Analysis of Commercial Age Composition Data for Paddlefish in the Mississippi and Ohio Rivers during 2014-2017

Final Report to the MICRA Paddlefish-Sturgeon Committee

June 27, 2019

Dr. Michael Wilberg

Atlantic Transglobal

Quantitative Natural Resource Consulting

4411 Kings Road

Saint Leonard, Maryland 20685

Introduction

The U.S. Fish and Wildlife Service commissioned a study to determine the sustainability of commercial paddlefish *Polyodon spathula* fisheries (Sharov et al. 2014) to support their responsibilities under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Sharov et al. (2014) recommended increased monitoring of the commercial paddlefish fisheries and use of spawning potential ratio target reference points for managing the fishery.

A target fishing mortality rate of $F_{30\%}$ was adopted for commercial paddlefish management. In addition, commercial data collection programs were initiated or expanded in states that commercially harvest paddlefish. Importantly, this data collection program included aging of the paddlefish using jaw bones.

These new data provide an opportunity to evaluate the status of the commercial paddlefish fishery in the Mississippi and Ohio rivers. Therefore, the objectives of this report were to 1) estimate mortality rates of paddlefish in the Mississippi and Ohio rivers, 2) update reference point models for the new information, and 3) compare the estimated mortality rates to the updated reference points.

Methods

Several analyses were conducted to estimate the status of Mississippi and Ohio river paddlefish against the adopted $F_{30\%}$ reference point. The data used in these analyses were collected during 2015-2017 in sampling of the commercial fishery in Indiana, Kentucky, Mississippi, Missouri, and Tennessee. The analyses included updating the von Bertalanffy L_∞ parameter (as the average length of individuals age-15 and older for each sex), updating the length-weight parameters (combined over sexes), updating the selectivity parameters, estimating a revised female maturity-at-length relationship, estimating the total and fishing instantaneous mortality rates, and estimating reference points. These analyses update those done in Sharov et al. (2014).

Data

Data from commercial monitoring was provided from five states. The data were collected in different years across the states: during 2006-2016 in Indiana, 2014-2015 in Kentucky, 2015-2018 in Missouri, 2014-2015 and 2015-2016 in Mississippi, and 2015-2017 in Tennessee. Only data from 2013 to 2016 were used from Indiana because ages were not available for fish sampled in earlier years.

von Bertalanffy growth parameters

Because the samples mostly represented the older, larger portion of the population, it was not possible to estimate all the von Bertalanffy growth model parameters. Therefore, I estimated L_∞ (asymptotic maximum size) as the average length of age-15+ fish for each sex from samples pooled over states and years. The values for the t_0 (an offset parameter) and K (parameter that describes how rapidly fish grow towards L_∞) parameters were sex-specific and were based on Sharov et al. (2014).

Mortality estimation

I estimated annual survival using the Chapman-Robson estimator (Seber 1980) and the observed age-frequency data combined across years (2014-2017) and states (Fig. 1),

$$X = \sum_{a=\tilde{a}}^{A} \left(a - \tilde{a}\right) n_a \,,$$

where X is the sum of the product of age, a, and observed numbers at age, n_a, summed over the starting age for the analysis, $\tilde{a}$, to the maximum age, A. Only data from the Mississippi and Ohio rivers were used. The Chapman-Robson estimator works well under a range of conditions (Millar 2015). The Chapman-Robson approach assumes constant mortality over the ages included in the analysis. This implies that selectivity should be constant over the ages used in the analysis. I conducted the analysis using a range of starting ages from age 10 to age 15.

Survival was estimated as

$$\hat{S} = X / (n + X - 1)\,,$$

where $\hat{S}$ is estimated survival and n is the total number of aged fish age $\tilde{a}$ and older. The standard error (SE) of the estimated survival was calculated using the approximation from Seber (1980),

$$SE = \sqrt{\hat{S}\left(\hat{S} - \frac{X-1}{n+X-2}\right)}\,.$$

Approximate 95% confidence intervals were calculated for survival as the estimate ± 2SE,

$$95\%CI = \hat{S} \pm 2SE\,.$$

The data were combined across years, states, and sexes to obtain a larger sample size and to more closely approximate the equilibrium assumptions of the estimator.

Total instantaneous mortality was calculated as

$$Z = -\log_e \hat{S} ,$$

where Z was the total instantaneous mortality rate. The approximate 95% confidence intervals for the total instantaneous mortality rate were also calculated using the above equation.

The instantaneous fishing mortality rate (F) was estimated as the difference between Z and an assumed natural mortality rate (M),

$$F = Z - M .$$

I used 0.093 yr^{-1} as the natural mortality rate following Timmons and Hughbank (2000).

Selectivity estimation

A pattern of selectivity-at-age is required for estimation of spawning potential ratio (SPR) reference points and represents the relative vulnerability of different ages or sizes of fish to the fishery. Selectivity includes the availability of the fish (i.e., the overlap between the spatial distribution of fish and fishing effort) as well as effects of the gear (e.g., mesh size, hanging ratio).

I used an age-, length-, and sex-structured model to estimate selectivity at length and age. The model assumed sex-specific von Bertalanffy growth, length-based selectivity, and constant natural mortality.

Relative abundance at age and sex in the population was calculated using the exponential mortality model,

$$N_{a+1,x} = N_{a,x} e^{-Z_{a,x}} ,$$

where $N_{a,x}$ is the abundance of paddlefish of age a and sex x, and $Z_{a,x}$ is the total instantaneous mortality rate.

The total instantaneous mortality rate was calculated as the sum of the instantaneous fishing ($F_{a,x}$) and natural mortality rates,

$$Z_{a,x} = F_{a,x} + M .$$

The instantaneous natural mortality rate was assumed to be 0.093 yr^{-1} (Timmons and Hughbank 2000).

The fishing mortality rate-at-age and sex was calculated as the weighted average fishing mortality rate in length bin l (F_l), weighted by the proportions at length for that age and sex ($P_{a,l,x}$),

$$F_{a,x} = \sum_l F_l P_{a,l,x} .$$

Fishing mortality at length was calculated as the product of the fully selected fishing mortality rate (F) and selectivity-at-length (s_l),

$$F_l = s_l F .$$

The selectivity-at-length was modeled using a logistic function,

$$s_l = \frac{1}{1+e^{-\alpha\left(L_l - L_{50}\right)}} ,$$

where α is the slope at the inflection point, and L_{50} is the length with 50% selectivity. The fully selected fishing mortality rate was assumed to be 0.34 yr^{-1} based on the results of the mortality rate estimation.

The proportions-at-length for a given age and sex were calculated assuming a normal distribution of length-at-age for each sex with a constant coefficient of variation (CV = 0.052; Sharov et al. 2014),

$$P_{a,l,x} = \Phi\left(\frac{L_{l+1} - \bar{L}_{a,x}}{CV \cdot \bar{L}_{a,x}}\right) - \Phi\left(\frac{L_l - \bar{L}_{a,x}}{CV \cdot \bar{L}_{a,x}}\right),$$

where Φ is the cumulative density function for the normal distribution, and L_l was the mean length in bin l, and $\bar{L}_{a,x}$ was the mean length-at-age for sex x.

Mean length-at-age for each sex followed a von Bertalanffy growth model,

$$\bar{L}_{a,x} = L_{\infty,x}\left(1 - e^{-K_x\left(a - t_{0,x}\right)}\right),$$

where a was age and $L_{\infty,x}$, K_x, and $t_{0,x}$ were the parameters of the growth model.

I used maximum likelihood to estimate the selectivity parameters of the model. The model was fitted to the observed proportions-at-length and proportions-at-age by sex using multinomial distributions (Fournier and Archibald 1982) for the age and length compositions,

$$\ell = -\sum_{l} p_l \log_e \hat{p}_l - \sum_{a} p_a \log_e \hat{p}_a ,$$

Where ℓ was the negative log likelihood, p_l was the observed proportions-at-length, $\hat{p}_l$ was the estimated proportions-at-length, p_a was the observed proportions-at-age, and $\hat{p}_a$ was the estimated proportions-at- or age.

A preliminary analysis that estimated selectivity individually for each state indicated very similar parameters for the selectivity function. In light of these results, it seems reasonable to combine the data over states despite different mesh sizes having been used for sampling.

Maturation and spawning frequency

We used two sets of female maturation-at-age and spawning frequency estimates. The first set was based on female maturity data from Arkansas, and the second set was from information in Sharov et al. (2014). For the Arkansas data, maturity-at-length was estimated using a logistic function, and maturity-at-age was estimated using the mean length-at-age using the von Bertalanffy growth parameters for females.

Reference point estimation

Sex-specific yield per recruit (YPR) and SPR models were developed to estimate the effect of fishing mortality on potential roe and meat yields as well as spawning potential of the population. The YPR-SPR model has a similar structure to the model used to estimate selectivity. The model was designed to evaluate the effects of alternative minimum size limits on reference points, and it includes the potential for mortality of released individuals.

Relative abundance at age and sex in the population was calculated using the exponential mortality model,

$$N_{a+1,x} = N_{a,x} e^{-Z_{a,x}} ,$$

where $N_{a,x}$ is the abundance of paddlefish of age a and sex x, and $Z_{a,x}$ is the total instantaneous mortality rate. The model assumed a 50:50 sex ratio at age 1.

The total instantaneous mortality rate was calculated as the sum of the instantaneous fishing ($F_{a,x}$), release ($r_{a,x}$) and natural mortality rates,

$$Z_{a,x} = F_{a,x} + r_{a,x} + M .$$

The instantaneous natural mortality rate was assumed to be 0.093 yr^{-1} (Timmons and Hughbank 2000).

The fishing mortality rate-at-age and sex was calculated as the product of an overall fishing mortality rate and selectivity by age and sex ($s_{a,x}$),

$$F_{a,x} = s_{a,x} F \ .$$

The selectivity-at-age and sex was the weighted average of selectivity-at-length (s_l) and the proportions-at-length for a given age and sex ($P_{a,l,x}$),

$$s_{a,x} = \sum_{l} s_l P_{a,l,x} \, .$$

The proportions-at-length for a given age and sex were calculated assuming a normal distribution of length-at-age for each sex with a constant coefficient of variation (CV = 0.052),

$$P_{a,l,x} = \Phi\left(\frac{L_{l+1} - \bar{L}_{a,x}}{CV \cdot \bar{L}_{a,x}}\right) - \Phi\left(\frac{L_l - \bar{L}_{a,x}}{CV \cdot \bar{L}_{a,x}}\right).$$

The mortality rate caused by releases was calculated as the product of the fishing mortality rate-at-age and sex, the proportion of the catch in an age bin below the minimum size limit (m), and the mortality rate of released fish (d),

$$r_{a,x} = F_{a,x}\left(1 - \Phi\left(\frac{\bar{L}_{a,x} - m}{CV \cdot \bar{L}_{a,x}}\right)\right) d \ .$$

The mortality rate of released fish (10% or 15% mortality; E. Ganus Pers. Comm.) and minimum size limit were specified.

The spawning stock biomass per recruit (SSB/R) was calculated as the product of the number of females at age (N_a), maturity-at-age (t_a), and the average female fecundity-at-age (r_a ; Fig. 2),

$$SSB/R = \sum_{a} N_a t_a f_a \, .$$

The SPR was calculated by dividing the SSB/R at a given fishing mortality rate (SSB/R_F) by the SSB/R with no fishing mortality $SSB/R_{F=0}$,

$$SPR = \frac{SSB/R_F}{SSB/R_{F=0}} \, .$$

SPR describes the expected lifetime spawning potential as a fraction of a scenario with no fishing. A fishing mortality reference point of $F_{30\%}$ (i.e., F that achieves an SPR = 0.3) has been adopted for management of paddlefish in the Mississippi and Ohio rivers. Spawning frequency was also included in a preliminary version of the model, but if spawning frequency is constant with respect to age for mature females, then it is in both the numerator and denominator of the SPR equation and thus cancels out.

Lastly, the roe per recruit was calculated to evaluate how fishing mortality rates and minimum size limits would be expected to affect the caviar fishery. Roe per recruit (RPR) was estimated as the product of the catch of females-at-age, maturity-at-age, spawning frequency (q), and fecundity-at-age summed over ages,

$$RPR = \sum_{a} C_a t_a f_a q \, .$$

The female retained catch-at-age was calculated using the Baranov catch equation (Quinn and Deriso 1999), which is the product of the fraction of the mortality due to fishing, the fraction of fish that die within a year, and the number of fish alive at the beginning of the year,

$$C_a = \frac{F_a}{Z_a}\left(1 - e^{-Z_a}\right) N_a \, .$$

Results

von Bertalanffy growth model

The average length of female fish age-15+ was 972.7 mm, and the average length of age-15+ males was 880.9 mm. The values of the other parameters for the von Bertalanffy model were t_0 =-0.34 and K =0.19 for females and t_0 =-0.32 and K =0.23 for males (Sharov et al. 2014). These parameter values resulted in slight differences between male and female growth patterns (Fig. 3). A common length-weight relationship was estimated for both sexes and all states (Fig. 3).

Mortality rates

The estimated survival rates ranged from 0.65 to 0.7 yr^{-1} depending on assumptions of the first age at full selection (Table 1). These survival rates correspond to total instantaneous mortality rate estimates of 0.35 to 0.43 yr^{-1}. Taking the total instantaneous mortality rate estimates and an assumed natural mortality rate (0.093 yr^{-1}; Timmons and Hughbank 2000), the estimated instantaneous fishing mortality rates were between 0.27 and 0.34. Given the results of the selectivity analysis, using a first fully selected age of 12 is recommended. For this set of assumptions, the estimated fishing mortality rate is 0.34 yr^{-1}.

Selectivity

The selectivity model fit the data relatively well, but the fit to the length data was better than the fit to the age data (Fig. 4). The estimated selectivity at length indicated an eye fork length (EFL) of 860 mm for 50% selectivity (Fig. 5).

Maturation and spawning frequency

The base female maturity-at-length and maturity-at-age functions were estimated using data from Arkansas (Fig. 6). An alternative and maturity-at-age relationships were estimated from data from Sharov et al. (2014) (Fig. 7). This alternative relationship shows a more rapid increase in maturity-at-age than the base scenario.

The data from Arkansas indicated less frequent (than annual) spawning by mature females if salt and pepper ovary condition indicates that a female will not spawn that year. The average spawning frequency from the Arkansas data was approximately 0.5 (i.e., the average female would spawn every other year). The alternative scenario assumed that the average spawning frequency was 0.75 (i.e., the average fish spawned once every 1.33 years (Sharov et al. 2014)).

Reference points

The SPR declined with increasing fishing mortality rate (Fig. 8), but the rate of decline depended on the minimum size limit. Larger minimum size limits resulted in less decline in SPR for any given fishing mortality rate as expected. The $F_{30\%}$ increased as the minimum size limit increased (Fig. 8). For the base set of assumptions and the estimated fishing mortality rate of 0.34 yr^{-1}, a minimum size limit of about 36 in would achieve $F_{30\%}$.

Changing the maturity function using the estimates from Sharov et al. (2014) had a large effect on the estimated SPR and $F_{30\%}$ (Fig. 9) compared to the base scenario. The SPR declined less rapidly with F than under the base scenario. Because of this less rapid decline, the $F_{30\%}$ values were substantially higher than the base scenario. Using the set of assumptions that included the maturity relationship from Sharov et al. (2014) and the estimated fishing mortality rate of 0.34 yr^{-1}, a minimum size limit of about 33 in would achieve $F_{30\%}$.

Increasing the release mortality rate to 15% did not have a substantial effect on the results (Figs. 10 and 11). In both cases, fishing mortality had a slightly larger effect on SPR than the cases with release mortality rates of 10%. Because SPR declined slightly more rapidly under these scenarios, the size limit that was expected to achieve $F_{30\%}$ given a fishing mortality rate of 0.34 yr^{-1}, was slightly larger (Figs. 10 and 11).

The spawning frequency of females had no effect on SPR because the same number is in the numerator and denominator of the final SPR calculation. Thus, it cancels out. However, the spawning frequency does affect the roe per recruit calculations.

RPR was maximized at intermediate values of fishing mortality, but the expected RPR and the fishing mortality that maximized RPR depended on the minimum size limit and assumptions about maturity and spawning frequency (Figs. 12 and 13). For the base scenario, RPR was maximized at a fishing mortality rate of about 0.2 yr^{-1} with a 32 in minimum size limit. If a 32 in minimum size limit reflects the integrated size regulations across states, then the estimated fishing mortality rate (F = 0.34 yr^{-1}) would represent growth overfishing (i.e., over the long term, a higher caviar yield would be achieved at a lower fishing mortality rate). The fishing mortality rate that maximizes RPR increases with increasing mesh sizes. At current estimated fishing mortality rates (F = 0.34 yr^{-1}), the minimum size limit would need to be 36 in to end growth overfishing under the base model assumptions (Fig. 12). These results are highly sensitive to the maturation-at-age relationship, as the alternative analysis using the Sharov et al. (2014) values did not indicate growth overfishing. This is likely because that analysis assumed earlier maturation-at-age.

Discussion

Collection of biological data from the commercial fishery for paddlefish in the Mississippi and Ohio rivers was recently implemented or enhanced. These data can be used to estimate mortality rates as well as reference points for sustainable fishery management. We used a combination of mortality rate estimation and SPR-based reference point models to evaluate sustainability of the fishery. Additionally, an RPR model was used to evaluate potential changes in fishing mortality rates on the caviar fishery. One of the primary reasons for conducting the analysis was to determine if the minimum length limits currently in place are adequate for management of commercial paddlefish fisheries in the Mississippi and Ohio rivers. A minimum size limit of 36 in was necessary to achieve estimated $F_{30\%}$ under the base maturity relationship. Indeed, in the analyses presented in this report, the caviar yield per recruit was expected to be higher under the highest minimum size limit. In contrast, the estimated fishing mortality rate (0.34 yr^{-1}) was near the estimated $F_{30\%}$ for a minimum size limit of 33 in (using the alternative assumptions). This difference in conclusions highlights the importance of understanding the maturity and growth for paddlefish to inform sustainable fishery management. It may be possible to use the data from the commercial monitoring programs to re-estimate that maturation curve for female paddlefish as the results of the model are very sensitive to these assumptions. Regardless of the data used to re-estimate to maturation of Mississippi and Ohio river paddlefish, this remains an important topic.

The target fishing mortality rate interacts with the minimum size limit. The analyses conducted in this study assumed that the goal was to find the minimum size limit that achieved the target fishing mortality rate assuming that the current fishing mortality rate would continue. One could consider changing the fishing mortality rate while keeping the minimum length limit constant or a combination of the two. In terms of the SPR model, there is an equivalency between increasing the minimum size limit and decreasing the fishing mortality rate in that either option could be done to achieve a specific SPR percentage. Therefore, management may want to consider ways to change the fishing mortality rate in addition to changes in the minimum size limit.

Hupfeld et al. (2016) conducted a similar analysis and recommended that minimum size limits for paddlefish be at least 32 in (810 mm). Although there are several differences between their analyses and the ones presented here, the two largest ones are the potential life span of paddlefish and the maturation curve. Hupfeld et al. (2016) assumed terminal ages of paddlefish equal to the maximum observed age in each system. This means that paddlefish longevity cannot exceed the highest observed age. In contrast, the analyses presented here assumed no maximum age because paddlefish have been aged to 60+ years in other parts of their range. The second important assumption is the maturation pattern. The maturation patterns in Hupfeld et al. (2016) assumed earlier maturation-at-age than the base scenario for this study, but were about the same as the relationship from Sharov et al. (2014). This difference in maturation-at-age is the cause of most of the difference in conclusions about the effects of minimum size limits between the two studies, and has been discussed as an important source of uncertainty at MICRA meetings (E. Ganus Pers. Comm.).

The analyses that were conducted assumed that paddlefish in the Mississippi and Ohio rivers constituted a mixed stock because all samples were pooled prior to analyses. This assumption about a common stock in this region seems reasonable given recent observations of the movement of tagged fish (Kramer et al. 2017). Given the likely mixing of paddlefish at this large scale, coordinated management among states will likely be necessary for fishery sustainability (Hupfeld et al. 2016, Kramer et al. 2017).

Interjurisdictional fisheries management is often complicated because of the coordination necessary for joint management. When jurisdictions have different regulations, it can cause problems for enforcement as well as assessment of mortality rates and other population parameters. In an ideal setting, jurisdictions that share resources would have the same regulations because differences in regulations can also cause issues in determining sustainable harvest rates and may result in a “fairer” distribution of the harvest. Because the idea of a fair distribution of harvest is subjective, a common problem for interjurisdictional management is the allocation of the resource among jurisdictions. There is rarely a biological solution to this problem.

The current study estimated total mortality rates between 0.35 and 0.43 yr^{-1}, depending on assumptions about the first age of full selection. Accounting for natural mortality of 0.093 yr^{-1} (Timmons and Hughbank 2000), fishing mortality rates were estimated to be between 0.26 and 0.34 yr^{-1}, which correspond to estimated exploitation rates (fraction of the population harvested) of 22-28% yr^{-1} for fully selected ages. These values are substantially higher than those that have been estimated from a recent tagging study. Kramer et al. (2017) estimated an exploitation rate of only 4% yr^{-1}. One possible explanation for the difference between the two studies is that the Kramer et al. (2017) estimate is over all ages and sizes of paddlefish that were tagged in their study, while the estimate in this study is only for fully selected ages (i.e., large) paddlefish. Many of the fish in the Kramer et al. (2017) study were small enough (range 559 - 1070 mm in 2016; S. Tripp, Pers. Comm.) that they would have low selection. For example, the mortality rate estimated in Kramer et al. (2017) is about the same as the mortality rate estimated in the current study for an 800 mm individual (0.06 yr^{-1}). In the future, it may be possible to compare length-specific exploitation rates for comparison with the current study. It may also be possible to use the data from Kramer et al. (2017) to estimate natural mortality for paddlefish in the system. It is possible that aging error (in particular, under-aging) could also reconcile the results of the two studies.

Aging error can cause substantial bias in the estimation of growth and mortality from age-structured data (Quinn and Deriso 1999). If fish are under-aged (i.e., the recorded age is lower than the individual's true age), on average, it will result in positively biased mortality rate estimates. Because of the importance of accurate ages for estimating mortality rates and age-specific life-history parameters, a study of the accuracy of jaw bone aging in the Mississippi and Ohio Rivers is recommended. Because there have been paddlefish tagged with coded wire tags at stocking, known age fish are available to study the accuracy of ages (even though the numbers are relatively low). It is recommended that a study to estimate aging error be conducted using known age fish.

The choice of a reference point for sustainable fisheries management usually involves some degree of expert judgement. In particular, the percentage used for SPR-based reference points is equivalent to making an assumption about the amount of density dependence in the stock-recruit relationship. Because of this equivalence, if the stock is less productive than is assumed, it is possible to overfish a stock if the wrong percentage is chosen. For example, Clark (1991) originally proposed $F_{35\%}$ for stocks with high longevity and low resiliency, but later updated the recommendations to $F_{40\%}$ (Clark 2002). Because of these recommendations and other analyses, longer-lived (i.e., 20+ years) marine fish stocks are commonly managed using SPR target percentages in the range of $F_{35\%}$-$F_{40\%}$. In many systems the target reference point includes some amount of precaution for uncertainty.

The models used in this study were all equilibrium models in that they did not consider the effects of variability in vital rates or recruitment. These types of equilibrium models are commonly used to determine sustainable fishing mortality rate reference points in many fisheries around the world, so they have a long and tested history. The portion of the analysis that is most likely affected by variability is the mortality rate estimation. While the method is approximately unbiased under random recruitment variability, if there has been a trend in recruitment, the mortality rate estimates can be biased. Lastly, the models used in this study assume constant growth patterns over time. If paddlefish prey availability changes substantially (e.g., due to an invasive species), then the analyses would need to be reconsidered in light of the new conditions.

In conclusion, this study estimated the mortality rates and SPR reference points for paddlefish in the Mississippi and Ohio rivers. The results of the reference point calculations indicated that under the base model assumptions a minimum size limit of 36 in may be appropriate to achieve $F_{30\%}$ and to increase caviar yield over the long term. However, the results were quite sensitive to assumptions about the female maturation curve, and additional research on this topic is warranted.

Acknowledgments

I thank all the states for providing the data and the state biologists for providing critical feedback on the analyses.

References

Clark, W. G. 1991. Groundfish exploitation rates based on life history parameters. Canadian Journal of Fisheries and Aquatic Sciences 48:734–750.

Clark, W.G. 2002. F35% revisited ten years later. North American Journal of Fisheries Management 22:251–257.

Fournier, D., and C.P. Archibald. 1982. A general theory for analyzing catch at age data. Canadian Journal of Fisheries and Aquatic Sciences 39:1195-1207.

Hupfeld, R.N., Q.E. Phelps. S.J. Tripp, D.P. Herzog. 2016. Mississippi River Basin Paddlefish Population Dynamics: Implications for the Management of a Highly Migratory Species. Fisheries 41:600-610.

Kramer, N., Q. Phelps, S. Tripp, and D. Herzog. 2017. Exploitation of paddlefish *Polyodon spathula* (Walbaum, 1792) in the Mississippi River. Journal of Applied Ichthyology 35:355–359.

Millar, R.B. 2015. A better estimator of mortality rate from age-frequency data. Canadian Journal of Fisheries and Aquatic Sciences 72:364–375.

Quinn, T.J. II, and R.B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.

Seber, G.A.F. 1980. Estimation of Animal Abundance, 2nd Edition. The Blackburn Press. Caldwell, NJ.

Sharov, A., M. Wilberg, and J. Robinson. 2014. Developing biological reference points and identifying stock status for management of Paddlefish (*Polyodon spathula*) in the Mississippi River basin. U.S. Fishand Wildlife Service, Final Report, Falls Church, Virginia.

Timmons, T.J., and T.A. Hughbank. 2000. Exploitation and Mortality of Paddlefish in the Lower Tennessee and Cumberland Rivers. Transactions of the American Fisheries Society 121:1171-1180.

Table 1. Estimated survival (S), total instantaneous mortality rate (Z), lower and upper 95% confidence interval bounds for Z (Z lower 95% and Z upper 95%), and instantaneous fishing mortality (F) for Mississippi and Ohio River paddlefish by assumed first age of full selection. The instantaneous fishing mortality rate was estimated (F = Z – M) by subtracting an assumed natural mortality rate (M = 0.093) from the estimated Z.

	First age of full selection					
Estimate	10	11	12	13	14	15
S	0.704	0.674	0.649	0.657	0.668	0.696
Z	0.351	0.394	0.433	0.421	0.404	0.362
Z lower 95%	0.333	0.372	0.404	0.386	0.363	0.316
Z upper 95%	0.368	0.417	0.462	0.456	0.447	0.410
F	0.258	0.301	0.340	0.328	0.311	0.269

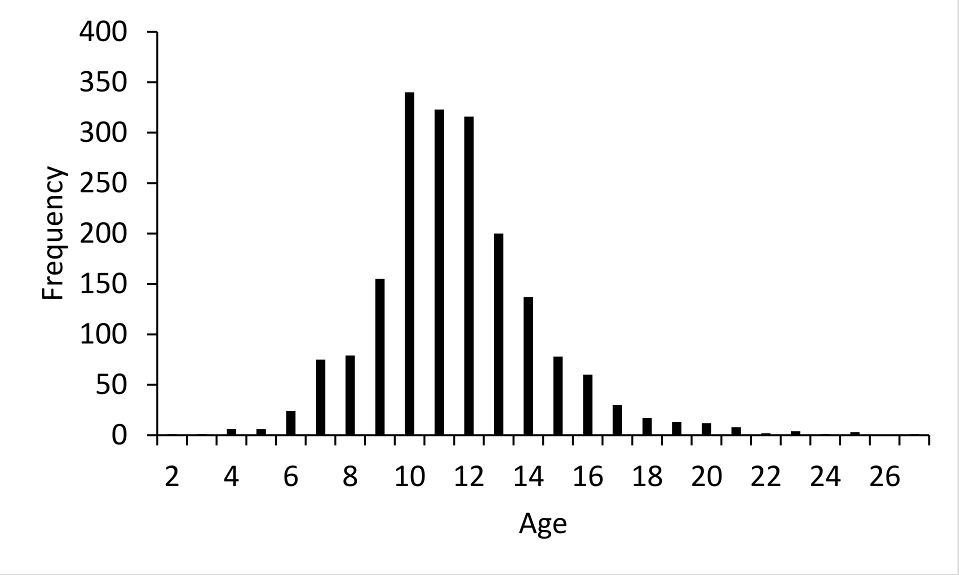

Fig. 1. Observed age frequency for Mississippi and Ohio River paddlefish from Indiana, Missouri, Ohio, and Tennessee during 2015-2017. Data were combined over states, sexes and years.

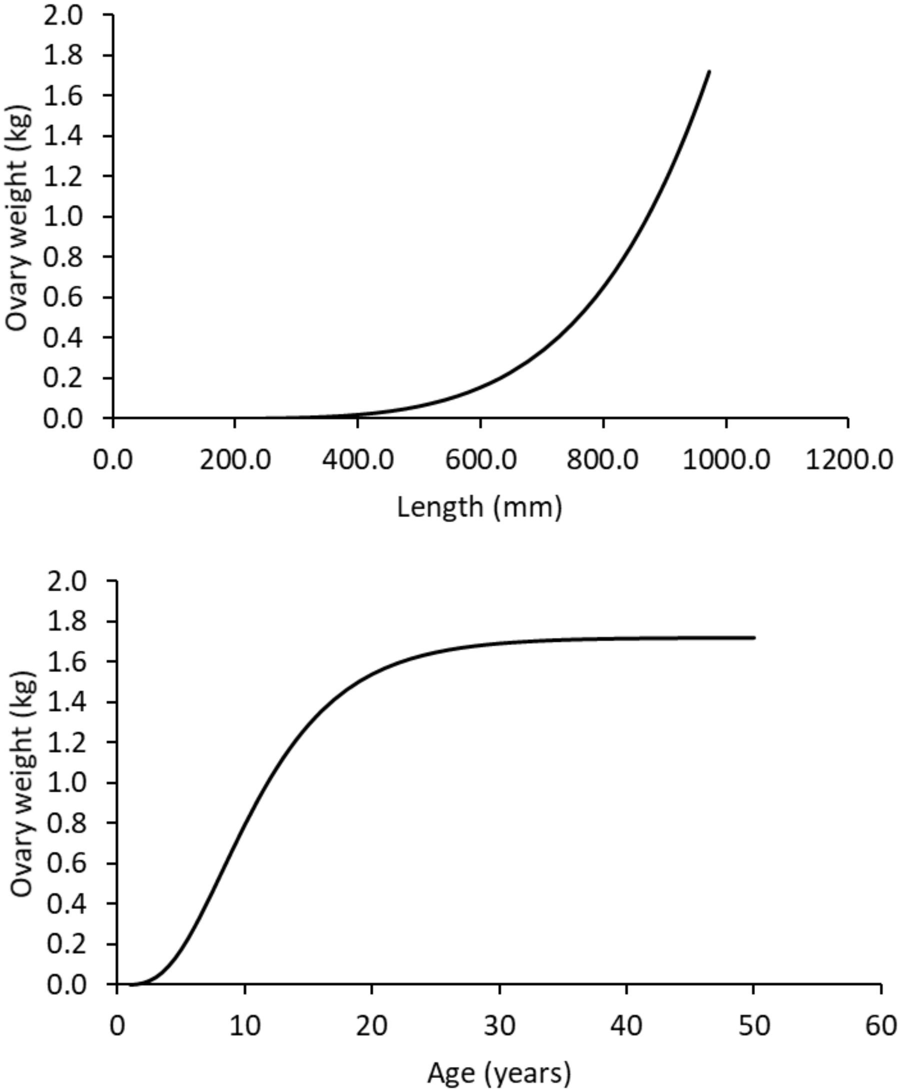

Fig. 2. Ovary weight used in the spawning potential ratio model as a function of length (upper panel) and age (lower panel).

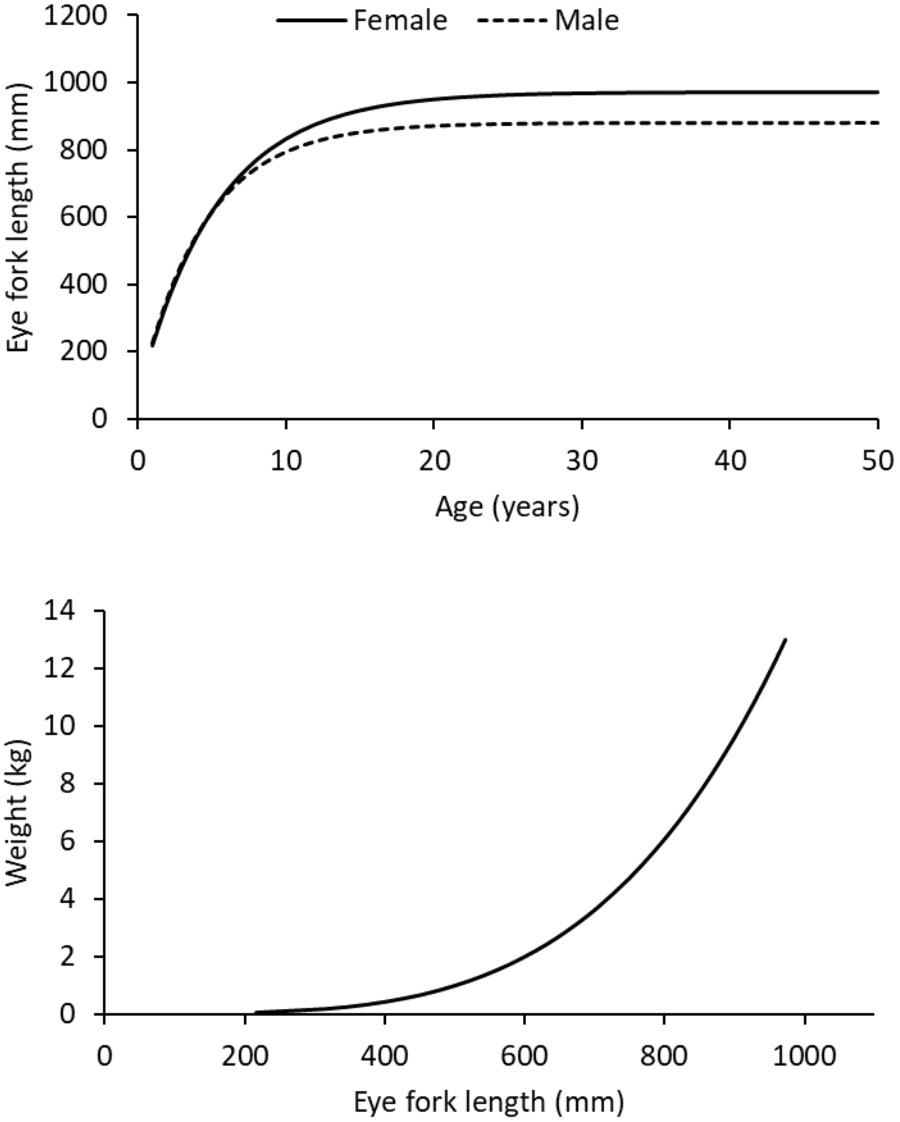

Fig. 3. Average eye fork length-at-age (upper panel) and average weight-at-length (lower panel) for Mississippi and Ohio River paddlefish.

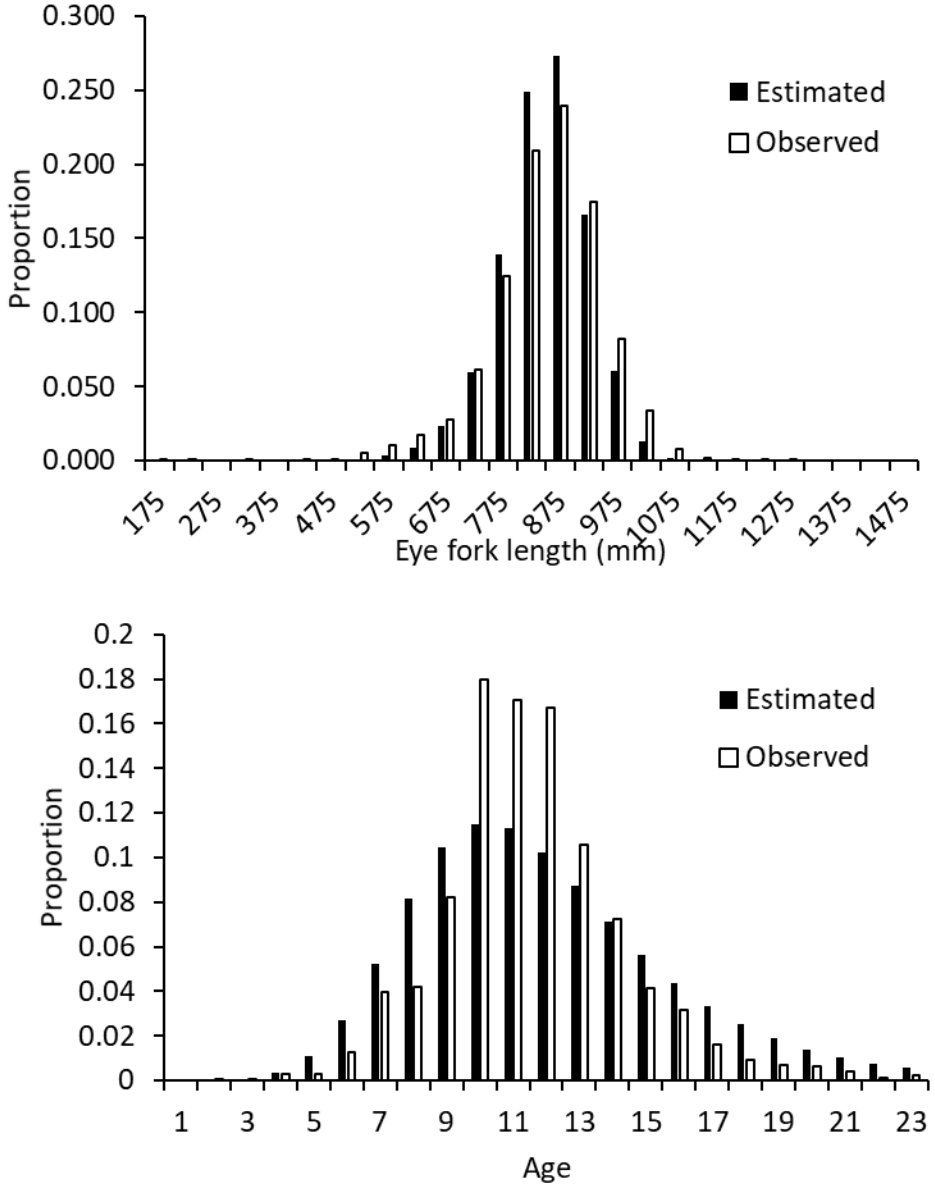

Fig. 4. Fits of selectivity model to the observed length (upper panel) and age (lower panel) frequencies of Mississippi and Ohio river paddlefish. The black bars indicate the observed values and the white bars the estimated values.

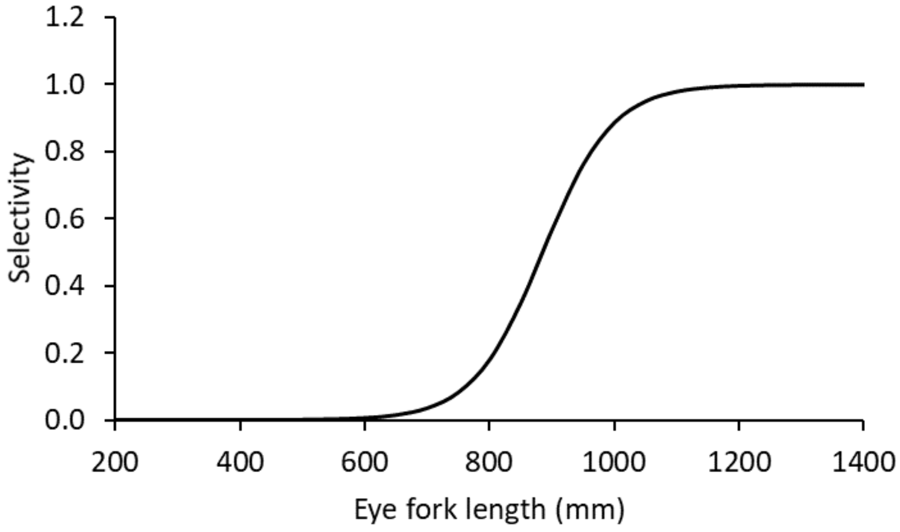

Fig. 5. Estimated selectivity-at-length for Mississippi and Ohio river paddlefish.

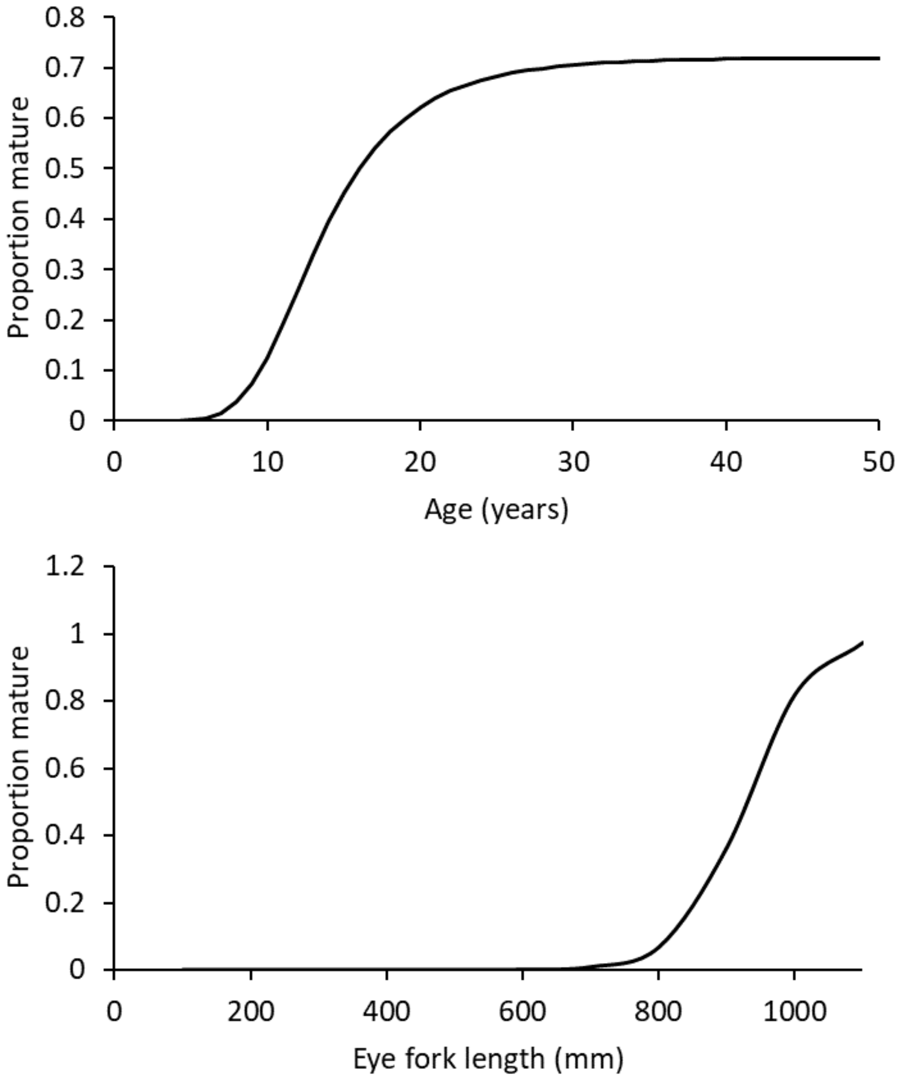

Fig. 6. Female maturity-at-length and maturity-at-age from Arkansas data.

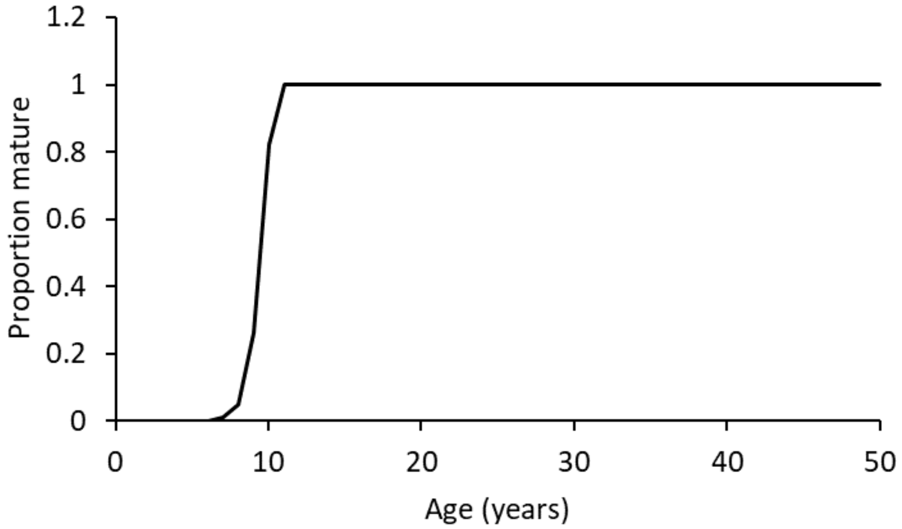

Fig. 7. Female maturity-at-age for paddlefish from Sharov et al. (2014).

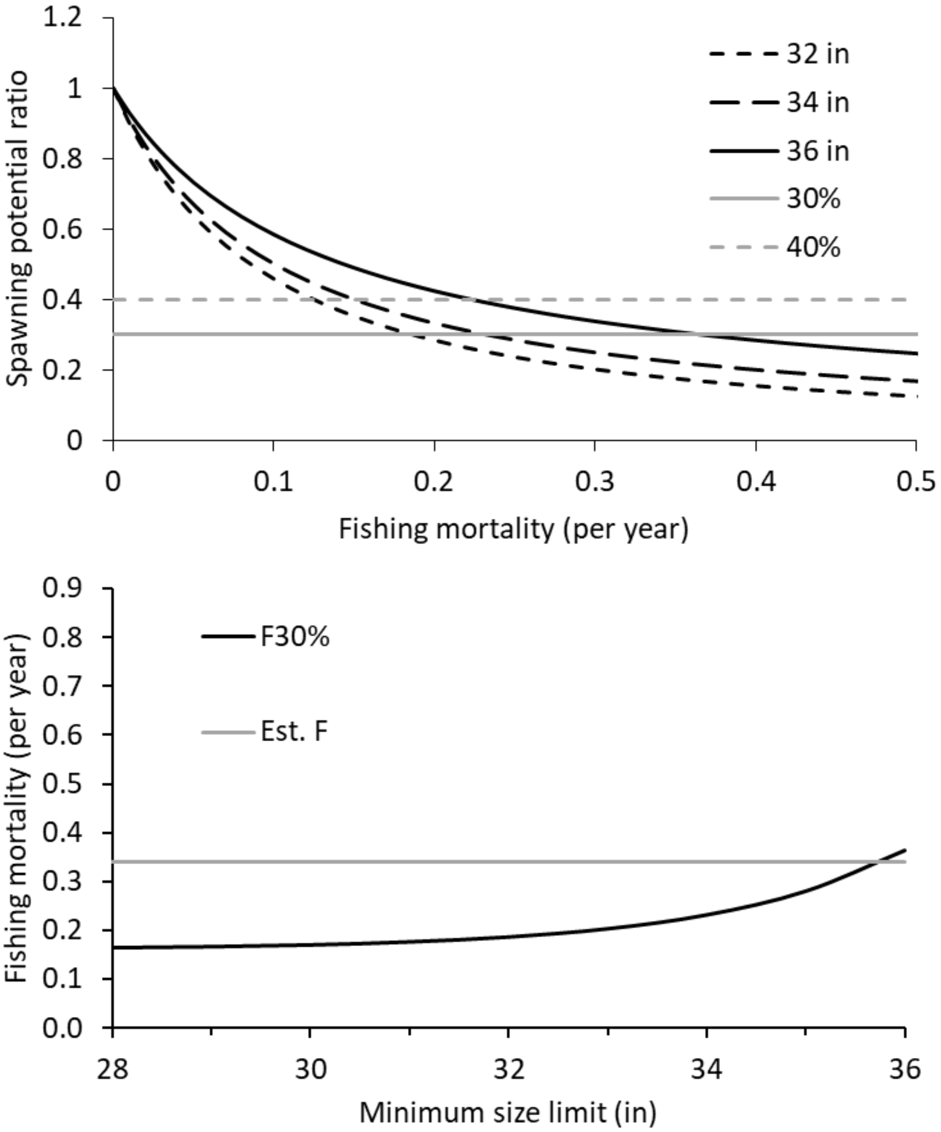

Fig. 8. Base scenario (using the Arkansas maturity schedule; release mortality = 0.1) spawning potential ratio (SPR) for Mississippi and Ohio river paddlefish versus fishing mortality rate (upper panel) and the fishing mortality rate that achieves 30% of maximum SPR (F30%) as a function of the minimum size limit (lower panel). In the upper panel, reference lines at 30% and 40% maximum SPR are included as commonly used reference points. In the lower panel, the estimated fishing mortality rate (Est. F) is included.

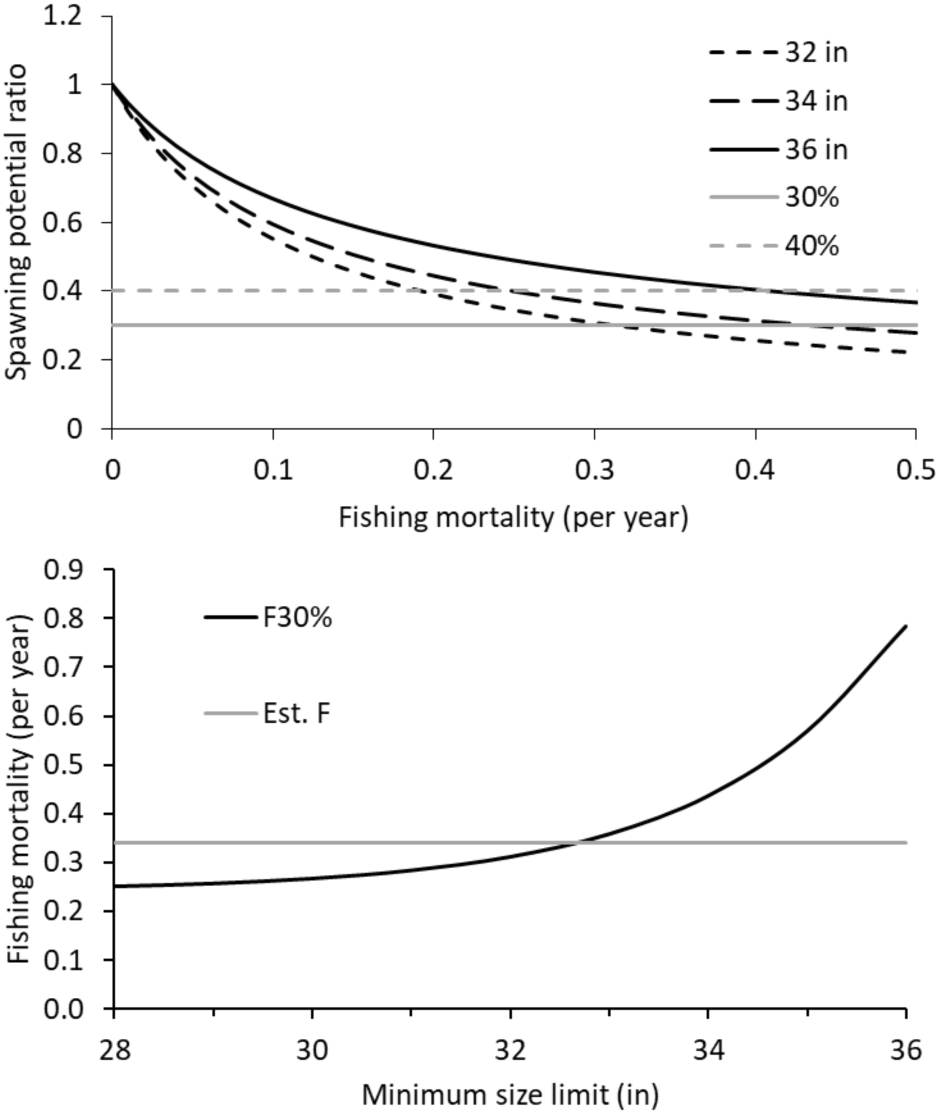

Fig. 9. Alternative scenario (maturity-at-age from Sharov et al. (2014); release mortality = 0.1) spawning potential ratio (SPR) for Mississippi and Ohio river paddlefish versus fishing mortality rate (upper panel) and the fishing mortality rate that achieves 30% of maximum SPR (F30%) as a function of the minimum size limit (lower panel). In the upper panel, reference lines at 30% and 40% maximum SPR are included as commonly used reference points. In the lower panel, the estimated fishing mortality rate (Est. F) is included.

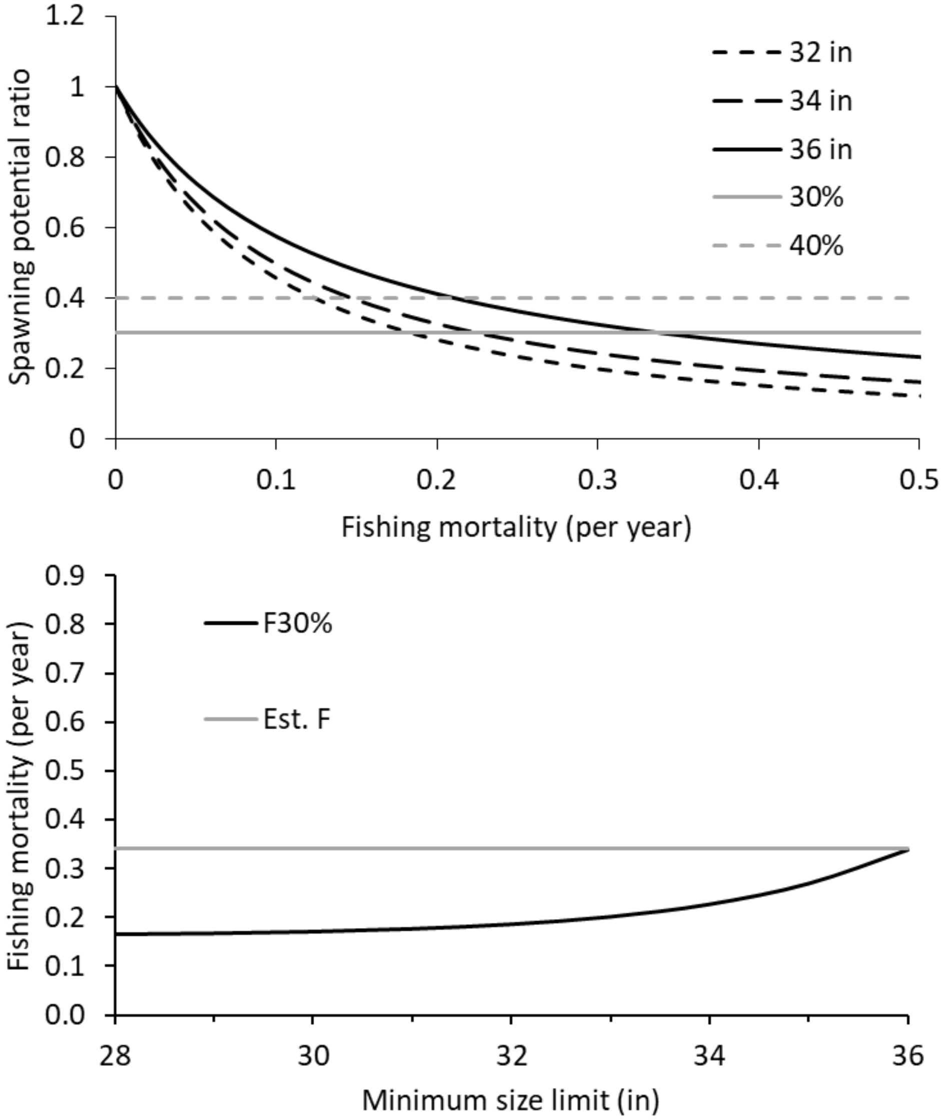

Fig. 10. Sensitivity scenario (Arkansas maturity schedule scenario; release mortality = 0.15) spawning potential ratio (SPR) for Mississippi and Ohio river paddlefish versus fishing mortality rate (upper panel) and the fishing mortality rate that achieves 30% of maximum SPR (F30%) as a function of the minimum size limit (lower panel). In the upper panel, reference lines at 30% and 40% maximum SPR are included as commonly used reference points. In the lower panel, the estimated fishing mortality rate (Est. F) is included.

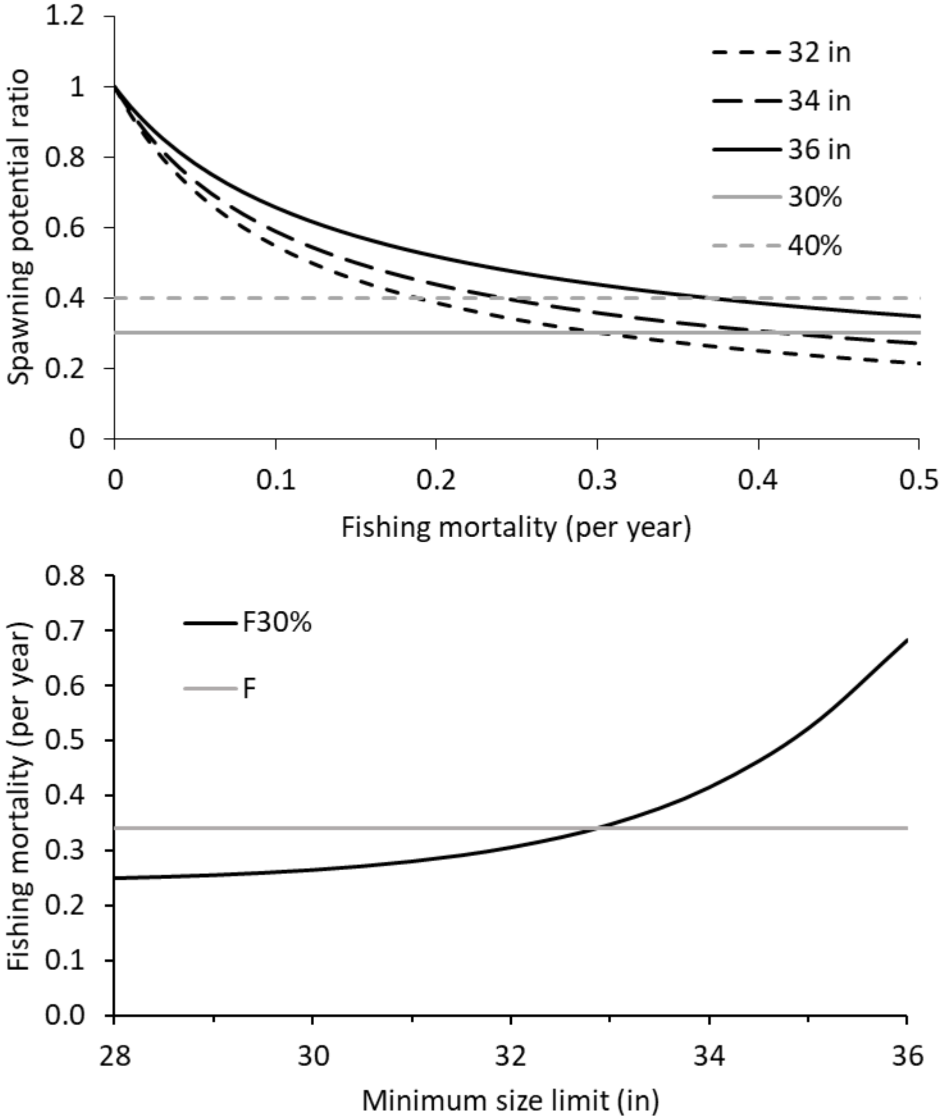

Fig. 11. Sensitivity scenario (Sharov et al. (2014) maturation; release mortality = 0.15) spawning potential ratio (SPR) for Mississippi and Ohio river paddlefish versus fishing mortality rate (upper panel) and the fishing mortality rate that achieves 30% of maximum SPR (F30%) as a function of the minimum size limit (lower panel). In the upper panel, reference lines at 30% and 40% maximum SPR are included as commonly used reference points. In the lower panel, the estimated fishing mortality rate (Est. F) is included.

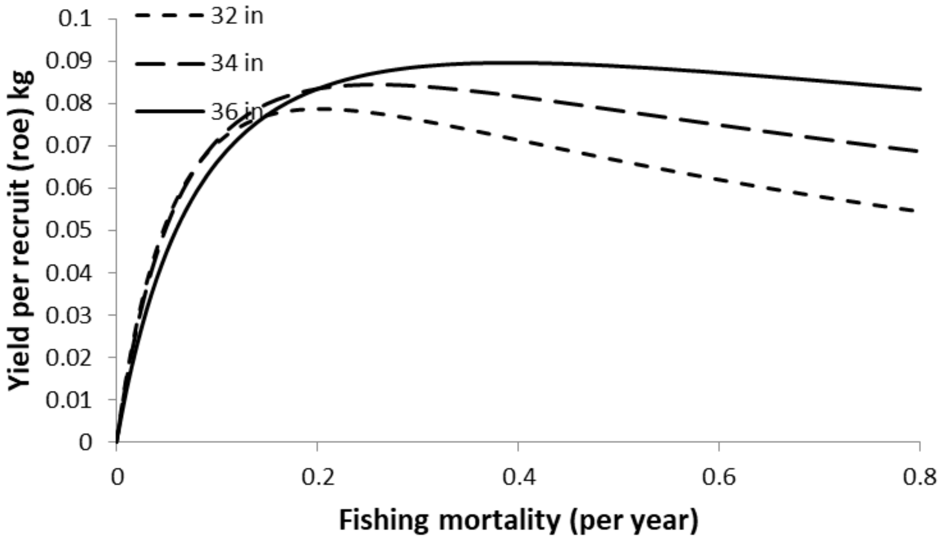

Fig. 12. Roe per recruit for Mississippi and Ohio rivers paddlefish for several potential minimum size limits (using the base model assumptions).

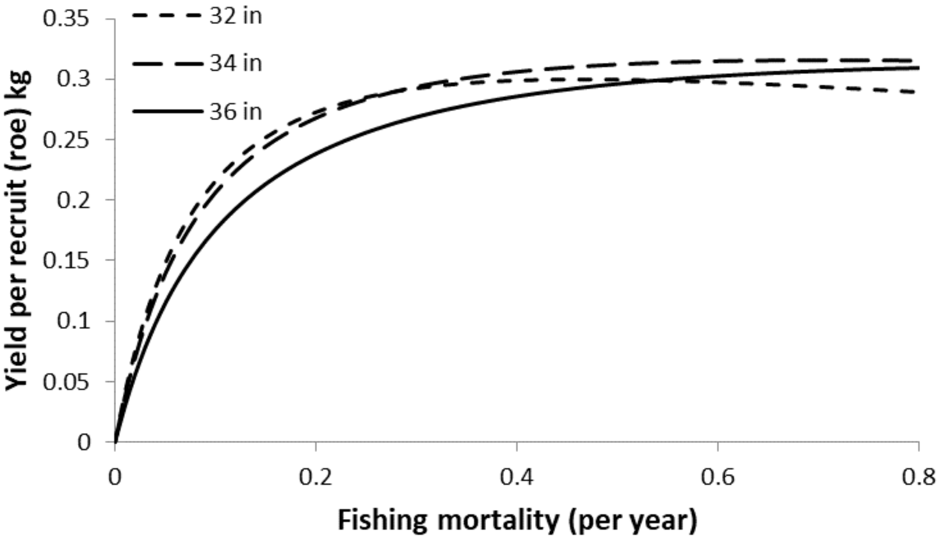

Fig. 13. Roe per recruit for Mississippi and Ohio rivers paddlefish for several potential minimum size limits (using the alternative Sharov et al. 2014 model assumptions).