITY
CHARLESTON, ILLINOIS

2018

YEAR

I HEREBY RECOMMEND THAT THIS THESIS BE ACCEPTED AS FULFILLING
THIS PART OF THE GRADUATE DEGREE CITED ABOVE

7/26/18
THESIS COMMITTEE CHAIR DATE

7/26/18
CHAIR'S DESIGNEE DATE

7/26/18
THESIS COMMITTEE DATE

7/26/18
THESIS COMMITTEE DATE

THESIS COMMITTEE MEMBER DATE

THESIS COMMITTEE MEMBER DATE

EVALUATION AND DEMOGRAPHIC RESPONSE OF THE SHOVELNOSE STURGEON COMMERCIAL CAVIAR FISHERY IN THE WABASH RIVER

by

Jessica L. Thornton

B.S. Eastern Illinois University

A Thesis

Submitted for the Requirements for the Degree of

Master of Science

Department of Biological Sciences

Eastern Illinois University

August 2018

ACKNOWLEDGEMENTS

First, I would like to thank my behind-the-scenes support. Thank you to my wonderful mother and father, Sharron and Rick Thornton, for encouraging and supporting me throughout this process. Thank you to my partner, Lucas Weir, for your continued encouragement and love. You all have made this process a little easier for me in one way or another.

I would also like to thank the Fisheries and Aquatic Research Team, I will forever miss being a part of this fun, goofy, and hard-working team. A big thanks to Cassi Moody-Carpenter for keeping this project on track and offering guidance and insightful advice. Thanks to all the technicians, interns, and graduate students who helped me in the field and lab, and who were always willing to commune at Taco Tuesday.

I am thankful to Illinois Department of Natural Resources (IL-DNR) for supporting this project with funds from the Federal Aid in Sport Fish Restoration Act. In addition, I appreciate the work of IL-DNR for years of shovelnose sturgeon monitoring on the lower Wabash River. I am also indebted to the Indiana Department of Natural Resources (IN-DNR) biologist, Craig Jansen, who provided many years of upper river monitoring data and keen insight on the outcomes of my project. Without your data and assistance, this project would not have been possible.

I have much appreciation for my research advisor, Dr. Robert E. Colombo. He has challenged me, but never beyond reason. I am a better scientist for it. Thank you for recognizing when I needed either a constructive criticism or a pep-talk. I also wish to thank my committee members Drs. Anabela Maia and Eric Bollinger for their patience, support, and suggestions.

ABSTRACT

Shovelnose sturgeon (*Scaphirhynchus platorynchus* Rafinesque) are considered one of the last commercially viable options for sturgeon roe harvest. Due to the collapse of several marine sturgeon fisheries and the Similarity of Appearances provision which protect shovelnose sturgeon in only a part of their range, the caviar fishery in the Wabash River remains an important point of supply for this lucrative natural resource. In this thesis, I presented an evaluation of the shovelnose sturgeon commercial caviar fishery in the Wabash River. More specifically, I described the demographic response of this population to continued exploitation over a 10-year period. Additionally, I presented the results of roe yield modeling and recommend new management regulations. This study highlights declines in shovelnose sturgeon population dynamics like size, condition, size and age-at-maturity, and reproductive output of females. Furthermore, I found evidence of a truncated age distribution and greater mortality rates in the population. In the second chapter of this study, I found further evidence of harvest-induced female reproductive dynamics and found that the sturgeon roe fishery is experiencing both growth and recruitment overfishing at the current minimum length limit (635-mm) and estimated levels of exploitation. These findings have highlighted the problems concerning the sustainability of this roe fishery. Changes in management regulations are suggested and future policies should remain conservative to preserve this fishery.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Figure 6 Predicted shovelnose sturgeon roe yields per 1,000 recruits for three levels of conditional mortality [*cm* = 5% (a), 10% (b), and 20% (c)] and three minimum length limits (mm; MLL) in the Wabash River. Vertical lines denote range of current level of harvest. Note that the y-axis differs among graphs a, b, and c, and that Figure 6 (a) is the same graph as above in Figure 4 (b).

Figure 7 Predicted shovelnose sturgeon spawning potential ratios (SPR) for three levels of conditional natural mortality [*cm* = 5% (a), 10% (b), and 20% (c)] and three minimum length limits (MLL; 635-mm, 660-mm, and 685-mm) in the Wabash River. Horizontal dashed lines represent the sustainable SPR threshold of 40%; horizontal dotted line represents critical SPR threshold of 30%. Vertical lines denote the range of current level of harvest.

MONITORING DEMOGRAPHICS OF A COMMERCIALLY EXPLOITED POPULATION OF SHOVELNOSE STURGEON IN THE WABASH RIVER, ILLINOIS/INDIANA, USA

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, I 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.

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 kilometers 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. I assessed size structure and condition trends, quantified age structure, estimated growth and mortality, and defined sex-specific demographics. I 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.

METHODS

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, I 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 = 3500-4500 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 minutes per site with two netters. DC electrofishing was conducted by the IN-DNR across all years of the study and consisted of three 20-minute 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 minutes. 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.

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.

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 (≤80x 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.

Commercial harvest

I 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 were compiled from the harvest season beginning in 2007 through 2016. I were limited by the assessments I could perform because requirements in reporting commercial fishing data have changed over time. In addition, I have no estimate of effort put forth by the commercial fishery. Therefore, I am limited in my ability to determine whether increase in catch was due to increased effort or increased catchability. Indiana commercial data are only available for the 2011-2015 harvest seasons.

Data analysis

All statistical analyses were performed in R version 3.4.3 (R Development Core Team, 2017). For the analyses, I pooled data from all agencies and sampling locations within the Wabash River. I 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, I 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

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

and the relative size distribution was calculated as

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

with a preferred FL of 510 mm, a memorable FL of 640 mm, and a trophy FL of 810 mm (Quist, Guy, & Braaten, 1998). I 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, I calculated the mean relative weight (W_r; Anderson and 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):

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

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

I plotted length-at-age for all age-classes; the average percent error and the CV ($100 \times [\text{SD}/\text{mean}]$) 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).

I 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:

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

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

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.

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: $\chi^2 = 340.64$, 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. I also saw a linear decrease in the overall W_r over time (W_r range = 80-91; $F_{1,8} = 55.16$, $R^2 = 0.86$, $P < 0.001$).

Upon defining sex-specific demographics, I 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). I 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, I saw a significant decline in the average size-at-maturity ($F_{1,8} = 25.79$, $P < 0.001$); Figure 4).

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).

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

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). I 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, I 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 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; $F_{1,8} = 10.5$, $P = 0.01$).

DISCUSSION

The population of 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 this study, the size distribution was skewed toward large fish (i.e., PSD = 97, PSD-M = 71). This is not unique to this 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 the 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). I observed decline in mean FL and W_r when calculating sex-specific demographics. I 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, I 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, I 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).

I used the fork lengths of FIV females in the 25th percentile as an estimate of size-at-maturity. In doing this, I could report the changes that have occurred in this study over time. I found that the size-at-maturity has decreased over the past decade. This might suggest that females are becoming mature earlier in life. I 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, those data support 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. I 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, I 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 I am unable to tease apart the contribution of harvest to the 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. The 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 et al. 2007b). 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, I 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 I am 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.

LITERATURE CITED

Anderson, R. O., & Neumann, R. M. (1996). Length, weight, and associated structural indices. In *Fisheries Techniques, 2nd edition* (pp. 447–482). Bethesda, Maryland: American Fisheries Society.

Bailey, R. M., & Cross, F. B. (1954). River sturgeons of the American genus *Scaphirhynchus*: characters, distribution, and synonymy. *Papers from the Michigan Academy of Science, Arts, and Letters*, *39*, 169–208.

Billard, R., & Lecointre, G. (2001). Biology and conservation of sturgeon and paddlefish. *Reviews in Fish Biology and Fisheries*, *10*, 355–392.

Boreman, J. (1997). Sensitivity of North American sturgeon and paddlefish to fishing mortality. *Environmental Biology of Fishes*, *48*, 399–405.

Colombo, R. E., Garvey, J. E., Jackson, N. D., Brooks, R. C., Herzog, D. P., Hrabik, R. A., & Spier, T. W. (2007). Harvest of Mississippi River sturgeon drives abundance and reproductive success: A harbinger of collapse? *Journal of Applied Ichthyology*, *23*(4), 444–451. https://doi.org/10.1111/j.1439-0426.2007.00899.x

Colombo, R. E., Garvey, J. E., & Wills, P. S. (2007). Gonadal development and sex-specific demographics of the shovelnose sturgeon in the Middle Mississippi River. *Journal of Applied Ichthyology*, *23*, 420-427. https://doi.org/10.1111/j.1439-0426.2007.00885.x

Everett, S. R., Scarnecchia, D. L., Power, G. J., & Williams, C. J. (2003). Comparison of age and growth of shovelnose sturgeon in the Missouri and Yellowstone Rivers. *North American Journal of Fisheries Management*, *23*(1), 230–240. https://doi.org/Doi 10.1577/1548-8675(2003)023<0230:Coaago>2.0.Co;2

Guy, C. S., Neumann, R. M., Willis, D. W., & Anderson, R. O. (2007). Proportional size distribution (PSD): a furthur refinement of population size structure index terminology. *Fisheries*, *32*, 348.

Hamel, M. J., Pegg, M. A., Goforth, R. R., Phelps, Q. E., Steffensen, K. D., Hammen, J. J., & Rugg, M. L. (2015). Range-wide age and growth characteristics of shovelnose sturgeon from mark–recapture data: implications for conservation and management. *Canadian Journal of Fisheries and Aquatic Sciences*, *72*(September 2014), 71–82. https://doi.org/10.1139/cjfas-2014-0238

Hintz, W. D., & Garvey, J. E. (2012). Considering a species-loss domino-effect before endangered species legislation and protected area implementation. *Biodiversity and Conservation*, *21*(8), 2017–2027. https://doi.org/10.1007/s10531-012-0293-3

Keenlyne, K. D. (1997). Life history and status of the shovelnose sturgeon, *Scaphirhynchus platorynchus*. *Environmental Biology of Fishes*, *48*, 291–298.

Kennedy, A. J., Daugherty, D. J., Sutton, T. M., & Fisher, B. E. (2007). Population characteristics of shovelnose sturgeon in the Upper Wabash River, Indiana. *North*

American Journal of Fisheries Management*, *27*(1), 52–62. https://doi.org/10.1577/M06-038.1

Kennedy, A. J., Sutton, T. M., & Fisher, B. E. (2006). Reproductive biology of female shovelnose sturgeon in the upper Wabash River, Indiana. *Journal of Applied Ichthyology*, *22*(3), 177–182. https://doi.org/10.1111/j.1439-0426.2006.00745.x

Koch, J. D., Quist, M. C., Pierce, C. L., Hansen, K. A., & Steuck, M. J. (2009). Effects of commercial harvest on shovelnose sturgeon populations in the Upper Mississippi River. *North American Journal of Fisheries Management*, *29*(1), 84–100. https://doi.org/Doi 10.1577/M08-115.1

Morrow, J. V, Kirk, J. P., Killgore, K. J., & George, S. G. (1998). Age, growth, and mortality of shovelnose sturgeon in the lower Mississippi River. *North American Journal of Fisheries Management*, *18*(3), 725–730. https://doi.org/10.1577/1548-8675(1998)018<0725:AGAMOS>2.0.CO;2

Nepal KC, V., Colombo, R. E., & Frankland, L. D. (2015). Demographics of Shovelnose Sturgeon in the Lower Wabash River, Illinois. *North American Journal of Fisheries Management*, *35*(4), 835–844. https://doi.org/10.1080/02755947.2015.1052161

Phelps, Q. E., Tripp, S. J., Hamel, M. J., Koch, J. D., Heist, E. J., Garvey, J. E., … Webb, M. A. H. (2016). Status of knowledge of the Shovelnose Sturgeon (*Scaphirhynchus platorynchus*, Rafinesque, 1820). *Journal of Applied Ichthyology*, *32*(Suppl. 1), 249–260.

Pikitch, E. K., Doukakis, P., Lauck, L., Chakrabarty, P., & Erickson, D. L. (2005). Status, trends and management of sturgeon and paddlefish fisheries. *Fish and Fisheries*, *6*(3), 233–265. https://doi.org/10.1111/j.1467-2979.2005.00190.x

Quist, M. C., Guy, C. S., & Braaten, P. J. (1998). Standard weight (Ws) equation and length categories for shovelnose sturgeon. *North American Journal of Fisheries Management*, *18*, 992–997. https://doi.org/10.1577/1548-8675(1998)018<0992:SWWSEA>2.0.CO;2

Quist, M. C., Guy, C. S., & Pegg, M. A. (2002). Potential influence of harvest on shovelnose sturgeon populations in the Missouri River system. *North American Journal of Fisheries Management*, *22*(February 2014), 537–549. https://doi.org/Doi 10.1577/1548-8675(2002)022<0537:Piohos>2.0.Co;2

R Development Core Team. (2017). R version 3.4.3. *The R Project for Statistical Computing*. Vienna.

Ricker, W. E. (1975). Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada*, (191), 401. https://doi.org/10.1038/108070b0

Robson, D. S., & Chapman, D. G. (1961). Catch curves and mortality rates. *Transactions of the American Fisheries Society*, *90*, 181–189.

Roseman, E. F., Boase, J., Kennedy, G. W., Craig, J., & Soper, K. (2011). Adaption of egg and larvae sampling techniques for lake sturgeon and broadcast spawning fishes in a deep river. *Journal of Applied Ichthyology*, *27*(SUPPL. 2), 89–92. https://doi.org/10.1111/j.1439-0426.2011.01828.x

Schwarz, G. (1978). Estimating the Dimension of a Model. *The Annals of Statistics*, *6*(2), 461–464. Retrieved from http://www.jstor.org/

Secor, D. H. (2000). Spawning in the nick of time? Effect of adult demographics on spawning behaviour and recruitment in Chesapeake Bay striped bass. *ICES Journal* *of Marine Science*, *57*(2), 403-411. https://doi.org/10.1006/jmsc.1999.0520

Shelton, A. O., Hutchings, J. A., Waples, R. S., Keith, D. M., Akc, H. R., & Dulvy, N. K. (2015). Maternal age effects on Atlantic cod recruitment and implications for future population trajectories. *ICES Journal of Marine Science, 72*(6), 1769–1778. https://doi.org/10.1093/icesjms/fsv058

Smith, M. W., Then, A. Y., Wor, C., Ralph, G., Pollock, K. H., & Hoenig, J. M. (2012). Recommendations for catch-curve analysis. *North American Journal of Fisheries Management*, *32*(5), 956–967. https://doi.org/10.1080/02755947.2012.711270

Tripp, S. J., Colombo, R. E., & Garvey, J. E. (2009). Declining recruitment and growth of shovelnose sturgeon in the middle Mississippi River: implications for conservation. *Transactions of the American Fisheries Society*, *138*(2), 416–422. https://doi.org/10.1577/T08-024.1

Tripp, S. J., Phelps, Q. E., Colombo, R. E., Garvey, J. E., Burr, B. M., Herzog, D. P., & Hrabik, R. A. (2009). Maturation and reproduction of shovelnose sturgeon in the middle Mississippi River. *North American Journal of Fisheries Management*, *29*(August), 730-. https://doi.org/10.1577/M08-056.1

Trippel, E. A. (1995). Age at maturity as a stress indicator in fisheries. *BioScience*, *45*(11), 759–771. https://doi.org/10.1525/bio.2010.60.10.17

United States Fish and Wildlife Service. (2010). Endangered and threatened wildlife and plants: threatened status for shovelnose sturgeon under the similarity of appearances provisions of the Endangered Species Act. *Federal Regulations*, *75*, 53598.

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 fork lengths (FL) without a letter in common are significantly different (ANOVA, $P<0.05$).

Gear	N	Percentage of total	Average fork length (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

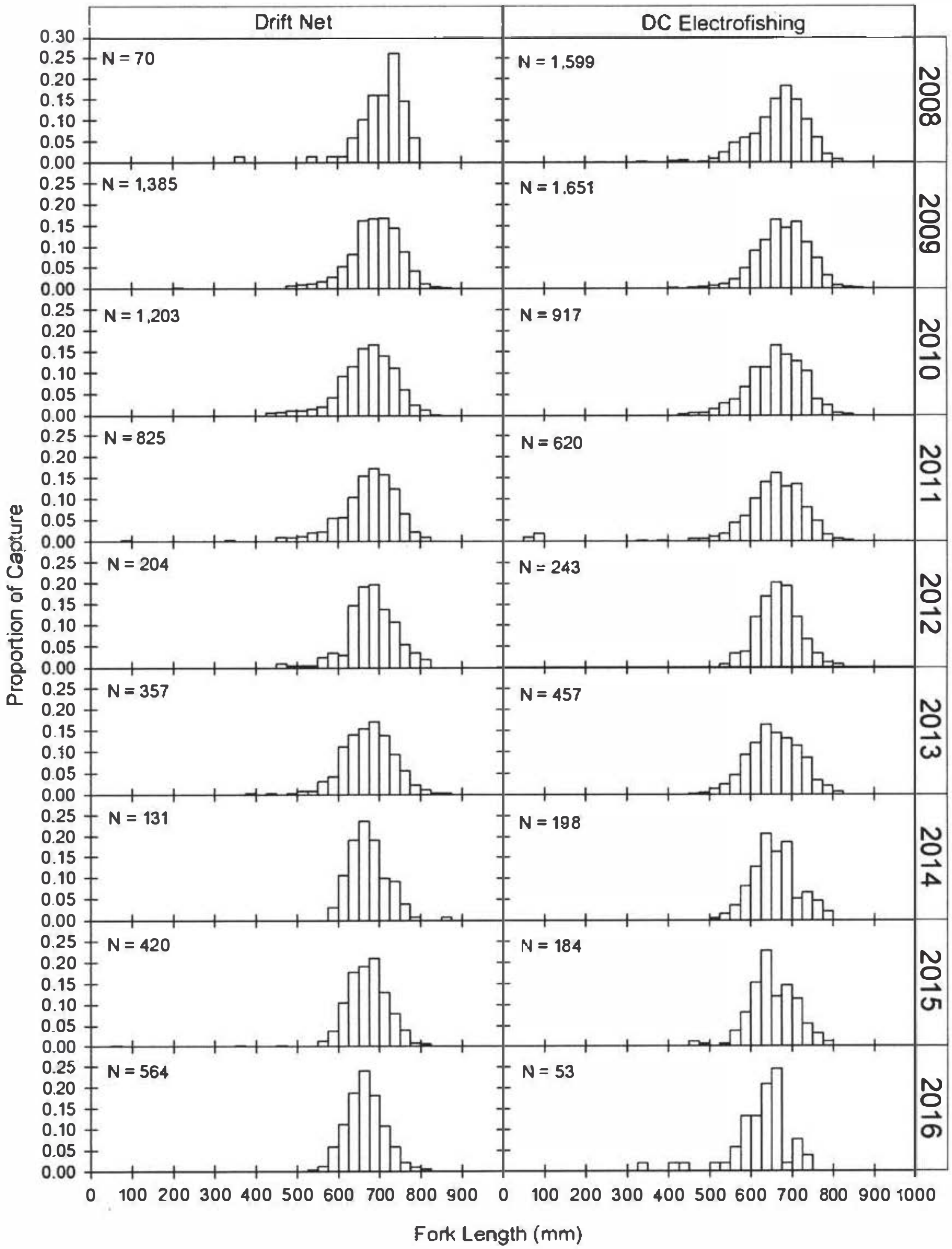

Figure 1. Length frequency histograms (fork length, mm) of shovelnose sturgeon sampled by drift nets and DC electrofishing in the Wabash River, 2008-2016 (*N* = number of fish).

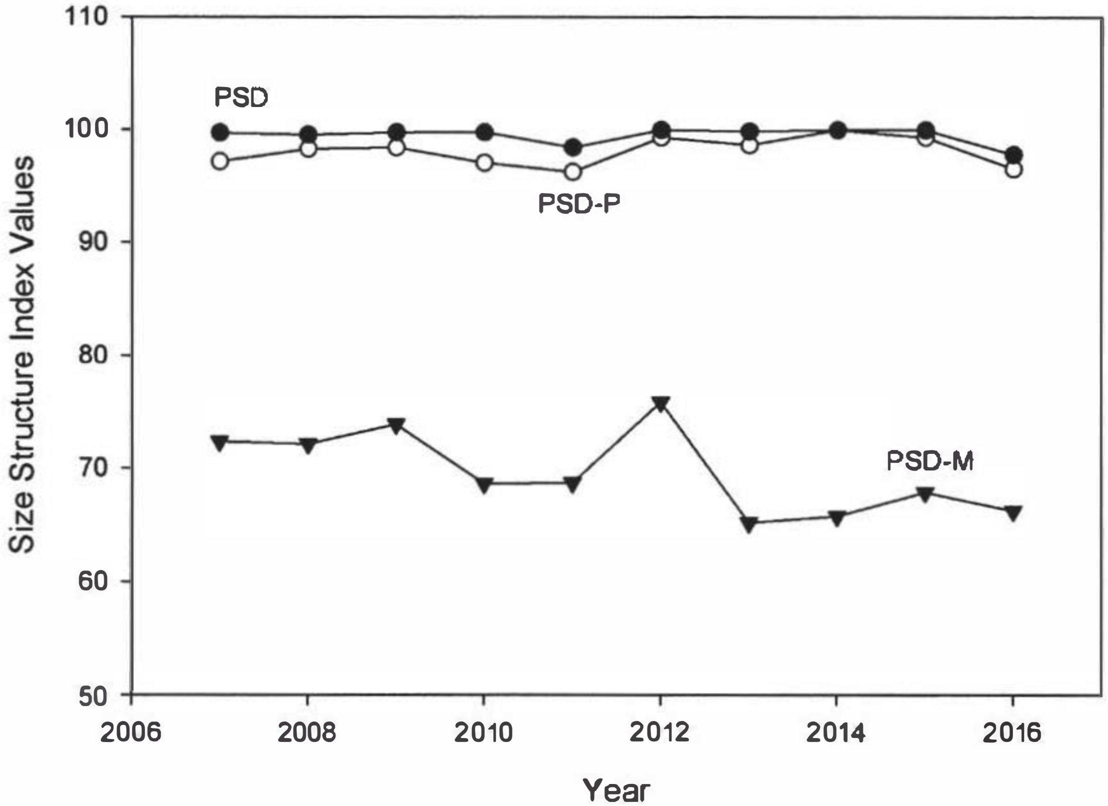

Figure 2. Size structure index values for shovelnose sturgeon in the Wabash River, 2007-2016 (PSD = proportional size distribution, percentage of fish ≥380 mm; PSD-P = percentage of preferred-length fish [≥510 mm]; PSD-M = percentage of memorable-length fish [≥640 mm]). There was a significant decrease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

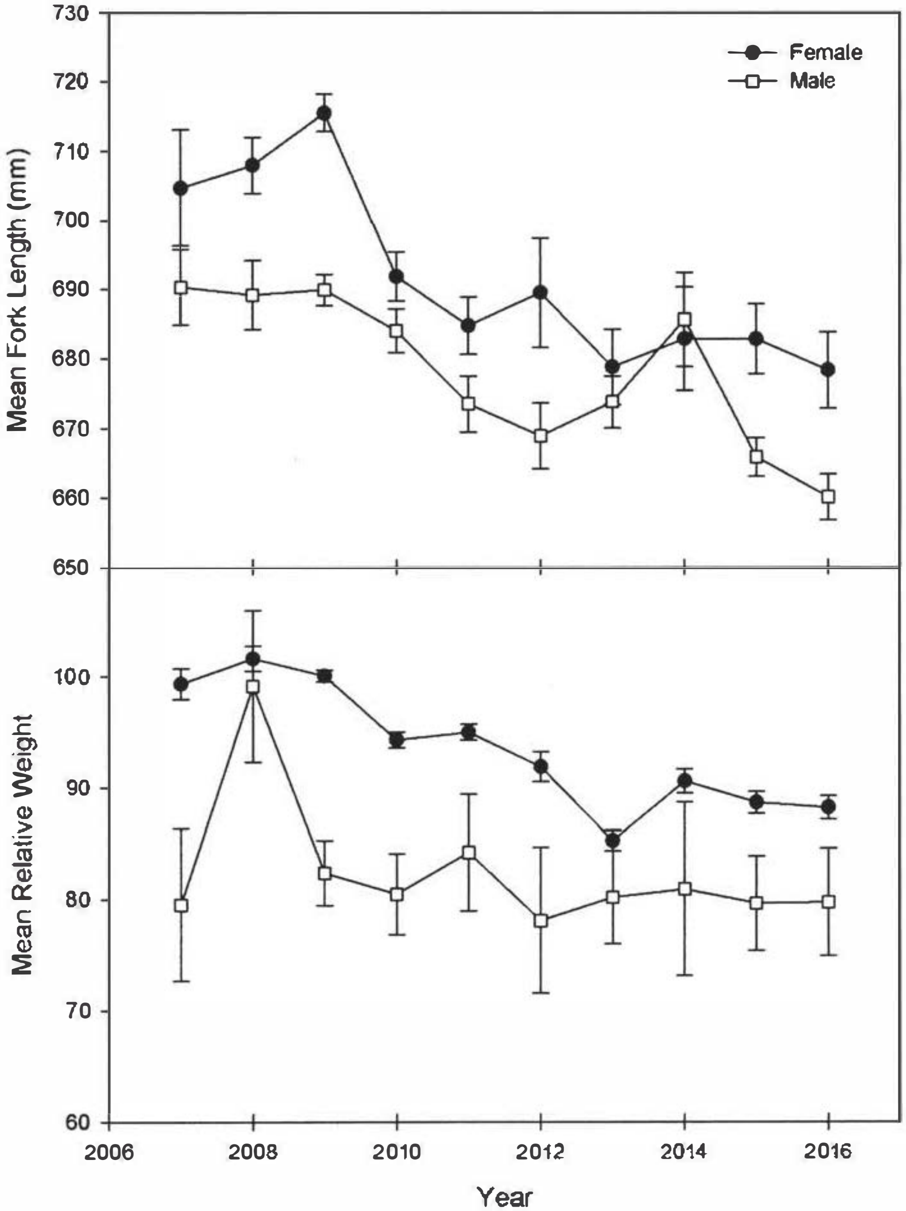

Figure 3. Mean fork length (FL ± SE) and relative weight (W_r ± SE) of male and female shovelnose sturgeon in the Wabash River, 2007-2016. There was a significant decrease in mean FL for both males and females (Male, $F_{1,8} = 16.0$, $R^2 = 0.62$, $P = 0.004$; Female, $F_{1,8} = 22.3$, $R^2 = 0.68$,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

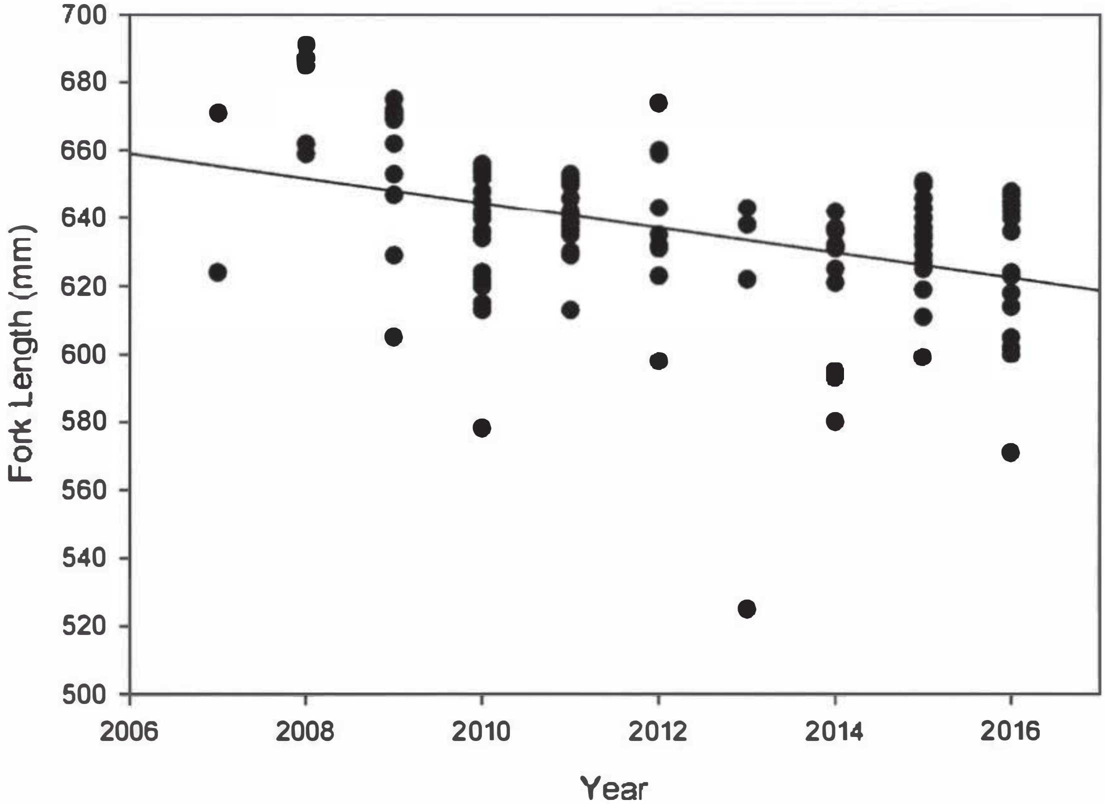

Figure 4. Gravid, FIV female shovelnose sturgeon in the 25th percentile of fork length ranges for each year (2007-2016), in the Wabash River. The 25th percentile of FLs for gravid FIV females represents the average size-at-maturity. There was a significant linear decrease in size-at-maturity for females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

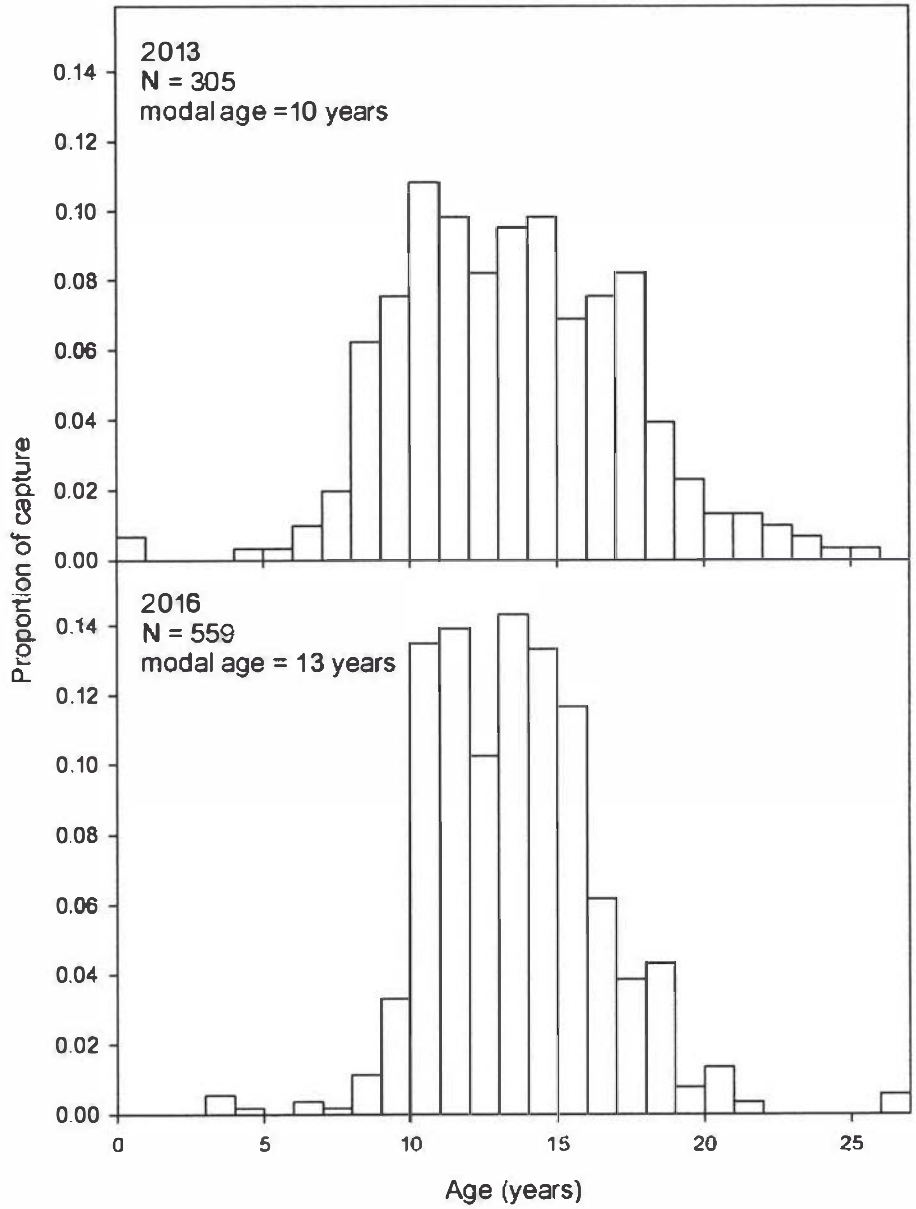

Figure 5. Age frequency diagrams of shovelnose sturgeon sampled from the LWR in 2013 with DC electrofishing and from the UWR in 2016 with drift nets. Age estimates were extrapolated from a length-stratified subsample (2013: N = 305, modal age = 10 years; 2016: N = 559, modal age = 13 years). The age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

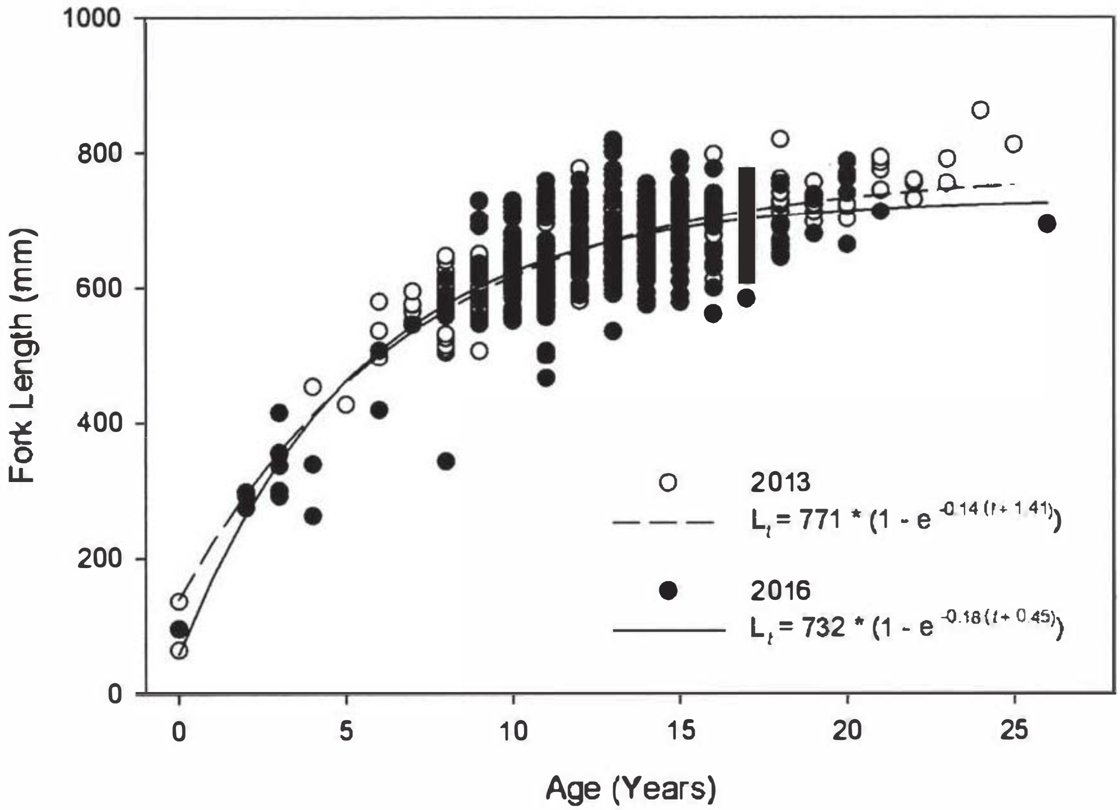

Figure 6. Fork length at age of shovelnose sturgeon sampled in the 2013 season in the lower Wabash River and sampled in the 2016 season in the entire Wabash River. The two lines and equations represent the fitted von Bertalanffy growth functions for each sampling year with no statistical difference found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

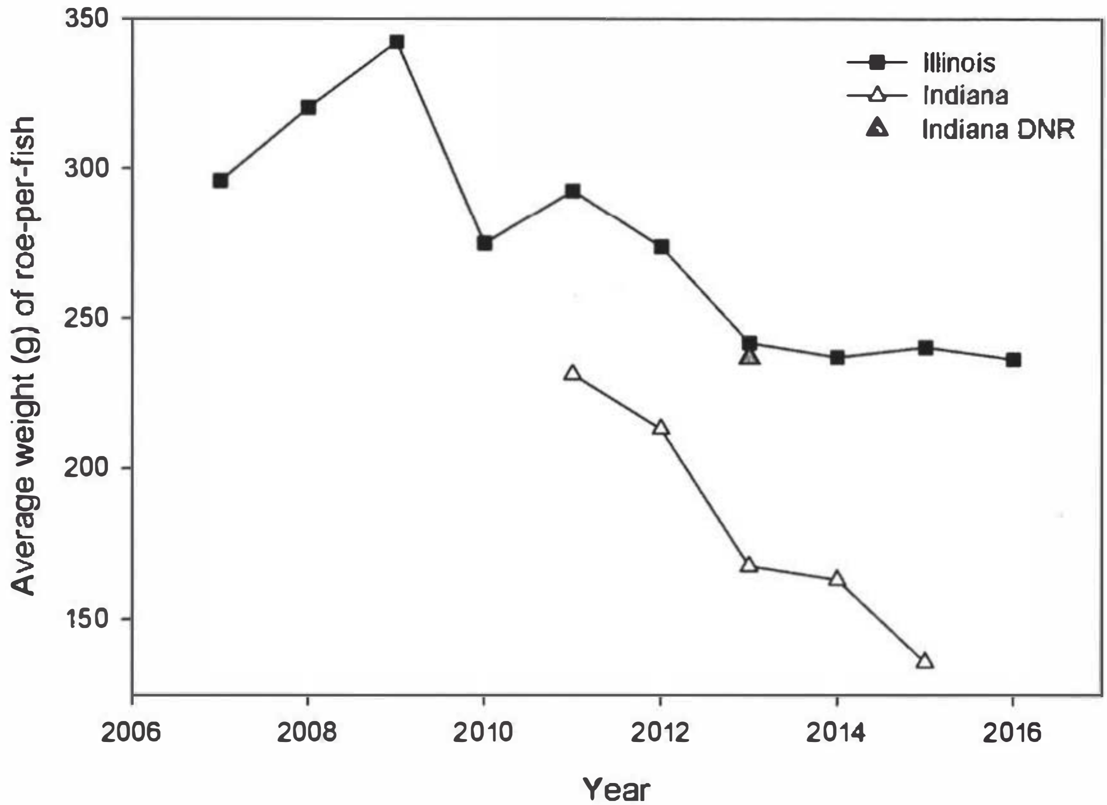

Figure 7. Average weight (g) of roe-per-fish for shovelnose sturgeon harvested in the Wabash River as reported by Illinois roe harvesters (2007-2016), Indiana roe harvesters (2011-2015), and from sacrificed FIV females collected by Indiana Department of Natural Resources (IN-DNR) in the 2013 sampling 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: $F_{1,3} = 60.63$, $R^2 = 0.94$, $P = 0.004$).

EVALUATION OF THE SHOVELNOSE STURGEON COMMERCIAL CAVIAR FISHERY IN THE WABASH RIVER

ABSTRACT

Considering the popularity and high price of caviar, harvest of smaller, inland roe-bearing species like the shovelnose sturgeon, is likely to persist. Predicting roe yields through an extension of the traditional biomass-based equilibrium yield model is a relatively new modeling approach that can be used to better manage roe-based fisheries. This population has faced declines in size and condition and increased mortality rates as highlighted by annual monitoring. Reduced size, condition, and size-at-maturity of females, has emphasized the need to assess female reproductive biology and to reassess current management regulations. Historically, the 635-mm minimum length limit (MLL) was determined to provide adequate protection from overfishing, as simulated through biomass-based equilibrium yield models. In this study, I find evidence of harvest-induced female reproductive dynamics and the modeling simulations suggest that the roe-fishery is experiencing both growth and recruitment overfishing at present harvest levels with the current MLL (635-mm). The analysis of roe yield was very sensitive to changes in conditional natural morality (*cm*). The threat of growth and recruitment overfishing were relieved at higher values of *cm*, but at the cost of greatly reduced roe yields. Results from the biomass-based assessment underestimated the severity of growth overfishing. This caused the overfishing threshold to be overestimated, with direct management implications and could help to explain the declines reported in population demographics over time. Only the most conservative MLL (685-mm) produced sustainable yields at current levels of harvest.

INTRODUCTION

Shovelnose sturgeon have experienced increased harvest pressure over the last several years due to sturgeon fishery declines in Europe and Asia (Birnstein, 1993; Hintz & Garvey, 2012). The population in the Wabash River has become unstable due to continued harvest, with many parameters declining over time (i.e. proportional size structure of memorable sized fish, relative weight, and size-at-maturity; Thornton et al., 2018). Previous studies have guided management decisions by modeling the effects of minimum length limits (MLL) on shovelnose sturgeon populations through biomass-based equilibrium yield assessments (Colombo, Garvey, Jackson, et al., 2007; Kennedy & Sutton, 2007; Koch, Quist, Pierce, Hansen, & Steuck, 2009; Quist, Guy, & Pegg, 2002); however, with new modeling techniques, managers can predict roe yields using an extension of the Beverton-Holt yield-per-recruit model, and manage caviar fisheries accordingly (Risley, Johnson, & Quinn, 2017). Colvin, Bettoli, & Scholten (2013) found that biomass-based equilibrium yield assessments are likely to underestimate the probability and severity of growth overfishing when paddlefish roe is targeted; thus, overestimating the overfishing threshold. There are direct management implications of this which may help to explain some of the demographic declines that have been recorded in the Wabash River shovelnose sturgeon population.

Sturgeon roe fisheries and the trade of caviar are now regulated under strict guidelines due to the overharvest of many sturgeon species (CITES, 2001). Though harvest is often touted for the cause of increased mortality rates, habitat loss and degradation have also contributed to increased mortality in populations (Birnstein, 1993; Williamson, 2003). Natural mortality (*M*) is expected to contribute more to the total mortality (*Z*) in degraded stream systems, and conversely, contribute less to *Z* in pristine systems (Birnstein, 1993). While most large rivers in the United States have been modified for flood control or navigation, the Wabash River has remained largely unaltered. The river features 661 km of free-flowing water before meeting its confluence with the Ohio River. This generally unimpacted river hosts an abundant shovelnose sturgeon population, which likely experiences lower rates of natural mortality compared to populations in heavily impacted systems (e.g. the Mississippi River).

Direct natural mortality (*M*) estimates are inherently difficult to obtain, but imperative for equilibrium yield models. Oftentimes, indirect estimates based on life history studies are the best option for estimating natural mortality in a population due to feasibility (Hewitt, Lambert, Hoenig, & Lipcius, 2007). Then, Hoenig, Hall, & Hewitt, (2015) recommended the $Hoenig_{nls}$ t_{max}-based estimator for *M* estimates. This estimator was found to outperform other empirical estimators when compared to over 200 independent, direct estimates of M, but it does not consider the life history of the species. For example, the estimator is based on longevity, and many sturgeon fin ray aging studies suggest that age is often underestimated due to the extremely slow growth that occurs at older ages (Hamel et al., 2014; Paragamian & Beamesderfer, 2003). In addition, the equilibrium yield models assume a constant *M* throughout the life of the cohort (Slipke & Maceina, 2010). Shovelnose sturgeon feature bony scutes along their body (Pikitch, Doukakis, Lauck, Chakrabarty, & Erickson, 2005), which will likely alleviate risk of predation once these fish reach a certain size. While natural mortality is likely high for early life stages, it should diminish throughout the life of the sturgeon at a quicker rate compared to fishes not protected by an armored exterior. This is why previous studies, even in highly impacted systems, predict low estimates of natural mortality for shovelnose sturgeon (5-10%; Colombo, Garvey, Jackson, et al., 2007; Kennedy & Sutton, 2007; Koch et al., 2009).

In general, it is believed that fishing mortality (*F*) is primarily what contributes to estimates of total mortality in roe-based fisheries (Boreman, 1997). In heavily harvested populations, large, fast-growing fish are removed from the population, and the resulting size selectivity for early maturation and truncated age distribution can contribute to declines in reproductive output for females (Trippel, 1995). More specifically, it can decrease the size of the eggs produced since female body size is a predictor of larval success (Buckley et al., 1991; Knutson & Tilseth, 1985). It is through this mechanism that harvest has potential to indirectly impact natural mortality rates in a population.

Shovelnose sturgeon are believed to be one of the last commercially viable options for roe harvest, because relative to other sturgeon species, they are small-bodied and fast growing (Keenlyne, 1997; Morrow, Kirk, Killgore, & George, 1998). Kennedy and Sutton (2007) found that for each level of harvest, population parameters increased with more restrictive MLL. Founded on the study's biomass-based equilibrium yield model, a 635-mm MLL was recommended for the Wabash River shovelnose sturgeon fishery. The analysis suggested that this MLL would allow population parameters to increase, while allowing 92% of the females to be available for harvest.

In light of the demographic declines highlighted by continuous monitoring of this population (Nepal KC, Colombo, & Frankland, 2015; Thornton et al., 2018), I think it wise to reassess current management regulations placed on the shovelnose sturgeon commercial caviar fishery in the Wabash River. Here I present evidence of harvest-induced female reproductive dynamics and use roe-based equilibrium yield modeling to assess current and more restrictive management strategies.

METHODS

Female reproductive dynamics and rate functions

Female shovelnose sturgeon were sampled in the Wabash River from 2007 to 2016 through annual monitoring by the Illinois Department of Natural Resources (IL-DNR) and Indiana Department of Natural Resources (IN-DNR). A further review of methods employed by the IL-DNR and IN-DNR can be found at Thornton et al. (2018). All fish captured were measured to the nearest mm fork length (FL), and weighed with 50 g precision.

In 2013 the IN-DNR sacrificed several fish for internal assessment of sex and maturity. Females were classified using the gonadal development guide for shovelnose sturgeon as described in (Colombo, Garvey, & Wills, 2007). Gravid (mature, FIV) females were classified by the presence of large dark oocytes, and non-gravid (non-mature) females were characterized by small yellow or no oocytes. Shovelnose sturgeon from the remaining sampling years were visually inspected for sex during the spring spawning months. 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.

One hundred and forty-four females were aged and pooled across the 2013-2016 sampling season using similar methods employed by Thornton et al. (2018). The age-length data for all females (aged 6-27), and immature fish (aged 0-3), were used to estimate growth using the von Bertalanffy growth function ($L_t = L_\infty * [1-e^{-k\,(t-t0)}]$). Ages 4-

5 were excluded in the analysis because there were no confirmed females in this age range and males are expected to spawn close to age 5. A general linear model assuming a binomial distribution was used to predict the proportion of sexually mature females as a function of FL (Colvin et al., 2013; Ogle, 2016). The logistic regression model was used to predict the percent mature by varying MLL. Size-at-maturity was determined at 10% gravidity (Kennedy, Sutton, & Fisher, 2006) and 50% gravidity. Length at age information from the von Bertalanffy growth function was then used to determine the age-at-maturity.

Gravid ovaries from six females and non-gravid ovaries from three females found in the 2013 sampling season were removed and weighed to the nearest gram. Five 10-egg subsamples from each ovary were weighed to the nearest 0.001 g and averaged. The total number of eggs per gravid female (i.e., absolute fecundity) was estimated by extrapolating the number of eggs from the 10-egg subsample to the entire ovary weight. Relative fecundity was calculated as eggs per kg of body weight and mean relative egg size was calculated as the number of eggs per gram of ovary weight (Kennedy et al., 2006). Gonadosomatic index (GSI) was calculated for all fish for which fecundity was estimated. GSI is calculated as:

$$GSI = \frac{gonad\ weight}{wet\ weight}\ x\ 100.$$

GSI was regressed against mean relative egg size for each fish and compared to the predicted values determined from a previous study of the female reproductive biology of shovelnose sturgeon in the Wabash River (predicted relative egg size = -3.65 × GSI + 167.6; Kennedy et al., 2006).

Simulation of equilibrium yield models

FAMS software was used as a traditional method of modeling that uses the Beverton-Holt equilibrium biomass-based yield model (Ricker, 1975; Slipke & Maceina, 2010). Simulations of three MLLs at a conditional natural mortality (*cm*) of 5% and varying conditional fishing mortality (*cf*) were performed for the biomass-based yield model.

An extension of the Beverton-Holt equilibrium yield-per-recruit model (Colvin et al., 2013) with female rate functions (growth, mortality, and length-weight relationship) was used to simulate the effects on roe yield and spawning potential ratio (SPR) of three different minimum length limits (MLL = 635-mm, 660-mm, and 685-mm) under varying conditional natural mortality (*cm*) estimates of 5%, 10%, and 20%, and across a range of conditional fishing mortalities (*cf* = 0-0.95). Roe yield-based modeling was performed in R by modifying an R script provided by M. Colvin (Mississippi State University) with the female shovelnose sturgeon rate functions. A MLL of 635-mm was assessed because it is the current regulation in place for the Wabash River sturgeon roe fishery. Two more conservative MLLs were evaluated in simulations: 660-mm and 685-mm (a recommended MLL for upper and middle Mississippi River; (Colombo, Garvey, Jackson, et al., 2007; Koch et al., 2009). Parameter estimates used in the model are provided in Table 1. The spawning potential ratio (SPR) is the number of eggs that could be produced by an average recruit in a fished stock divided by the number of eggs that could be produced by an average recruit in an unfished stock. A sustainable threshold value of 40% SPR was used, in addition to a critical threshold value of 30% SPR. Below SPR_{40}

harvest is not considered sustainable, and SPR_{30} is the threshold below which recruitment overfishing could occur (Colombo, Garvey, Jackson, et al., 2007; Goodyear, 1993).

RESULTS

Female reproductive dynamics and rate functions

A total of 886 female shovelnose sturgeon were sampled between 2007 and 2016. Female shovelnose sturgeon ranged in size from 396 to 776-mm FL. The weight-length regression for females was $\log_e(W) = 2.91 * \log_e(FL) - 11.86$ ($P < 0.001$, $r^2 = 0.85$; Table 1). Known females ranged in age from 6 to 27 years old, ages 24-26 were not represented in the catch. Immature fish captured ranged in age from 0-3 years old. The von Bertalanffy growth function was predicted for females and immature fish pooled from the 2013-2016 sampling season. The model predicted that females grew at an average rate of 53 mm/year up to age 8, an average of 20 mm/year from ages 9 to 16 and reached an L_∞ of 800-mm FL (Table 1; Figure 1). The oldest individuals (17+) experienced average growth rates of just 5 mm/year. The function predicts that female shovelnose sturgeon become vulnerable to the fishery at age 11.2 years, when they reach the current MLL of 635-mm. The 660-mm and 685-mm MLL corresponded to ages 12.5 and 14.1 years, respectively.

The instantaneous mortality rate (*Z*) was derived from the entire population and was estimated to be 0.42 (Thornton et al., 2018). Instantaneous natural mortality (*M*) was estimated using an indirect life history-based model. The $Hoenig_{nls}$ equation estimated *M* to be 0.22 based on a t_{max} of 30 years (Then et al. 2015; Kennedy et al. 2006). The instantaneous fishing mortality (*F*) was then estimated to be 0.20.

FIV females are defined as mature, gravid females in the black egg stage of reproduction (Colombo, Garvey, & Wills, 2007). Only 9% of captured FIV females were smaller than the current MLL (635-mm), compared to 22% of the FIV females that are protected by a 660-mm MLL, and 38% smaller than the 685-mm MLL. The youngest gravid female sampled was 525 mm and estimated to be 7 years old. From the logistic maturity-length regression coefficients, FL at which 10% of females are mature was found to be 485-mm (Figure 2, Table 1) corresponding to an age of 6 years old (Figure 1). In addition, FL at 50% maturity was 553-mm corresponding to an age of 8 years old and FL at 90% maturity was 621-mm and 10 years old (Figure 2). The logistic regression predicted that 94% of females were mature at the current MLL (635-mm), 97% were mature at 660-mm MLL, and 99% were mature at 685-mm MLL (Figure 2, Table 1).

Fecundity was estimated for nine gravid females from the 2013 harvest season (615-728 mm FL; 0.975-1.65 kg wet weight). Estimated absolute fecundity (number of eggs per female) ranged from 16,168 to 33,619 eggs (mean = 24,960; SE = 1,938). While relative fecundity (number of eggs per kg of wet weight) ranged from 15,398 to 23,160 eggs$\cdot$kg^{-1}. Relative egg size (number of eggs per gram of ovary weight) ranged from 96 to 161 eggs$\cdot$g^{-1} (Figure 3). The log-log ovary weight function was $\log_e(OW) = 3.05 * \log_e(FL) - 14.488$ ($P < 0.05$, $r^2 = 0.48$; Table 1).

Simulation of equilibrium yield models

Simulation modeling based on a *cm* of 5% had varying overfishing thresholds for each MLL in both the biomass-based and roe-based model (Figure 4). For the 635-mm MLL, biomass yield increased with increase in *cf*, until it reached an F_{max} of 0.35, while roe yield increased up until it reached and F_{max} of 0.25. For 660-mm MLL and 685-mm

MLL biomass yield increased up to an F_{max} of 0.45 and 0.8, respectively, showing little evidence of growth overfishing (Figure 4). However, the yield-based model predicted an F_{max} of 0.25 for the current 635-mm MLL and 0.3 for the 660-mm MLL. Both MLL simulations predict growth overfishing is occurring at current harvest levels and only the 685-mm MLL has an F_{max} above current harvest levels at 0.45 (Figure 4). The biomass-based yield model overestimates the overfishing threshold (F_{max}) compared to the roe yield model.

Modeling roe yield (kg) per 1,000 recruits was very sensitive to differences in *cm* (Figure 5). Modeling predicted the greatest roe yields at *cm* = 5% and a 685-mm MLL. This MLL also provided an overfishing threshold that was above the current level of harvest, suggesting that a conservative MLL of 685-mm could prevent growth overfishing. As natural mortality increased to 10% and 20%, the utility of higher length limits to achieve maximum yield was diminished. At *cm* = 10% both the 660-mm MLL and 685-mm MLL prevented growth overfishing, while the current MLL reached an F_{max} of 0.6. At *cm* = 20%, all MLLs prevented growth overfishing, and the current MLL yielded the most roe (Figure 6).

At current harvest levels, the threat of recruitment overfishing is high for the current MLL at 5% *cm*. In addition, the 660-mm MLL falls below the sustainable threshold of SPR at all levels of current harvest. The threat of overfishing is only diminished at the most conservative MLL (685-mm). At 10% *cm*, the current MLL falls below the sustainable threshold within the current level of harvest, but recruitment overfishing would not occur until harvest reaches a conditional fishing mortality (*cf*) of

0.55. At current levels of harvest and conditional natural mortality (*cm*) at 20%, the SPR is between 60% and 80% for all MLLs (Figure 7).

DISCUSSION

In this study, age estimates of mature females were within the range previously reported for this population (ages 6-27). The smallest gravid female in this study was 525 mm FL, compared to the smallest mature female previously reported at 570-mm FL (Kennedy et al., 2006). In addition to reporting smaller mature females, I found an earlier age-at-maturation (6-8 years) compared to previous findings of 8-9 years (Kennedy & Sutton, 2007; Kennedy et al., 2006). Due to declining size and condition of female shovelnose sturgeon and earlier age-at-maturation, I believe that harvest is selecting for smaller, early maturing fish. Size selectivity for early maturation occurs in heavily harvested populations when large and late maturing fish are targeted for harvest, while the small and early maturing fish participate in breeding before becoming vulnerable to the fishery. The results of size-selectivity for early maturation are reduced reproductive traits like egg size or length of spawning season (Trippel, 1995). Declines in roe-per-fish based on commercial fishing data have been reported in this population (Thornton et al., 2018), and while fecundity estimates are high, the relative egg size (number of eggs$\cdot g^{-1}$) has increased, further indicating a decline in egg size.

Population characteristics of female shovelnose sturgeon in the Wabash River are consistent with those of heavily harvested stocks. Total annual mortality was recently estimated to be 34% for the entire population (Thornton et al., 2018) and is consistent with highly exploited stocks of the Mississippi River (middle: 37%, Colombo, Garvey, Jackson, et al., 2007; upper: 31-42%, Koch et al., 2009). Natural mortality of shovelnose sturgeon in this study appeared to exceed fishing mortality, though the best *M* estimator (Then et al., 2015) was based on longevity (t_{max}) for a species that is oftentimes underestimated in age (Hamel et al., 2014; Paragamian & Beamesderfer, 2003). In addition, previous studies have modeled shovelnose sturgeon yield by using a conditional natural mortality estimates of 5-10% (Colombo, Garvey, Jackson, et al., 2007; Kennedy & Sutton, 2007; Koch et al., 2009).

A previous study (Kennedy & Sutton, 2007) used a biomass-based equilibrium yield model and found that a 635-mm MLL was sufficient to prevent growth and recruitment overfishing for shovelnose sturgeon in the Wabash River. In addition, this MLL allowed for the increase in population parameters over a short time period (30 years). Modeling shovelnose sturgeon biomass yield in the upper and middle Mississippi River found that a more conservative MLL of 685-mm was needed to maintain a sustainable stock (Colombo, Garvey, Jackson, et al., 2007; Koch et al., 2009), though MLLs as small as 508-mm were found to be appropriate for the shovelnose sturgeon population in the Missouri River system (Quist et al., 2002).

Long-term monitoring data on shovelnose sturgeon in the Wabash River have shown declines in several population parameters (i.e. FL, condition, and size-at-maturity; Thornton et al., 2018), despite following the management recommendations of Kennedy and Sutton (2007) and implementing a 635-mm MLL. Colvin et al. (2013) found that biomass-based modeling underestimated the severity of growth and recruitment overfishing when compared to a roe-based model. In fact, this study found the same trend. The biomass-based equilibrium yield model for this population overestimated growth overfishing thresholds (F_{max}), which may help explain the declines in size, condition, and age-at-maturity reported in the Wabash River shovelnose sturgeon population.

The roe-based equilibrium model provides evidence for growth and recruitment overfishing at the current MLL of 635-mm with low natural mortality. The 660-mm MLL was just under the sustainable threshold for SPR at the lowest natural mortality (5%), and experienced growth overfishing at current levels of harvest. Modeling suggested that higher natural mortality rates allowed the stock to sustain greater levels of harvest, but this came at a price of significantly reduced yields.

As natural mortality increases, the utility of higher length limits to achieve maximum yield is diminished (Slipke & Maceina, 2010). Yield dramatically decreases because greater numbers of fish are being removed from the population due to natural mortality. With an increase to 10% conditional natural mortality (*cm*), maximum yield was achieved at high *cf* (0.6) for the current MLL. At the conditional natural mortality rate of 20%, which was estimated for this population using the $\text{Hoenig}_{\text{nls}}$ estimator, all MLLs prevented growth and recruitment overfishing and yield increased with increased fishing mortality, but at a cost of dramatically reduced roe yields (maximum yield = 5.6 kg for 635-mm MLL) compared to yields in the simulation with low natural mortality (maximum yield = 53 kg for 685-mm MLL). This is predicted because the natural mortality rate of $M = 22\%$ is multiplicative across years, and with current growth parameters, female shovelnose sturgeon do not reach 635-mm until age 11, by which time 91% of the original 1,000 recruits has been removed by natural mortality. Furthermore, normal modeling assumes that fish grow throughout their life, but previous mark-recapture studies on shovelnose sturgeon have found very little to no growth in developed individuals (Nepal KC et al., 2015). This complicates the model by potentially overestimating the severity of natural mortality.

Changing the estimate of *M* from 5% to 22% per year would reflect a dramatic shift in the understanding of population dynamics for this species. Consequently, the age structure of the stock and its ability to support a roe fishery, would be highly dependent on the magnitude of annual recruitment (Hewitt et al., 2007). Because the reliability of the $Hoenig_{nls}$ estimator is dependent on the variability of *M* among species with the same longevity, and because it is unlikely that this stock would be able to support the current fishery that it does with a natural mortality rate of 22%, I believe that 5-10% natural mortality is a more reliable estimate for this population. Future studies should attempt to provide a more reliable direct estimate of *M* in this population. Another unknown is the effect of spawning frequency on the methods of this model. I am interested in this because shovelnose sturgeon are known to spawn periodically every 2-3 years (Quist et al., 2002). However, it is still suggested as a better alternative to the biomass-based model and it is believed that the model can be generalized to roe-bearing species that have variable spawning frequencies (Colvin et al., 2013).

Considering the high price and popularity of caviar, it is expected that harvest will persist for this species. Given that the current minimum length limit (635-mm) does not provide adequate protection from growth and recruitment overfishing, I suggest implementing a more conservative minimum length limit of 685-mm. I also believe that all management decisions should focus on the need to reduce harvest pressure such that older age classes persist in the population. Moratoria on fishing have been implemented to allow stocks to rebuild rather than being fished to the point of extinction. When the reproductive capacity of a population is jeopardized, management should consider the possibility of a population collapse. A two-year moratorium on commercial fishing would help to rebuild the age structure and move toward improving the outlook of recruitment for this population.

LITERATURE CITED

Birnstein, V. J. (1993). Sturgeon and Paddlefishes: Threatened Fishes in Need of Conservation. *Conservation Biology*, *7*(4), 773–787. Retrieved from http://www.jstor.org/stable/2386809

Boreman, J. (1997). Sensitivity of North American sturgeon and paddlefish to fishing mortality. *Environmental Biology of Fishes*, *48*, 399–405.

Buckley, L. J., Smigielski, A. S., Halavik, T. A., Caldarone, E. M., Burns, B. R., & Laurence, G. C. (1991). Winter flounder *Pseudopleuronectes americanus* reproductive success. II. Effects of spawning time and female size on size, composition and viability of eggs and larvae. *Marine Ecology Progress Series*, *74*(2/3), 125–135.

CITES. (2001). *Sturgeons and Cites.* Retrieved from https://www.cites.org/eng/prog/sturgeon.php

Colombo, R. E., Garvey, J. E., Jackson, N. D., Brooks, R. C., Herzog, D. P., Hrabik, R. A., & Spier, T. W. (2007). Harvest of Mississippi River sturgeon drives abundance and reproductive success: A harbinger of collapse? *Journal of Applied Ichthyology*, *23*(4), 444–451. https://doi.org/10.1111/j.1439-0426.2007.00899.x

Colombo, R. E., Garvey, J. E., & Wills, P. S. (2007). Gonadal development and sex-specific demographics of the shovelnose sturgeon in the Middle Mississippi River.

Journal of Applied Ichthyology, *23*, 420–427. https://doi.org/10.1111/j.1439-0426.2007.00885.x

Colvin, M. E., Bettoli, P. W., & Scholten, G. D. (2013). Predicting Paddlefish Roe Yields Using an Extension of the Beverton-Holt Equilibrium Yield-per-Recruit Model. *North American Journal of Fisheries Management*, *33*(5), 940–949. https://doi.org/10.1080/02755947.2013.820242

Goodyear, C. P. (1993). Spawning stock biomass per recruit in fisheries management: foundation and current use. *Canadian Special Publication of Fisheries and Aquatic Sciences*, (July), 67–82. https://doi.org/10.1017/CBO9781107415324.004

Hamel, M. J., Koch, J. D., Steffensen, K. D., Pegg, M. A., Hammen, J. J., Rugg, M. L., & Jech, J. M. (2014). Using mark–recapture information to validate and assess age and growth of long-lived fish species. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(4), 559–566. https://doi.org/10.1139/cjfas-2013-0393

Hewitt, D. A., Lambert, D. M., Hoenig, J. M., & Lipcius, R. N. (2007). Direct and Indirect Estimates of Natural Mortality for Chesapeake Bay Blue Crab. *Transactions of the American Fisheries Society*, *136*, 1030–1040. https://doi.org/10.1577/T06-078.1

Hintz, W. D., & Garvey, J. E. (2012). Considering a species-loss domino-effect before endangered species legislation and protected area implementation. *Biodiversity and Conservation*, *21*(8), 2017–2027. https://doi.org/10.1007/s10531-012-0293-3

Keenlyne, K. D. (1997). Life history and status of the shovelnose sturgeon, *Scaphirhynchus platorynchus*. *Environmental Biology of Fishes*, *48*, 291–298.

Kennedy, A. J., & Sutton, T. M. (2007). Effects of harvest and length limits on shovelnose sturgeon in the upper Wabash River, Indiana. *Journal of Applied Ichthyology*. Purdue University, Purdue. https://doi.org/10.1111/j.1439-0426.2007.00886.x

Kennedy, A. J., Sutton, T. M., & Fisher, B. E. (2006). Reproductive biology of female shovelnose sturgeon in the upper Wabash River, Indiana. *Journal of Applied Ichthyology*, *22*(3), 177–182. https://doi.org/10.1111/j.1439-0426.2006.00745.x

Knutson, G. M., & Tilseth, S. (1985). Growth, development, and feeding success of Atlantic cod *Gadus morhua* larvae to egg size. *Transactions of the American Fisheries Society*, *114*, 507–511.

Koch, J. D., Quist, M. C., Pierce, C. L., Hansen, K. A., & Steuck, M. J. (2009). Effects of commercial harvest on shovelnose sturgeon populations in the Upper Mississippi River. *North American Journal of Fisheries Management*, *29*(1), 84–100. https://doi.org/Doi 10.1577/M08-115.1

Morrow, J. V, Kirk, J. P., Killgore, K. J., & George, S. G. (1998). Age, growth, and mortality of shovelnose sturgeon in the lower Mississippi River. *North American Journal of Fisheries Management*, *18*(3), 725–730. https://doi.org/10.1577/1548-8675(1998)018<0725:AGAMOS>2.0.CO;2

Nepal KC, V., Colombo, R. E., & Frankland, L. D. (2015). Demographics of Shovelnose Sturgeon in the Lower Wabash River, Illinois. *North American Journal of Fisheries Management*, *35*(4), 835–844. https://doi.org/10.1080/02755947.2015.1052161

Ogle, D. H. (2016). Recruitment. Retrieved July 24, 2018, from http://derekogle.com/IFAR/supplements/maturity/index.html

Paragamian, V. L., & Beamesderfer, R. C. P. (2003). Growth estimates from tagged white sturgeon suggest that agesfrom fin rays underestimate true age in the Kootenai River, USA and Canada. *Transactions of the American Fisheries Society*, *132*(5), 895–903. https://doi.org/10.1577/T02-120

Pikitch, E. K., Doukakis, P., Lauck, L., Chakrabarty, P., & Erickson, D. L. (2005). Status, trends and management of sturgeon and paddlefish fisheries. *Fish and Fisheries*, *6*(3), 233–265. https://doi.org/10.1111/j.1467-2979.2005.00190.x

Quist, M. C., Guy, C. S., & Pegg, M. A. (2002). Potential influence of harvest on shovelnose sturgeon populations in the Missouri River system. *North American Journal of Fisheries Management*, *22*(February 2014), 537–549. https://doi.org/Doi 10.1577/1548-8675(2002)022<0537:Piohos>2.0.Co;2

Ricker, W. E. (1975). Computation and interpretation of biological statistics of fish populations. *Bulletin of the Fisheries Research Board of Canada*, (191), 401. https://doi.org/10.1038/108070b0

Risley, J. T., Johnson, R. L., & Quinn, J. W. (2017). Evaluation of the Commercially Exploited Paddlefish Fishery in the Lower Mississippi River of Arkansas. *Journal of Southeastern Association of Fish and Wildlife Agencies*, *4*, 52–59.

Slipke, J. W., & Maceina, M. J. (2010). FISHERY ANALYSIS and MODELING SIMULATOR (FAMS 1.0): a software program and manual. Auburn University, Auburn, AL.

Then, A. Y., Hoenig, J. M., Hall, N. G., & Hewitt, D. A. (2015). Evaluating the predictive performance of empirical estimators of natural mortality using information on over 200 fish species. *ICES Journal of Marine Science*, *72*, 82–92.

Thornton, J. L., Nepal KC, V., Frankland, L. D., Jansen, C. R., Hirst, J., & Colombo, R.

E. (2018). Monitoring demographics of a commercially exploited population of shovelnose sturgeon in the Wabash River, Illinois/Indiana, USA. *Journal of Applied Ichthyology*, *00*, 1–10. https://doi.org/https://doi.org/10.1111/jai.13749

Trippel, E. A. (1995). Age at maturity as a stress indicator in fisheries. *BioScience*, *45*(11), 759–771. https://doi.org/10.1525/bio.2010.60.10.17

Williamson, D. F. (2003). *Caviar and Conservation: Status, management, and trade of North American sturgeon and paddlefish*. Washington DC. Retrieved from www.traffic.org

Table 1. Selected female population parameters used to simulate the effect of harvest on shovelnose sturgeon in the Wabash River.

Metrics	**Parameters modeled**
Weight-length coefficients	Intercept (a) = -11.86 Slope (b) = 2.91
von Bertalanffy growth coefficients	$L_\infty = 800$ K = 0.125 $t_0 = -1.41$
Logit maturity-length coefficients	Intercept = -17.89 Slope = 0.03
Ovary-weight coefficients	Intercept = -14.488 Slope = 3.05
Maximum age	30 years
Conditional natural mortality (*cm*)	0.05, 0.10, 0.20
Conditional fishing mortality (*cf*)	0 to 0.95
Minimum length limits	635, 660, 685-mm
Proportion of females	0.5

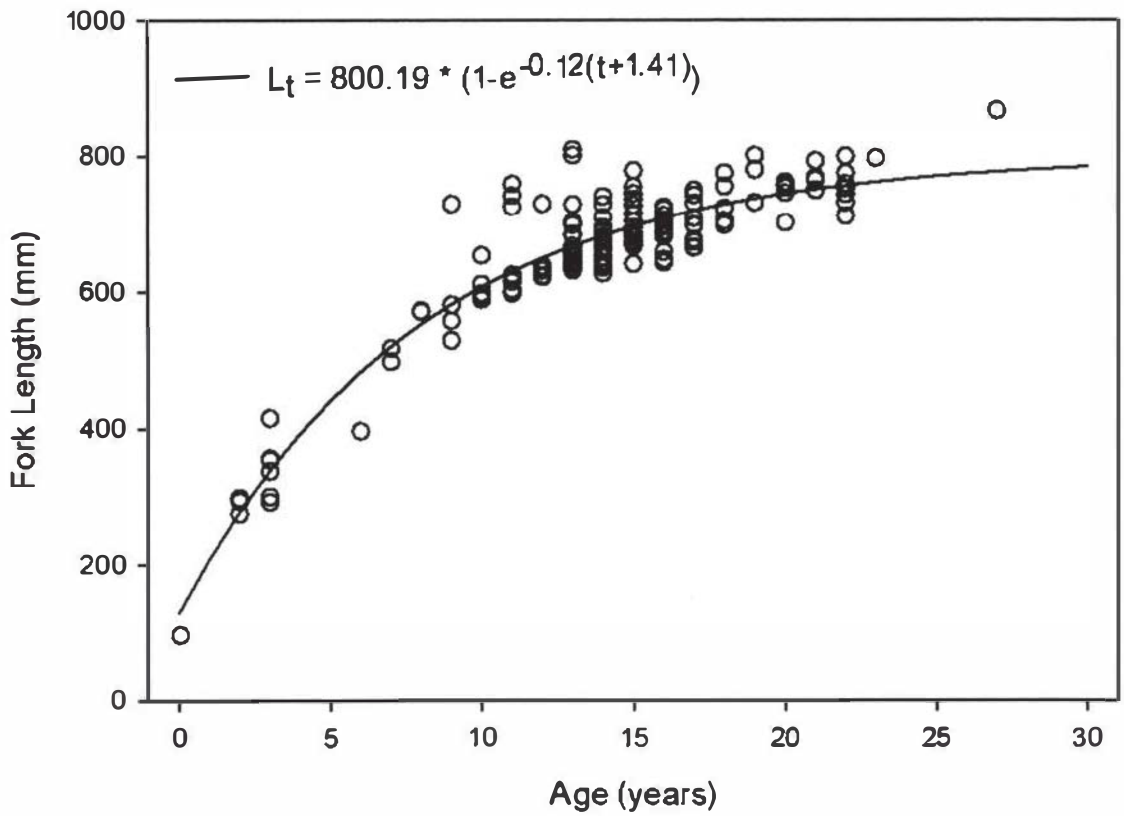

Figure 1. Fork length at age of female shovelnose sturgeon pooled from females and juveniles (aged 0-3 years) sampled in the 2013-2016 seasons in the Wabash River. The line and equation represent the von Bertalanffy growth function for female shovelnose sturgeon.

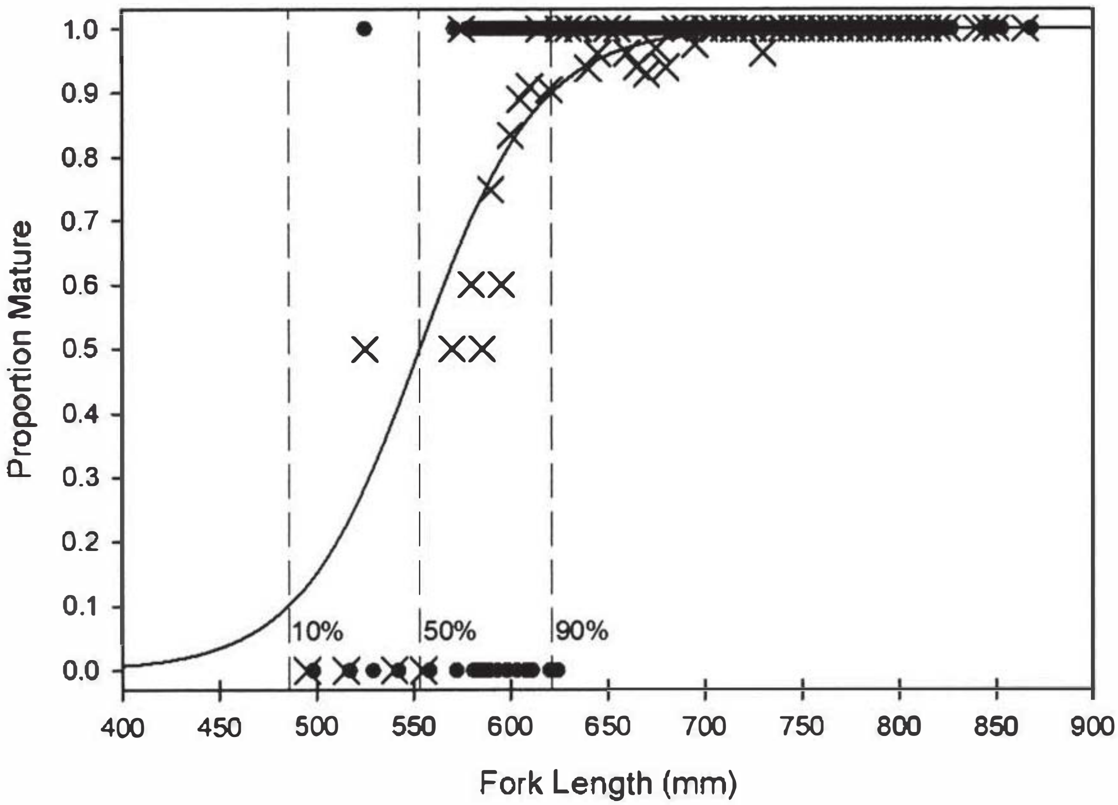

Figure 2. Plot of the proportion of mature females as a function of fork length for shovelnose sturgeon in the Wabash River. Mature females were gravid and in the black egg stage. The x's indicate the proportion of mature females per 5-mm length-group, the gray points are the observed data, the solid line represents a logistic function fitted to the observed data, and the vertical dashed lines indicate 10%, 50%, and 90% gravidity.

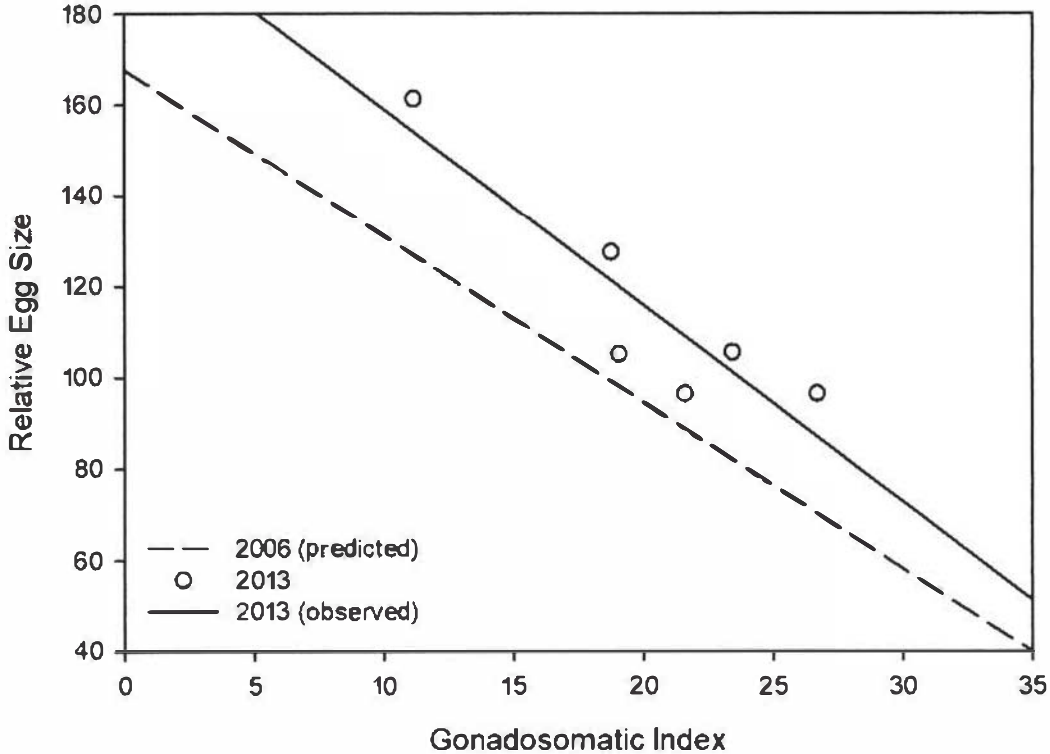

Figure 3. Mean relative egg size (RES; number of eggs per gram of ovary weight) and gonadosomatic index (GSI) of black egg stage (FIV) female shovelnose sturgeon (n = 6) in the Wabash River. The dashed line represents the predicted relationship between GSI and relative egg size based on a previous study on the reproductive biology of female shovelnose sturgeon in the Wabash River (Kennedy et al., 2006). Points represent the observed data in 2013 and the solid line is the linear regression fitted to the observed data. Predicted relationship: $RES = -3.65 \times GSI + 167.6$; observed relationship: $RES = -4.31 \times GSI + 202.1$.

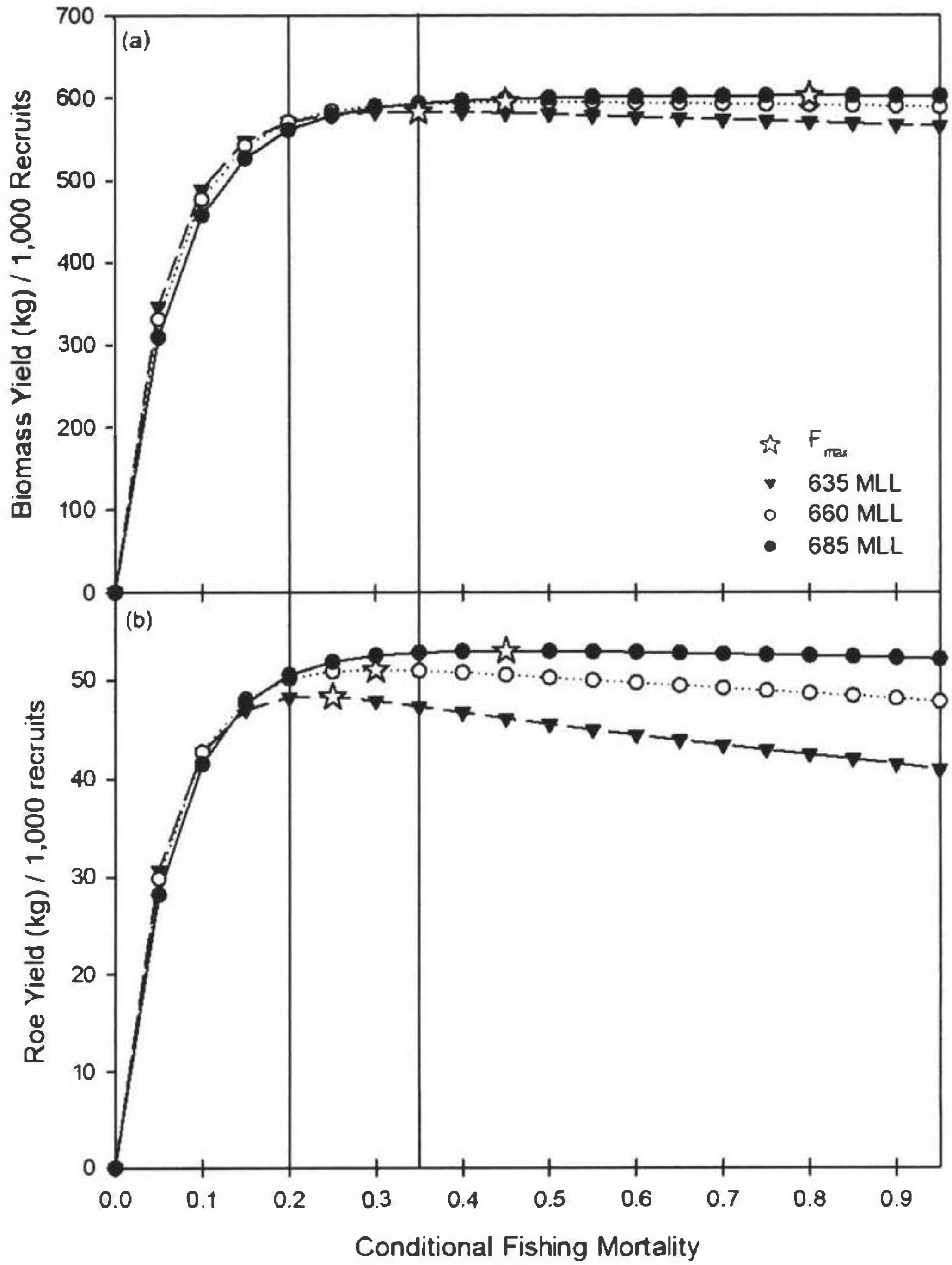

Figure 4. Predicted shovelnose sturgeon biomass yield (a) and roe yield (b) per 1,000 recruits simulated with a conditional natural mortality of 5% and three minimum length limits (MLL = 635-mm, 660-mm, and 685-mm) in the Wabash River. Vertical lines denote range of current level of harvest.

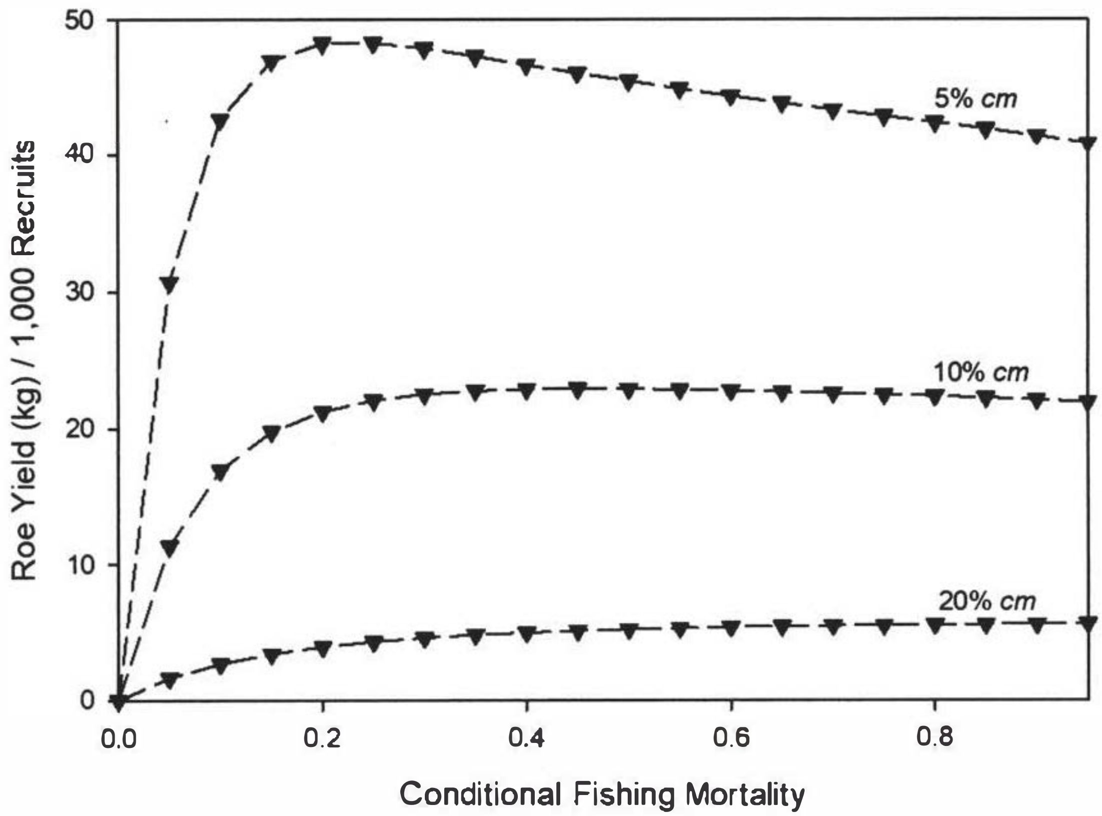

Figure 5. Predicted shovelnose sturgeon roe yields per 1,000 recruits showing model sensitivity to three varying levels of conditional natural mortality (*cm* = 5%, 10%, and 20%) at the current minimum length limit (635-mm) in the Wabash River.

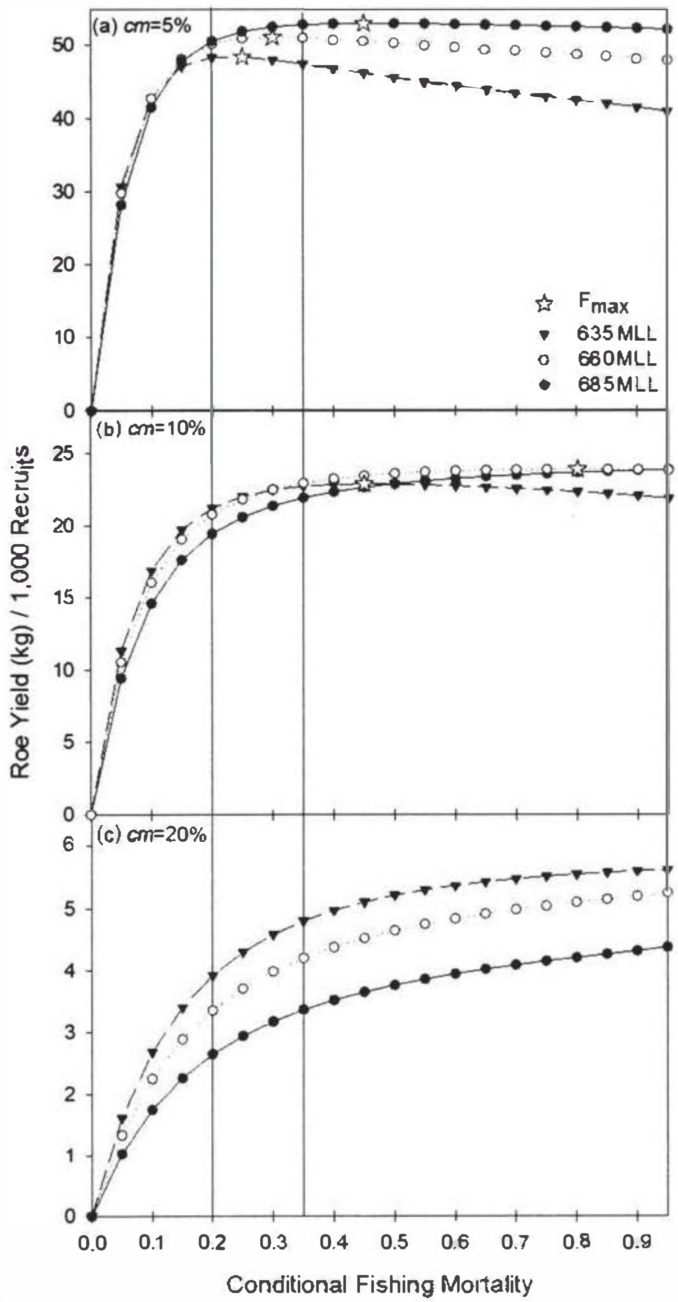

Figure 6. Predicted shovelnose sturgeon roe yields per 1,000 recruits for three levels of conditional mortality [*cm* = 5% (a), 10% (b), and 20% (c)] and three minimum length limits (mm; MLL) in the Wabash River. Vertical lines denote range of current level of harvest. Note that the y-axis differs among graphs a, b, and c, and that Figure 6 (a) is the same graph as above in Figure 4 (b).

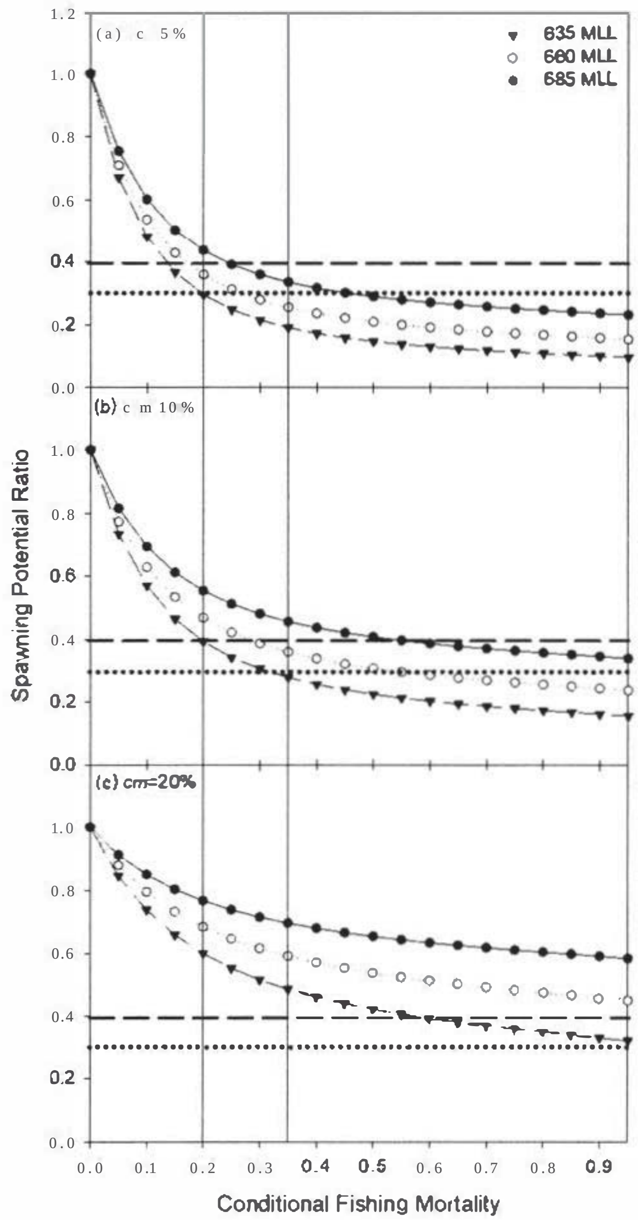

Figure 7. Predicted shovelnose sturgeon spawning potential ratios (SPR) for three levels of conditional natural mortality [*cm* = 5% (a), 10% (b), and 20% (c)] and three minimum length limits (MLL; 635-mm, 660-mm, and 685-mm) in the Wabash River. Horizontal dashed lines represent the sustainable SPR threshold of 40%; horizontal dotted line represents critical SPR threshold of 30%. Vertical lines denote the range of current level of harvest.

CONCLUSIONS: PROBLEMS, MANAGEMENT RECOMMENDATIONS, AND RESEARCH NEEDS

Shovelnose sturgeon in the Wabash River have experienced variable exploitation in response to several regulations that have been implemented in the history of the commercial caviar fishery. First, the Similarity of Appearances provisions of the Endangered Species Act closed commercial fishing of shovelnose sturgeon in areas where they coexist with the endangered Pallid Sturgeon (e.g. middle Mississippi River, Colombo et al. 2007). This was believed to cause a refocusing of efforts from the roe harvest market to unprotected areas like the Wabash River (Hintz & Garvey, 2012). Also, in 2014 "leads" were banned for use in commercial hoop net fishing. This was in response to reports of commercial fishermen misusing leads as entanglement gear, which is also banned for use in the Wabash River. The results of this new policy left some roe harvesters without nets to fish, so commercial harvest reports showed a decline during this time. However, caviar continues to be a popular food item that fetches high prices, making sturgeon roe harvest lucrative. Because shovelnose sturgeon are believed to be one of the last commercially viable options for roe harvest, management should take a conservative approach with this fishery in order to keep it sustainable.

Previously, policy for this species has been guided by modeling the effects of minimum length limits (MLL) on shovelnose sturgeon populations through biomass-based Beverton-Holt equilibrium yield assessments (Colombo et al., 2007; Kennedy & Sutton, 2007; Koch, Quist, Pierce, Hansen, & Steuck, 2009). However, new modeling techniques that focus on predicting roe yields instead of biomass yields have improved the prediction-power for roe-based fisheries (Colvin, Bettoli, & Scholten, 2013; Risley, Johnson, & Quinn, 2017). Furthermore, Colvin et al. (2013) found that biomass-based equilibrium yield models are likely to underestimate the probability and severity of growth overfishing when paddlefish are targeted for roe instead of flesh.

Kennedy and Sutton (2007) utilized a biomass-based equilibrium yield model to determine appropriate harvest levels for the population of shovelnose sturgeon in the upper Wabash River. He found that a 635-mm minimum length limit was sufficient to protect shovelnose sturgeon from declines in population parameters. However, following their study and the subsequent application of a 25-in (635-mm) minimum length limit on the fishery, there have been declines in population parameters such as size structure and relative weight condition over time, as highlighted by annual monitoring (Thornton et al., 2018). In addition, the population is experiencing greater levels of mortality (34%) and a truncated age distribution. The new level of mortality reflects that of other highly exploited populations of shovelnose sturgeon (37% in middle Mississippi River, Colombo et al., 2007; 31-42% in the upper Mississippi River, Koch et al., 2009) and a loss of older age classes have been shown to negatively affect recruitment in several fish species (Secor, 2000; Shelton et al., 2015; Trippel, 1995).

Upon further investigation of female reproductive dynamics and rate functions, a decline in both the size and age-at-maturity of females was found. In this study, 10% of females were found to be gravid at a length of 485-mm, corresponding to an age of 6 years old. A more conservative estimate of size and age at maturity, is at 553-mm (8 years old) when 50% of females are found to be mature. In 2006, Kennedy et al. reported a size and age-at-maturity of 600-mm and 9 years old. These declines in size and age of mature females are further evidence for size-selectivity at early maturation. This occurs in heavily harvested populations when large and late maturing fish are targeted for harvest, while the small and early maturing fish participate in breeding before becoming vulnerable to the fishery (Trippel, 1995).

Female body size is a predictor of larval success, so early maturation and small body size could cause declines in reproductive output of females (Knutson & Tilseth, 1985). Size-selectivity for early maturation and reduced reproductive output was further evidenced by declines in the weight of roe-per-fish calculated from the commercial fishing data. Both Illinois and Indiana roe harvest permit holders experienced declines in their reports of roe-per-fish over time. And while commercial harvest data may not be the best predictor of female reproductive output, these data were found to match what the Indiana Department of Natural Resources found upon sacrificing FIV (black egg-stage) females in the 2013 sampling season. Additionally, these FIV females were also found to have greater relative egg size (number of eggs per gram of ovary weight) than what was predicted based on the 2006 study by Kennedy et al., which suggests that the eggs produced by females are getting smaller.

To address the issues of declining parameters, an extension of the Beverton-Holt yield-per-recruit model was used to predict roe yields and spawning potential ratio for the shovelnose sturgeon in the Wabash River, using female-specific rate functions. When comparing the biomass-based model to the roe-based model with the same female rate functions, the biomass-based model was found to overestimate the growth overfishing threshold (F_{max}). In fact, for the roe-based model at low levels of conditional natural mortality (*cm* = 5%), the current 635-mm minimum length limit resulted in both growth and recruitment overfishing. This has had direct management implications for this population and help to explain the declines seen in size, condition, and age-at-maturity. In fact, only the most conservative minimum length limit of 685-mm protected shovelnose sturgeon from both growth and recruitment overfishing.

Considering the high price and popularity of caviar, it is expected that harvest will persist for this species. Given that the current minimum length limit (635-mm) does not provide adequate protection from growth and recruitment overfishing, I suggest implementing a more conservative minimum length limit of 685-mm. I also believe that all management decisions should focus on the need to reduce harvest pressure such that older age classes persist in the population. Moratoria on fishing have been implemented to allow stocks to rebuild rather than being fished to the point of extirpation. When the reproductive capacity of a population is jeopardized, management should consider the possibility of a population collapse. A two-year moratorium on the commercial fishing of shovelnose sturgeon in the Wabash River would help to rebuild the age structure and move toward improving the outlook of recruitment for this population.

Additional research is needed for the shovelnose sturgeon population in the Wabash River and future studies should address population size, female reproductive biology, and direct estimates of natural mortality. The current survey techniques employed by the Department of Natural Resources do not allow for relevant estimates of population size and the sampling techniques used in this study are not standardized. Moving forward, biologists should implement a standardized sampling protocol. The trends I found upon evaluating female reproductive biology were alarming and further assessment and tracking of these metrics will be important for a recovering population. And finally, due to the sensitivity of modeling to natural mortality rates, it should be a priority of biologists to obtain a direct estimate of natural mortality. A tagging study done in cooperation with commercial fishermen would help to achieve a direct and more reliable estimate of fishing and natural mortality.

LITERATURE CITED

Colombo, R. E., Garvey, J. E., Jackson, N. D., Brooks, R. C., Herzog, D. P., Hrabik, R. A., & Spier, T. W. (2007). Harvest of Mississippi River sturgeon drives abundance and reproductive success: A harbinger of collapse? *Journal of Applied Ichthyology, 23*(4), 444-451. https://doi.org/10.1111/j.1439-0426.2007.00899.x

Colvin, M. E., Bettoli, P. W., & Scholten, G. D. (2013). Predicting Paddlefish Roe Yields Using an Extension of the Beverton-Holt Equilibrium Yield-per-Recruit Model. *North American Journal of Fisheries Management*, *33*(5), 940–949. https://doi.org/10.1080/02755947.2013.820242

Hintz, W. D., & Garvey, J. E. (2012). Considering a species-loss domino-effect before endangered species legislation and protected area implementation. *Biodiversity and Conservation*, *21*(8), 2017–2027. https://doi.org/10.1007/s10531-012-0293-3

Kennedy, A. J., & Sutton, T. M. (2007). Effects of harvest and length limits on shovelnose sturgeon in the upper Wabash River, Indiana. *Journal of Applied Ichthyology*. Purdue University, Purdue. https://doi.org/10.1111/j.1439-0426.2007.00886.x

Kennedy, A. J., Sutton, T. M., & Fisher, B. E. (2006). Reproductive biology of female shovelnose sturgeon in the upper Wabash River, Indiana. *Journal of Applied Ichthyology*, *22*(3), 177–182. https://doi.org/10.1111/j.1439-0426.2006.00745.x

Knutson, G. M., & Tilseth, S. (1985). Growth, development, and feeding success of Atlantic cod *Gadus morhua* larvae to egg size. *Transactions of the American*

Fisheries Society, *114*, 507–511.

Koch, J. D., Quist, M. C., Pierce, C. L., Hansen, K. A., & Steuck, M. J. (2009). Effects of commercial harvest on shovelnose sturgeon populations in the Upper Mississippi River. *North American Journal of Fisheries Management*, *29*(1), 84–100. https://doi.org/Doi 10.1577/M08-115.1

Risley, J. T., Johnson, R. L., & Quinn, J. W. (2017). Evaluation of the Commercially Exploited Paddlefish Fishery in the Lower Mississippi River of Arkansas. *Journal of Southeastern Association of Fish and Wildlife Agencies*, *4*, 52–59.

Secor, D. H. (2000). Spawning in the nick of time? Effect of adult demographics on spawning behaviour and recruitment in Chesapeake Bay striped bass. *ICES Journal of Marine Science*, *57*(2), 403–411. https://doi.org/10.1006/jmsc.1999.0520

Shelton, A. O., Hutchings, J. A., Waples, R. S., Keith, D. M., Akc, H. R., & Dulvy, N. K. (2015). Maternal age effects on Atlantic cod recruitment and implications for future population trajectories. *ICES Journal of Marine Science*, *72*(6), 1769–1778. https://doi.org/10.1093/icesjms/fsv058

Thornton, J. L., Nepal KC, V., Frankland, L. D., Jansen, C. R., Hirst, J., & Colombo, R. E. (2018). Monitoring demographics of a commercially exploited population of shovelnose sturgeon in the Wabash River, Illinois/Indiana, USA. *Journal of Applied Ichthyology*, *00*, 1–10. https://doi.org/https://doi.org/10.1111/jai.13749

Trippel, E. A. (1995). Age at maturity as a stress indicator in fisheries. *BioScience*, *45*(11), 759–771. https://doi.org/10.1525/bio.2010.60.10.17