Evaluation of the Commercially Exploited Paddlefish Fishery in the Lower Mississippi River of Arkansas

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Abstract: Paddlefish (*Polyodon spathula*) are a commercially-exploited species harvested primarily for their roe. The objectives of this study were to describe population characteristics of paddlefish in the lower Mississippi River (LMR) of Arkansas and use population-simulation software to determine the length limit required to prevent recruitment overfishing by maintaining spawning potential ratios (SPR) over 30%. Paddlefish ($n = 534$) were collected from the LMR in cooperation with commercial fishers during the 2008–2011 commercial seasons. Lengths ranged 150–1095 mm eye-fork length and ages, 2–24 years. Total annual mortality was estimated from catch curves at 28%, and mean instantaneous natural mortality was estimated to be 0.19, conferring an estimated exploitation of 10%. Only 10% of gravid females were under the existing 864-mm minimum-length limit (MLL), but changing the MLL to 889 mm would protect an additional 10%. Growth models predicted that fish required 10.8 and 11.8 years to reach 864 mm and 889 mm, respectively. Population simulations predicted higher roe yields for 899- and 916-mm MLL compared to the existing 864-mm MLL. The threat of recruitment overfishing appeared to be low at 10% exploitation rate for all MLLs. Based on the results of this study, the Arkansas Game and Fish Commission instituted an 889-mm MLL in 2013 to protect the sustainability of the paddlefish population in the LMR. As of 2016, the effectiveness of this regulation had not been assessed yet due to lack of funding.

Key words: Polyodon spathula, harvest, spawning potential ratio, population modeling

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Paddlefish (*Polyodon spathula*) are long-lived, large-river fish that prefer habitats with abundant zooplankton and reduced current velocities (Jennings and Zigler 2000). They are harvested by recreational and commercial fishers, but commercial fishing has been shown to negatively impact paddlefish populations, especially in lentic waters where gill nets are highly effective (Pasch and Alexander 1986, Scholten and Bettoli 2005, Quinn 2009). Paddlefish roe can be up to 200 times more valuable than their flesh (Colvin et al. 2013); thus, harvest efforts are directed towards large, egg-bearing females (Quinn et al. 2009). Selective harvest of gravid females can increase the threat of recruitment overfishing, especially because paddlefish require 8–10 years to mature and females may not reproduce annually (e.g., Scarnecchia et al. 2007, Sharov et al. 2014).

Since the 2008–2009 season, all states bordering the lower Mississippi River (LMR) except Louisiana allowed commercial harvest. At the time this study was conducted, the minimum-length limit (MLL; hereafter, existing MLL) on the Mississippi River in Arkansas was 864-mm (eye-fork length [EFL]), with an open season from 20 November to 10 April (142 days). However, commercial fishing regulations varied among states bordering the LMR (Scholten 2009), despite the interjurisdictional nature of the fishery. The Mississippi River is the top-ranked paddlefish-roe-producing river in Arkansas, and annual mean processed roe harvest from 2002 to 2015 averaged 2070 kg (SD = 880; Arkansas Game and Fish Commission, unpublished data).

The ability of the paddlefish population in the LMR to sustain this level of harvest is unknown. Therefore, the purpose of this study was to determine the MLL required for sustainable commercial harvest in the Arkansas section of the LMR. The objectives of this study were to 1) describe the population characteristics of paddlefish in the LMR, and 2) use population simulation software to determine susceptibility of paddlefish to recruitment overfishing with varying modeled length limits.

Methods

Paddlefish were collected from the Mississippi River in cooperation with commercial fishers during the 2008–2011 commercial seasons. Paddlefish were collected upstream and downstream of the confluence of the White River (river km 933 to 982) and near Greenville, Mississippi (~ river km 842 to 879). We accompanied commercial fishers as they checked their gear. Fishers used monofilament hobbled gill nets ranging in length from 45.7 to 182.9 m, with net heights ranging from 3 to 9 m, and 127-mm bar mesh.

Soak time varied from 24 to 72 h, depending on weather conditions.

All paddlefish captured were measured (EFL, mm), weighed to the nearest 0.05 kg, and gender was assigned by internal exam. Males were identified by the presence of tubular testes. Females were classified as gravid (large dark eggs) or non-gravid (white or pink striated ovaries). Ovaries with salt-and-pepper coloration (atretic oocytes) were noted, which indicated that these fish may have spawned the previous season (Bruch et al. 2001). Mean lengths and weights were calculated for males, non-gravid females, salt-and-pepper females, and gravid females. An analysis of variance (ANOVA) was used to determine differences in mean length and weight among groups. A Tukey's multiple comparison test was used to test differences between groups when significance was identified. Length-frequency distributions were compiled in Excel. An analysis of covariance (ANCOVA) was used to examine differences in male and female weight-length regressions (Pope and Kruse 2007).

All paddlefish collected had the left dentary bone extracted for age determination (Adams 1942, Scarnecchia et al. 2006). Using a low-speed Buehler Isomet 1000 saw, five to seven 0.8-mm thick cross sections were cut from the dentary posterior to the mesial arm. A double blind procedure was used to assign ages. Two readers independently assigned age without knowledge of size or gender. If ages did not agree after the initial reading, fish were independently aged again. If ages did not agree after the second reading, readers aged the fish together. If consensus was not reached during the third reading, age was not assigned and the fish was removed ($n = 7$) from analyses (Scarnecchia et al. 2006).

After ages were assigned, cross sections were used to back-calculate length-at-age. Measurements were made between annuli from the central lumen to the edge of the mesial arms using Motic Images Plus Version 2.0 software (Hoffnagle and Timmons 1989, Reed et al. 1992). The direct proportion method was used to estimate length at age. Von Bertalanffy growth curves were fitted to mean back-calculated length-at-age data by gender. We used the Akaike Information Criterion, corrected for small sample size (AICc), to select the most parsimonious model that describes differences in von Bertalanffy growth parameters (L_∞, K, t_0) between genders (Ogle 2016a). Eight alternative models were considered including a full three parameter model (growth varies by L_∞, K, t_0), three models that combined two of the three parameters (e.g., L_∞, K), three one-parameter models (e.g., L_∞), and one null model where all parameters do not vary. Models with the lowest AICc were considered the best fit. The ratio of the weights is the strength of evidence of one model over another, and models with weights >0.25 should be retained (Williams et al. 2002).

Total annual mortality (A) and total instantaneous mortality (Z) were calculated for each gender using a weighted catch curve for ages 9 (full recruitment) to 24 (Ricker 1975, Maceina 1997). An ANCOVA was used to examine differences in slope of weighted catch curves among genders. Natural and fishing mortality rates of paddlefish were unknown; therefore, instantaneous natural mortality (M) and conditional natural mortality (*cm*) were estimated by averaging the results from four natural mortality equations (i.e., Hoenig 1983, Chen and Watanabe 1989, Jensen 1996, Quinn and Deriso 1999) in the Fisheries Analysis and Modeling Simulator (FAMS; Slipke and Maceina 2010). We calculated instantaneous fishing mortality (F) as $F = Z - M$. Exploitation (u) was calculated as $u = \frac{F \times A}{Z}$.

Ovaries of gravid females were extracted and weighed to the nearest gram. All eggs were counted from a 50-g subsample to estimate fecundity. Total number of eggs per gravid female (i.e., absolute fecundity) was estimated by extrapolating number of eggs in the subsample to total ovary weight. Relative fecundity was estimated as eggs per kg of body weight (Reed et al. 1992). Linear regression was used to derive fecundity-length and fecundity-weight relationships. We used logistic regression, specifying a binomial distribution, to predict gravidity (gravid females) and maturity (gravid and salt-and-pepper females) as a function of EFL (Colvin et al. 2013, Ogle 2016b). We used the maturity model to predict the percent mature by size limit, and 95% confidence intervals were developed by bootstrapping (Ogle 2016b). Logistic regression models were also used to calculate length at 50% maturity and gravidity, and linear regression was used to predict ovary weight from EFL using natural logarithm-transformed data.

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 effects of five different MLLs on roe yield (kg) and Spawning Potential Ratio (SPR; Goodyear 1993) across a range (0.05–0.60) of exploitation rates. Modelling was conducted by modifying an R script provided by M. Colvin (Mississippi State University). We used female rate functions for modeling because they are targeted and selected by the fishers. Because we found no gravid females smaller than 762 mm EFL, this length was used to simulate a no-MLL scenario. Other MLLs evaluated included: 838 mm (requested by commercial fishermen), 864 mm (existing regulation), 889 mm, and 914 mm. The larger two length limits modeled were chosen because they have been used in other Arkansas waters. Parameter estimates used in the model are provided in Table 1. All four estimates of cm were within a 0.02 range; therefore models were conducted using the mean cm. Critical levels of SPR used were 30% (SPR_{30}), below which harvest may not be sustainable, and 20% (SPR_{20}), below which recruitment overfishing could occur (Scholten and Bettoli

Table 1. Parameters used for population modeling. Growth coefficients and weight-length regression were derived from female paddlefish. Conditional natural morality rates were estimated from four equations found in the Fisheries Analysis and Modeling Software package.

Metrics	Parameters modeled
Weight-length coefficient	Intercept (a) = –5.625
	Slope (b) = 3.258
von Bertalanffy growth coefficients	L_∞ = 1083 mm
	K = 0.137
	t_0 = –0.941
Logit gravidity-length coefficients	Intercept = –12.765
	Slope = 0.0128
Ovary-weight coefficients	Intercept = –19.502
	Slope = 2.95
Maximum age	24 yr
Conditional natural mortality	0.18
Conditional fishing mortality	0.05 to 0.60
Minimum length limits modeled	762, 838, 864, 889, and 914 mm
Proportion female	0.54
Female conditional natural mortality estimates:	
• Chen and Watanabe (1989) – 0.18	
• Hoenig (1983) – 0.16	Mean = 0.18
• Jensen (1996) – 0.19	
• Quinn and Deriso (1999) – 0.18	

Table 2. Mean lengths (mm) and weights (kg) of gravid females, salt and pepper females, non-gravid females, and males collected in this study. Mean lengths or weights sharing superscripts did not differ (Tukey's multiple comparison test, *P* > 0.05).

	Length (mm)			Weight (kg)		
	n	*Mean*	*SE*	*n*	*Mean*	*SE*
Gravid females	61	946[a]	8	55	12.7[a]	0.4
Salt-and-pepper females	36	959[a]	12	36	11.7[a]	0.5
Non-gravid females	185	813[b]	9	185	7.7[b]	0.2
Males	243	797[b]	6	243	7.2[b]	0.2
Total	525	831	5	519	8.3	0.1

Table 3. Akaike Information Criterion model selection of Von Bertalanffy growth parameter differences between female and male paddlefish using back-calculated mean lengths-at-age. The full model indicates all three growth parameters (L_∞, K, and t_0) differ between genders and the null model indicates constant parameters between genders.

Model	Parameters	AICc	ΔAIC	Weight
Full	6	345.34	0.00	0.58
L_∞, K	5	345.97	0.64	0.42
L_∞, t_0	5	359.11	13.78	0.01
L_∞	4	364.46	19.13	0.00
K, t_0	5	378.50	33.16	0.00
K	4	381.99	36.66	0.00
Null	3	386.38	41.05	0.00
t_0	4	388.17	42.84	0.00

2005, Colombo et al. 2007). We determined the percentage of fish captured that would be protected under several length limits (762, 838, 864, 889, 914 mm), by gender and reproductive status. The number of age-1 recruits in the model was fixed at 1000 individuals, which is a commonly used value for yield models (Colvin et al. 2013).

Results

Paddlefish were sampled twelve days in the 2008–2009 season, three days in the 2009–2010 season, and two days in the 2010–2011 season. A total of 534 paddlefish was collected in 12,573 m of netting. Data from nine juveniles (150–175 mm EFL) were not used in analyses because gender could not be assigned. Gender was determined for 525 paddlefish (243 males, 185 non-gravid females, 36 salt-and-pepper females, and 61 gravid females). The percent of males (46%) collected was similar to that of females (54%). Gravid females represented 12% of fish collected (Table 2). Over half of the female paddlefish (59%) and almost a quarter of the male paddlefish (22%) collected were longer than the existing 864-mm MLL (Figure 1). There was a significant difference in mean lengths ($F = 61.67$; $df = 3, 521$; $P < 0.001$) and mean weights ($F = 77.89$; $df = 3, 515$; $P < 0.001$) among males, and the various maturity categories of females, with gravid females and salt-and-pepper females having higher mean lengths and weights than non-gravid females and males (Table 2). However, weight-length regressions were similar between genders ($F = 1.17$; $df = 1, 515$; $P = 0.28$). The weight-length regression for females was $\log_{10}(g) = -5.63 + 3.26 \log10$ (EFL; $P < 0.001$; $r^2 = 0.96$) and males was $\log_{10}(g) = -5.41 + 3.19 \log10$ (EFL; $P < 0.001$; $r^2 = 0.94$).

Paddlefish ranged in age from 3 to 24 years (mean = 10 years; SE = 0.1; Figure 1). The von Bertalanffy growth equation for females was $L_t = 1083\ [1 - e^{-0.14\ (t + 0.94)}]$ and for males was $L_t = 990\ [1 - e^{-0.17\ (t + 0.65)}]$ (Figure 2). Model selection using AICc supported a difference in growth parameters between genders (Table 3). Models retained with weights >0.25 included the full model and the two-parameter model L_∞, K. The full model was 1.38 times (0.58/0.42) more likely than the L_∞, K model. The von Bertalanffy models predicted female and male paddlefish reached the existing 864-mm MLL in 10.5 and 11.5 years, respectively. Growth of both sexes slowed above this length, although females grew faster than males.

Total annual mortality (A) was 27% for females ($Z = 0.308$) and 41% for males ($Z = 0.527$). There was a significant difference in weighted catch curves between genders ($F = 12.77$; $df = 1, 17$;

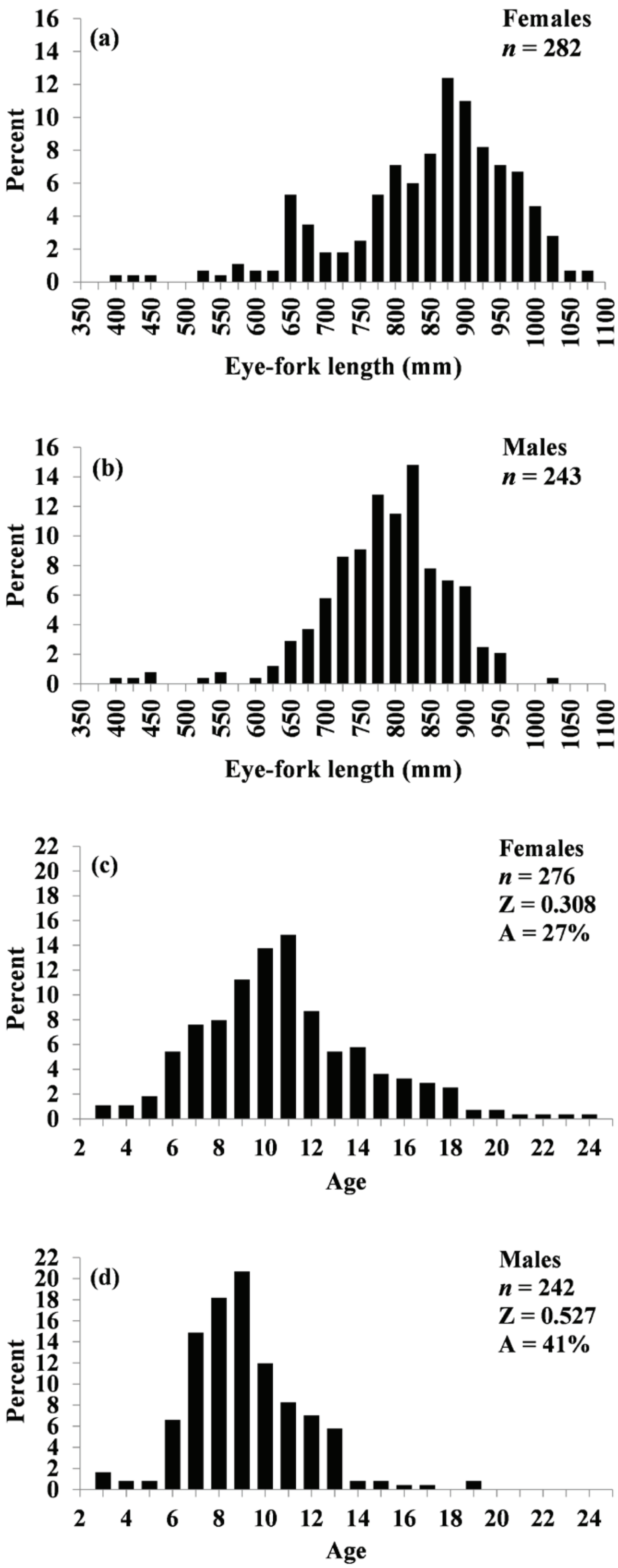

Figure 1. Relative frequency distribution of (a) females and (b) males, and age frequency distribution of (c) female and (d) male paddlefish collected from the lower Mississippi River, Arkansas, in 2008–2011. The Z and A values in (c) and (d) were derived from weighted catch curves.

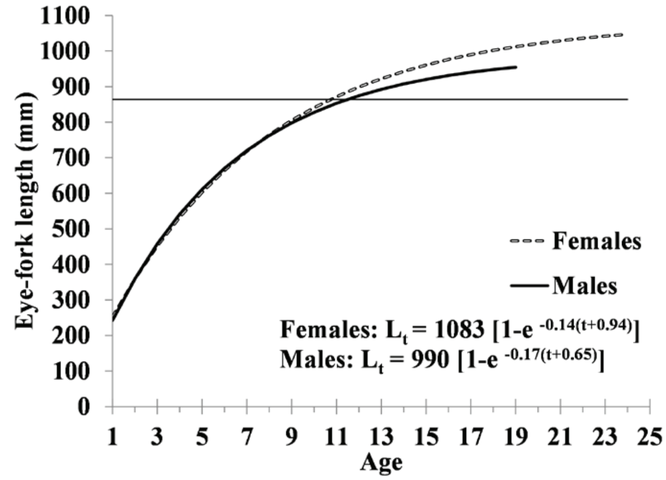

Figure 2. Von Bertalanffy growth curves for female (dashed line) and male (solid line) paddlefish collected in the lower Mississippi River in Arkansas using back-calculated lengths-at-age. The horizontal line represents the existing 864-mm MLL.

$P = 0.002$). Mean M was 0.19 (range = 0.17 to 0.21) and mean *cm* was 0.18 (range = 0.16 to 0.19) for females. Instantaneous fishing mortality (F) was 0.11 and *u* was estimated to be 10% using Z and mean M estimates.

Fecundity was estimated for 55 gravid females (814–1095 mm; 7.5–21.0 kg), with ovarian weights ranging from 961 to 3943 g (mean = 2124 g; SE = 86). Estimated absolute fecundity ranged from 117,992 to 460,431 (mean = 239,140, SE = 9488) and the relative fecundity ranged from 12,321 to 25,753 eggs kg^{-1} (mean = 18,777; SE = 371). Although both parameters were highly correlated ($P < 0.001$), fecundity had a higher correlation with weight (fecundity = 20,627 [weight in kg] – 22,860; $r^2 = 0.76$) compared to length (fecundity = 751.67 [length in mm] – 472,367; $r^2 = 0.50$).

Only 10% of gravid females sampled were smaller than the existing MLL, compared to 3%, 20%, and 31% smaller than the 838-mm, 889-mm, and 914-mm MLLs, respectively (Table 4). In contrast, 22% of males were larger than the existing MLL, and only 14% and 7% of males captured exceeded the 889-mm and 914–mm MLLs, respectively. The youngest gravid females were age 10, with a mean length of 880 mm EFL (range 814–896 mm; $n = 10$). Excluding one 685-mm outlier, the youngest females with salt-and-pepper ovaries were age 11 with average length of 877 mm EFL (range 840–898 mm; $n = 4$).

Female length at 50% maturity was 927 mm EFL (95% CI, 914–943 mm, Figure 3). Logistic regression predicted that only 3% (95% CI, 1%–7%) of females were mature at 762 mm EFL, and 21% (95% CI, 14%–28%) were mature at the existing MLL. At the 889-mm and 916-mm MLLs, 31% (95% CI, 24%–39%) and 44% (37%–52%) were mature, respectively (Figure 3). Length at 50%

Table 4. Percentages of gravid females ($n = 61$), salt and pepper females ($n = 36$), non-gravid females ($n = 185$), and males ($n = 243$) collected in this study protected by various minimum-length limits (MLL).

MLL	Gravid females	Salt and pepper females	Non-gravid females	Males
762 mm	0%	3%	28%	31%
838 mm	3%	3%	49%	66%
864 mm	10%	6%	59%	78%
889 mm	20%	11%	70%	86%
914 mm	31%	22%	80%	93%

gravidity was not reached until 1002 mm (95% CI, 972–1043 mm, Figure 3). The existing MLL would only protect 15% (95% CI, 10%–20%) of gravid females; whereas, more conservative MLLs of 889 and 916 mm would protect 25% (95% CI, 20%–31%) and 31% (25%–39 %) of gravid females, respectively (Figure 3).

Modeling results estimated roe yield was highest with a 914-mm MLL and u of 53% (Figure 4). At $u = 10\%$, roe yield varied less than 10% among MLLs. At $u = 40\%$, roe yield was 8% and 14% higher with the 889- and 914-mm MLLs, respectively, compared to the existing MLL. Yields were predicted to increase 8% and 6% under the 914-mm MLL and 889-mm MLL scenarios, compared to the existing MLL over the range of exploitation (0.05%–60%). Roe yields were predicted to decline 32% and 8% under the no-MLL and 838-mm MLL scenarios, respectively, compared to the existing MLL over the same range of exploitation (Figure 4). The roe yield model indicated that overfishing was likely (i.e., dome-shaped) with the current MLL once exploitation rate exceeded 30%. Overfishing was predicted to occur with the 762-mm and 838-mm MLL once exploitation rates exceeded 16% and 25%, respectively (Figure 4).

The threat of recruitment overfishing appeared to be low when u was 10%, with predictions above SPR_{20} and SPR_{30} for all MLLs (Figure 4). Predicted exploitation rates producing SPR_{20} and SPR_{30} increased with increased MLLs over the range of exploitation (0.05%–60%). At u of 40%, predicted SPR was 0.25 for the existing MLL and 0.32 for the 889 MLL. SPR_{20} was not predicted for 889 and 914-mm MLLs and SPR_{30} was not predicted for 914-mm MLL (Figure 4).

Discussion

Population characteristics of paddlefish from 2008 to 2011 in the lower Mississippi River were consistent with those of a lightly exploited stock. Numerous paddlefish larger than 1000 mm EFL and older than age 18 were captured in our study, although commercial fishing has the potential to quickly deplete large fish (Pasch and Alexander 1986, Quinn 2009, Quinn et al. 2009). Maximum

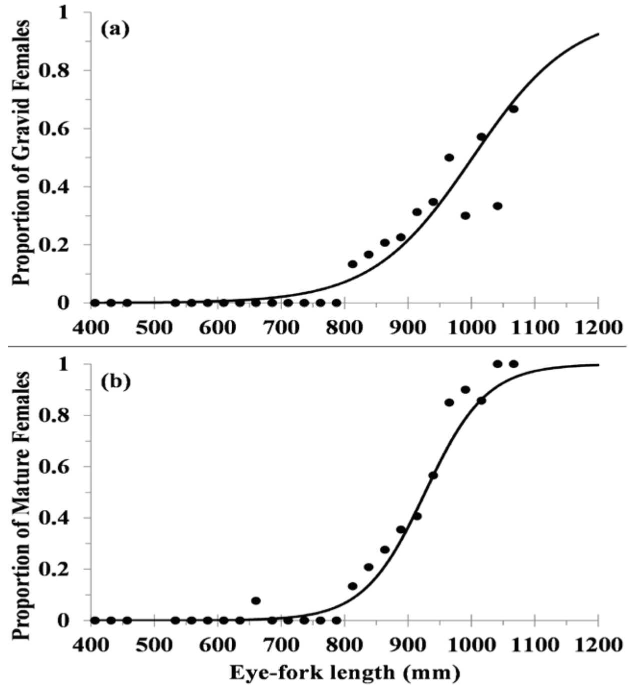

Figure 3. Logistic regression plots of eye-fork length and proportion of female paddlefish that were (a) gravid or (b) mature from the lower Mississippi River, Arkansas. Mature females had gravid or salt-and-pepper ovaries.

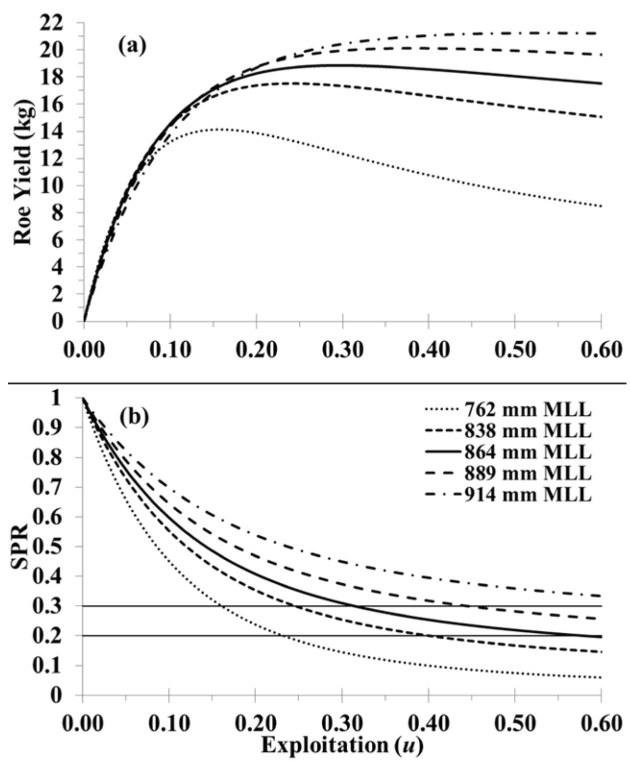

Figure 4. Predicted (a) roe yield and (b) spawning potential ratio (SPR) (per 1000 age-1 recruits) for different minimum-length limits (MLL) and exploitation rates for the lower Mississippi River paddlefish fishery using parameters derived from females. Conditional natural mortality (*cm*) was set at 18%. The solid horizontal lines in (b) represent the 20% (i.e., critical minimum) and 30% (i.e., target) thresholds.

age (24 years) was similar to modestly exploited stocks (e.g., Purkett 1963, Rosen et al. 1982, Scarnecchia et al. 2011). In contrast, highly-exploited reservoir paddlefish populations in the southern U.S. have been found to have a maximum age <16 years (e.g., Bronte and Johnson 1984, Timmons and Hughbanks 2000, Scholten and Bettoli 2005, Leone et al. 2012). We estimated that total annual mortality was 28% in the Arkansas portion of the LMR, compared to the 50%–70% annual mortality that has been found for more heavily-fished stocks (e.g., Hoffnaggle and Timmons 1989, Henley et al. 2001, Scholten and Bettoli 2005, Leone et al. 2012). Natural mortality of paddlefish in this study appeared to exceed exploitation, which is characteristic of lightly exploited populations (Slipke and Maceina 2010). Further, harvests below 1 kg ha^{-1} are generally not associated with overfishing, and Quinn (2009) estimated that harvest for the Arkansas portion of the LMR was 0.6 kg ha^{-1}.

Some studies on paddlefish fisheries (e.g., Pasch and Alexander 1986) reported that exploitation of 11% to 22% is generally sustainable; Timmons and Hughbanks (2000) reported the Kentucky Lake population was recovering with 14% exploitation. Quinn et al. (2009) documented 19%–40% exploitation occurred in a 5- to 10-day season for two paddlefish populations in Arkansas River navigation impoundments, which was 1.5–3.3 times as high as what we estimated for the LMR population over a 142-day season. Lower exploitation in the LMR could largely be due to its difficulty to fish with gill nets. This area of the river is characterized by fast current velocities, high debris load, and a shifting bedload of sand, all of which make fishing gill nets problematic, especially at high discharges (Scholten and Bettoli 2005). Also, prior to this study the Mississippi portion of the river was closed to harvest, and the Louisiana segment of the river downstream had been closed for over a decade. These closures also likely contributed to the low exploitation rates derived for the LMR.

Common-sense goals to maintain sustainability of commercially-fished stocks are to protect fish until they have spawned once and harvest fish near the optimal size (Scarnecchia et al. 1989, Froese 2004). Protecting fish until they reached 50% maturity appeared to be a reasonable reference point, although the exact length where all fish have spawned is difficult to determine due to uncertainties in the frequency of skip spawning. Length limits less than the existing 864 mm MLL appeared risky because they protected less than 15% of mature female paddlefish. Relatively high roe yield was observed with the 914-mm MLL, and the 914-mm MLL was near the length at 50% maturity (927 mm EFL). The 889-mm MLL appeared reasonable under conditions of low exploitation, as it protected 31% of mature fish. However, high variability within our length at gravidity data due to low sample size of large fish (>1000 mm EFL) and probable skip spawning indicated that further research may be required to better identify benefits of specific MLLs (Sharov et al. 2014).

A potential problem associated with higher MLLs is that sublegal fish will suffer additional potential bycatch mortality. However, Arkansas commercial seasons are typically associated with water temperatures of less than 10° C, and bycatch mortality was shown to double when temperatures increased from 10° to 14° C (Bettoli and Scholten 2006). The temperature range during the commercial season of the LMR from late November to early April fits within the thermal range associated with low bycatch mortality.

This study was initiated because exploitation of paddlefish in the LMR was expected to increase. Mississippi re-opened commercial fisheries in its border waters with Arkansas beginning with the 2008–2009 season. Further, we anticipated sturgeon fishers in nearby states may start targeting paddlefish because shovelnose sturgeon (*Scaphirhynchus platorynchus*) were listed and their harvest was closed due to their morphological similarity with endangered pallid sturgeon (*S. albus*) (U.S. Fish and Wildlife Service 2010). Finally, international exports from Kentucky Lake, historically one of the largest paddlefish fisheries in the U.S., were banned by CITES, which apparently prompted many Kentucky Lake fishers to switch to the Mississippi River (Colvin et al. 2013).

A conservative approach should be used for managing the Mississippi River paddlefish fishery, because it is the center of the species' distribution within North America (Jennings and Zigler 2000). Due to uncertainties about the accuracy of ageing paddlefish, natural mortality rate, exploitation rate, and predicted increases in fishing intensity, the MLL was increased to 889-mm EFL in 2013 by the Arkansas Game and Fish Commission to reduce the possibility of recruitment overfishing.

We have not performed post-regulation monitoring since 2013 due to lack of funding. Federal aid has not been available to assess inland freshwater commercial fisheries, which results in inland fisheries being understudied and often overfished (Alan et al. 2005). Evaluation of the 889-mm MLL using commercial harvest data is also hindered by lack of fishing effort data. Currently, roe buyer/exporters are required to report monthly purchases of roe and number of fish purchased from each fisher. Arkansas is the only state bordering the LMR that does not require commercial fishers to report fishing effort, number of fish harvest, and weight of flesh harvested. Therefore, we recommend that commercial reporting requirements be improved for Arkansas to ensure that rapid increases of u may be identified in a timely manner. Results from this study can then be used to raise MLLs to appropriate levels to protect the spawning stock and avoid the fishery collapses observed for other commercially-exploited paddlefish stocks.

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