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William J. Radigan
University of Nebraska-Lincoln, wradigan2@huskers.unl.edu

Seth Fopma
Iowa Department of Natural Resources, Bellevue

Jason Sorensen
South Dakota Department of Game, Fish, and Parks, Chamberlain

Christopher M. Longhenry
South Dakota Department of Game, Fish, and Parks, Chamberlain

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ARTICLE

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Factors affecting the catch and harvest rates of paddlefish downstream of Gavins Point Dam, South Dakota, 2000–2020

William J. Radigan[1] | **Seth Fopma[2]** | **Jason Sorensen[3]** | **Christopher M. Longhenry[3]**

[1]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

[2]Iowa Department of Natural Resources, Bellevue, Iowa, USA

[3]South Dakota Department of Game, Fish, and Parks, Chamberlain, South Dakota, USA

Correspondence
William J. Radigan, School of Natural Resources, University of Nebraska-Lincoln, 3310 Holdrege St, Lincoln, NE USA 68503.
Email: wjradigan2@huskers.unl.edu

Abstract

Paddlefish, *Polyodon spathula* (Walbaum), provide an important snagging and bowfishing fishery below Gavins Point Dam in South Dakota. During 2009–2020, snagging catch rates of paddlefish decreased below Gavins Point Dam to presumed "normal" lower pre-2004 levels, while bowfishing catch (harvest) rates significantly increased during 2000–2020. Because Paddlefish are highly migratory, both local (i.e., monthly gauge height, precipitation, and air temperature near Gavins Point Dam) and remote (difference in Mississippi and Missouri River discharge near their confluence) environmental conditions were used to explain variation in snagging catch rates and bowfishing harvest rates. Snagging catch rates were related to October gauge height, whereby deeper water in October led to decreased catch rates below Gavins Point Dam. Bowfishing harvest rates increased significantly after a 2016 regulation change moved the season from July 1 to July 31, and from June 1 to June 30, likely because water clarity was greater in June than in July. Mean annual air temperature and precipitation explained variation in bowfishing harvest rates prior to the 2016 regulation change. Our findings, the first to examine both snagging and bowfishing fisheries below Gavins Point Dam, suggest that local abiotic factors are likely more important than remote discharge for explaining variation in snagging catch rates and bowfishing harvest rates in the channelised Missouri River.

KEYWORDS
AIC, biological, bowfishing, CPUE, environmental, management

1 | INTRODUCTION

The North American paddlefish *Polyodon spathula* (Walbaum) is likely the only remaining extant species of paddlefish because the Chinese paddlefish *Psephurus gladius* (Martens) likely went extinct between 2005 and 2010 (Zhang et al., 2020). Globally, paddlefish are among the most commercially valuable species of fishes (Gessner et al., 2013), and paddlefish are imperiled worldwide due to growing black caviar markets (Onders & Mims, 2015; Pikitch et al., 2005) and overfishing (Glassic et al., 2020; Jennings & Zigler, 2000). In the United States, paddlefish are native to lotic systems, such as both the Missouri and Mississippi River basins (Carlson & Bonislawsky, 1981). Latitudinal gradients in paddlefish population characteristics (i.e., fecundity; Reed et al., 1992; survival; Hoxmeier & DeVries, 1997; maximum age; Paukert & Fisher, 2001a; maturity; Scarnecchia et al., 2011) exist in what is left of the native range of paddlefish. Although few paddlefish fisheries are sustained (Pierce et al., 2011) or created by stocking in parts of their distribution (Grady & Elkington, 2009), carefully managed exploitable populations exist throughout the nation (Hupfeld et al., 2016).

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Managed fisheries in both the Mississippi (Kramer et al., 2018) and Missouri River systems and elsewhere (i.e., the Alabama River; Lein & Devries, 1998) support recreational fisheries, while also maintaining stable populations (Mestl et al., 2019). Paddlefish exploitation rates in both the Mississippi and Missouri Rivers have been estimated to range 15%–20.1% (Hupfeld et al., 2016). However, exploitation rates may be 4% along the State of Missouri's eastern border (Kramer et al., 2018). Dead recovery models applied to 33 years of tag recovery data suggest that exploitation rates at or greater than 15% greatly increase mortality rates of adult paddlefish (Pierce et al., 2015), thereby suggesting low exploitation rates (i.e., 5%) are prudent (Pierce et al., 2011). Even in systems with exploitation rates below 5%, paddlefish management requires consideration of long-term factors such as episodic recruitment (Scarnecchia et al., 2014) and protecting paddlefish through maturation (Kramer et al., 2018).

Despite historically high mortality rates (18%; Rosen et al., 1982), the paddlefish population below Gavins Point Dam in the Missouri River of South Dakota fosters both recreational snagging and bowfishing fisheries, and a population with an increasing size structure (i.e., increased mean length; Mestl et al., 2019). Natural paddlefish recruitment and variable entrainment of stocked age-0 paddlefish through Gavins Point Dam (Pracheil et al., 2014) support the population below Gavins Point Dam (Bettoli et al., 2009; Mestl et al., 2005; Pierce et al., 2011). Abundance ranges from 65,000 to 137,000 individuals below Gavins Point Dam to the confluence with the Big Sioux River (Mestl et al., 2005).

Regulations allow for a maximum harvest of 5.70% (n = 3700 fish) based on a minimum estimated abundance of 65,000 fish (Mestl et al., 2005). Realised exploitation from 1995–2003 was variable, reaching a maximum of 4.47% (Mestl et al., 2005). Paddlefish snagging catch rates (both catch and release and harvest) rates have declined and bowfishing catch (hereafter harvest, retention is mandatory) rates have increased in recent years. Bowfishing harvest rates may have increased due to the season moving to the month of June to increase bowfishing efficiency (i.e., because of presumably clearer water than in July), because snaggers switched to bowfishing for slot-protected fish when snagging success decreased, or because paddlefish spawning during June are more likely to congregate near Gavins Point Dam.

State fisheries management personnel speculated that discharge in the Mississippi River and other rivers may temporally influence paddlefish abundance in the Missouri River. However, the relative role of local and remote discharge on local conditions (i.e., population abundance, temperature, precipitation) play in affecting the catch rates of paddlefish below Gavins Point Dam has not been investigated. Our objective was to determine the extent to which local and remote environmental variables (i.e., gauge height, precipitation, and air temperature) and biological variables (i.e., population abundance) influenced snagging catch rates and bowfishing harvest rates of paddlefish during 2000–2020. To achieve our objective, we first described trends in catch and harvest rates of paddlefish during 2000–2020, and then used linear models to describe how catch and harvest rates were related to environmental and biological variables. Based on our findings, we provided management recommendations to maximise sustainable catch and harvest rates of paddlefish.

2 | METHODS

2.1 | Study site

Gavins Point Dam is the farthest downstream dam on the Missouri River. The Missouri River below the dam forms the border between South Dakota and Nebraska and is characterised by a complex and diverse river channel for nearly 100 km before becoming a channelised river downstream of Sioux City, Iowa (Figure 1). Paddlefish were historically stocked above Gavins Point Dam, and many of these fish were entrained through the dam (Grady et al., 2005).

South Dakota Game, Fish, and Parks and the Nebraska Game and Parks Commission jointly manage paddlefish snagging and bowfishing fisheries using the same regulations below Gavins Point Dam (Mestl & Sorensen, 2009). Snagging seasons run from October 1 to October 31 from 0700 hours to 1900 hours (Nebraska Game and Parks, 2019; South Dakota Legislature, 2020). As of 2022, bowfishing seasons were from sunrise to sunset, from June 1 to June 30 (Nebraska Game and Parks, 2019; South Dakota Legislature, 2020). Prior to 2016, bowfishing seasons were open from July 1 to July 31. A one-fish possession limit was in effect since 1989 (Mestl et al., 2005), but an angler could

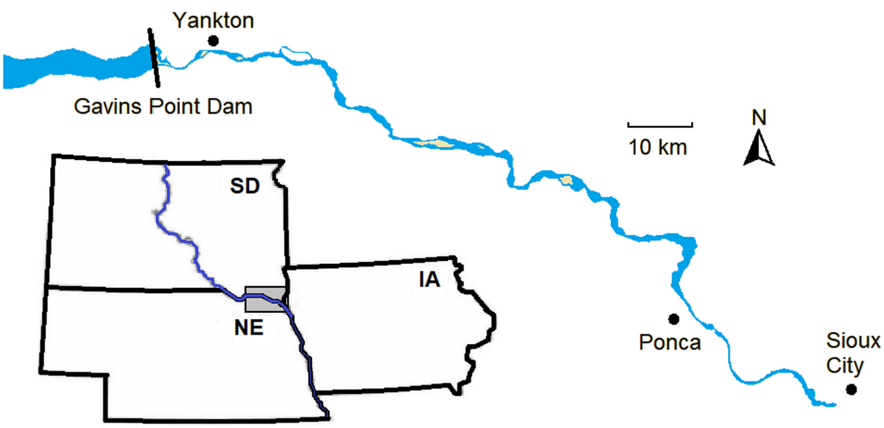

FIGURE 1 Sample area map. The Missouri River below Gavins Point Dam extends from the dam to Sioux City, Nebraska, for this study.

obtain a second paddlefish permit and tag after September 1 of each year. The paddlefish snagging season was limited to 3200 paddlefish harvested, with 1600 tags allotted to Nebraska (either resident or non-resident) and South Dakota (1550 resident, 50 non-resident). The paddlefish snagging fishery was regulated with an 889–1143 mm protected slot (Mestl et al., 2005), but catch and release of any-sized fish was permitted. Snagging was limited to a single line with a single hook (single or treble) not larger than 17 mm in size (South Dakota Legislature, 2020). Seasonal bowfishing harvest was restricted by the number of permits issued (275 permits for each state, 550 total), with no slot or length limit. Catch and release was not permitted for the bowfishing fishery. Permits come with one tag for both snagging and bowfishing seasons. Tag draws for the snagging season and bowfishing seasons were independent of one another.

2.2 | Creel

With each issued snagging or bowfishing tag, anglers were issued a response card with questions regarding participation, if a fish was harvested, the number of released paddlefish caught within length groups (e.g., longer than, within, or shorter than the protected slot), and hours fished (Appendix A). After the season closed, reminder cards were mailed within 3–4 weeks to increase response rates.

2.3 | Environmental variables

Mean monthly precipitation (mm), air temperature (C), and Palmer drought severity index (Palmer, 1965) were collected using a method described by Karl and Koss (1984) from the National Oceanic and Atmospheric Administration (NOAA) climate website (NOAA, 2018). Mean monthly river discharge and gauge height were obtained from the United States Geological Survey (USGS) water database website (USGS, 2018). The USGS gauge at Yankton, SD, was used to assess local water conditions (i.e., mean monthly gauge height). Due to their proximity to the confluence of the Mississippi and Missouri Rivers, USGS gauges at Grafton, IL, and St. Charles, MO, were used to assess the effect of remote discharge on paddlefish catch rates and harvest rates. Remote discharge was calculated as the difference between mean April Missouri River discharge (m^3/s) at St. Charles, MO, and mean April Mississippi River discharge at Grafton, IL, each year. Environmental (i.e., temperature, precipitation) variables were taken from June or October to coincide with paddlefish bowfishing or snagging seasons.

2.4 | Statistical analysis

Variation in catch and harvest rates of paddlefish were modelled using multiple linear models, with two geographic scales of environmental variables: (1) remote abiotic environmental variables and (2) seasonal local abiotic environmental variables (e.g., seasonal precipitation, temperature, and gauge height). Both geographic scales were assessed using single parameter models. Logical parameters were then combined to create multi-parameter models. Fishing effort was correlated with catch rates ($F_{1,19}$ = 84.65, r^2 = 0.82, $p<0.01$) and harvest rates ($F_{1,18}$ = 49.17, r^2 = 0.73, $p<0.01$) but was not included in analyses because we focused on the relative importance of local and remote abiotic environmental variables. Normality was tested using a Shapiro–Wilk test (Shapiro & Wilk, 1965), and non-normal data were transformed into natural logarithms (ln[x + 1]), as in prior research (DeBoer et al., 2013). Catch and harvest rates during 2000–2020 were included. Seasons changed in 2016 for bowfishing, so the pre-regulation period (2000–2015) was examined separately. A *t*-test was used to test for differences between pre-regulation and post-regulation periods (Figure 5). Variance inflation factors (VIFs) were used to test for variable multi-collinearity (O'Brien, 2007) and multi-collinear variables were removed until VIF <10 (Hair Jr. et al., 1995). Akaike's Information Criterion (AICc; Burnham & Anderson, 2002) was used to select models (Table 1) that were best supported. Goodness-of-fit for global models was assessed using a Hosmer-Lemeshow test (Hosmer & Lemeshow, 1980). Statistical significance for all analyses was set at $\alpha = 0.05$. Analyses were performed using R version 4.0.2 (R Development Core Team, 2020).

3 | RESULTS

3.1 | Catch rates

Snagging catch rates of paddlefish did not significantly change during 2000–2020 (Table 2). Catch rates were higher than prior to 2004, and peaked in 2009 (Figure 2). The number of paddlefish snagged and released longer than 1143 mm was constant during 2000–2020 (Table 2, Figure 3). The proportion of paddlefish harvested by snagging shorter than the 889–1143 mm slot limit was less variable since 2011 (coincident with a flood in that year), and ranged 15%–60% pre-flood and 10%–40% post-flood (Figure 3). The proportion of paddlefish snagged and harvested shorter than 889 mm and longer than 1143 mm did not change over the study period (Table 2). The proportion of total paddlefish snagged (released and harvested) shorter than 889 mm decreased from over 60% during 2000–2004 to under 40% during 2018–2020, whereas the proportion longer than 1143 mm increased from 1.0%–2.0% during 2000–2004 to 4.0%–5.0% during 2011–2020 (Figure 4).

South Dakota mean October gauge height explained the most variation in and was negatively related to paddlefish snagging catch rates, while the environmental model including October gauge height, precipitation, and temperature was also supported (Table 3). By contrast, global models that included all environmental variables poorly described variation (i.e., low goodness-of-fit) in both snagging catch rates (χ^2 = 6.49, p = 1.00) and bowfishing harvest rates (χ^2 = 0.26, p = 1.00).

TABLE 1 Model names and terms for candidate models used to explain adult catch rates and harvest rates (2000–2020) of adult paddlefish *Polyodon spathula* (Walbaum) below Gavins Point Dam in South Dakota during 2000–2020

Model name	Model definition
Discharge_Diff	Difference between Mississippi River and Missouri River mean monthly discharge for a given year near their confluence
SD_Jun_DSI	South Dakota June Drought Severity Index
SD_Mean_Annual_Precip	South Dakota mean annual precipitation
SD_Mean_Annual_Temp	South Dakota mean annual air temperature
SD_Mean_Annual_Precip + SD_Mean_Annual_Temp	South Dakota mean annual precipitation + South Dakota mean annual air temperature
SD_Jun_P	South Dakota June precipitation
SD_Jun_T	South Dakota June temperature
SD_Jun_GH	South Dakota June gauge height at Yankton, SD
SD_Jun_PT	South Dakota June precipitation + temperature
SD_Jun_PT_SD_Jun_GH	South Dakota June precipitation + temperature + South Dakota gauge height
Global	Global model including all other models

Note: October monthly environmental factors (i.e., drought severity index, precipitation, temperature, gauge height) was used for snagging catch rates, while the June monthly environmental factors were used for bowfishing harvest rates.

TABLE 2 *F*-statistic, *p*-value, r^2 (regression coefficient), slope, and residual standard error (SE) values for multiple linear regressions of paddlefish *Polyodon spathula* (Walbaum) catch per unit effort below Gavins Point Dam in South Dakota during 2000–2020

	Variable	*F*	*p*	r^2	Slope	SE	Trend
Snagging	Number of Participants	0.76	1.00	0.04	6.52	207.4	±
	Harvested <889 mm	3.84	0.72	0.17	−16.57	234.60	±
	Harvested >1143 mm	3.70	0.77	0.16	4.82	69.48	±
	Released <889 mm	0.08	1.00	0.00	−25.63	2573.00	±
	Released slot	3.02	1.00	0.14	151.90	2425.00	±
	Released >1143 mm	8.20	0.12	0.30	4.73	45.87	±
	Hours fished	0.78	1.00	0.04	74.25	2340.00	±
	Average hours fished	2.33	1.00	0.11	0.12	2.18	±
	Total catch	0.41	1.00	0.02	119.20	5138.00	±
	Catch rate	0.00	0.98	0.00	4.42×10^{-4}	0.52	±
	Total harvest	1.98	1.00	0.09	−11.75	231.70	±
	Harvest rate	1.91	1.00	0.09	-1.35×10^{-3}	0.03	±
	% successful	1.41	1.00	0.07	-8.02×10^{-3}	0.19	±
	% harvest <889 mm	9.81	0.07*	0.34	-1.12×10^{-2}	0.10	±
	% harvest >1143 mm	9.81	0.07*	0.34	1.12×10^{-2}	0.10	±
Bowfishing	Number of participants	14.51	<0.01***	0.45	−3.32	24.19	−
	Harvested <889 mm	2.86	0.44	0.14	0.84	13.84	±
	Harvested >1143 mm	13.33	<0.01***	0.43	1.06	8.07	+
	Harvested 889–1143 mm	17.56	<0.01***	0.49	2.79	18.46	+
	Hours fished	0.11	0.75	0.01	−6.02	511.20	±
	Average hours fished	2.46	0.39	0.12	−0.11	1.96	±
	Total harvest	13.71	<0.01***	0.43	4.70	35.17	+
	Harvest rate	10.61	<0.03**	0.37	1.86×10^{-3}	0.02	+
	% successful	13.41	<0.03**	0.43	1.88×10^{-2}	0.14	+
	% harvest <889 mm	9.28	<0.01***	0.34	-1.20×10^{-2}	0.11	−
	% harvest 889–1143 mm	4.48	0.36	0.20	9.38×10^{-3}	0.12	+
	% harvest >1143 mm	1.47	0.48	0.08	2.58×10^{-3}	0.06	±

Note: For bowfishing regressions, 2011 is omitted because the season was closed for the year due to a large flood. For trends, a *p*-value of <0.05 was deemed significant, and "+" denotes an increasing trend, "±" denotes a stable trend, and "−" denotes a decreasing trend. *p*-Values were adjusted using the Bonferroni-Holm adjustment for multiple comparisons. *p*-Values are denoted as follows: <0.10 (*), 0.05(**), or 0.01(***).

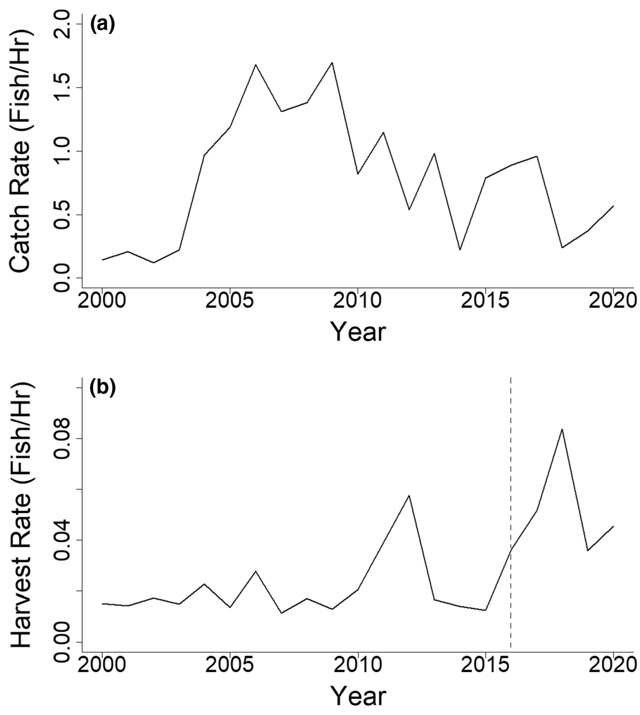

FIGURE 2 Paddlefish *Polyodon spathula* (Walbaum) (a) snagging catch rates (fish/hour) and (b) bowfishing harvest rates (fish/hr) in the Missouri River below Gavins Point Dam from 2000–2020. For bowfishing harvest rates, 2011 is omitted because the season was closed for the year due to a large flood. The dotted line at 2016 depicts a regulation change.

3.2 | Harvest rates

Bowfishing harvest rates of paddlefish increased significantly during 2000–2020 (Table 2, Figure 2). Bowfishing harvest rates were stable during 2000–2010 (in 2011, a catastrophic flood year, the fishery was closed due to unsafe water conditions). Bowfishing harvest rates peaked in 2012 and during 2016–2020 (Figure 2). During 2000–2020 bowfishing seasons, the number of participants and proportion of harvest shorter than 889 mm decreased, whereas the number of fish harvested between 889 and 1143 mm, number of fish harvested over 1143 mm, total harvest, and percent success increased (Table 2). Harvest rates were significantly higher during 2000–2015 than during 2016–2020 ($t = -3.40$, $df = 4.95$, $p = 0.02$; Figure 5).

During 2000–2020, the proportion of paddlefish harvest by bowfishing of fish shorter than 889 mm decreased from 40%–60% during 2000–2006 to 20% since 2019, whereas the proportion of harvest by bowfishing of fish longer than 1143 mm remained stable at 10%–30% over the entire period (Figure 3). However, the proportion of harvest by bowfishing of fish between 889 and 1143 mm varied from less than 20% to more than 60% during the period (Figure 3). The model, including all local and remote abiotic factors, explained the most variation in paddlefish bowfishing harvest rates during 2000–2020 (Table 4), whereas mean annual air temperature explained the most variation in and was positively related to bowfishing harvest rates prior to the regulation change (2000–2015) (Table 5).

4 | DISCUSSION

We hypothesised that both local abiotic factors and remote discharge influenced local paddlefish abundance, thereby affecting catch rates and harvest rates of paddlefish below Gavins Point Dam. We found that local flows explained more variation in snagging catch rates and bowfishing harvest rates than remote discharge. Our study is the first to quantify the relative importance of local and remote abiotic factors in determining snagging catch rates and bowfishing harvest rates of paddlefish below Gavins Point Dam.

4.1 | Catch rates

We found that local conditions, including October gauge height, air temperature, and precipitation, explained more variation in paddlefish catch rates than remote discharge. For example, shallower water, indexed by lower October gauge height, likely increased vulnerability to snagging. Evidence of deeper water decreasing catch rates has been documented for both snagging and sampling. High water in the lower area of the Lake of the Ozarks decreased paddlefish participation by 70% due to difficulty associated with snagging paddlefish in deeper water (Purkett Jr., 1963). Gill-netting catch was less than expected for paddlefish in Keystone Reservoir compared to telemetry, presumably due to lower sampling efficiency in deep water (Paukert & Fisher, 2001b). Further, Spring temperature and flow determine paddlefish spawning time and success (Jennings & Zigler, 2009), and development and maturation of gametes (Jennings & Zigler, 2000), which may lead to earlier spawning when water temperatures reach 10–20°C (Firehammer & Scarnecchia, 2006) and earlier hatching of fertilised eggs (Jennings & Zigler, 2009), thereby increasing the growing season and overwinter survival of age-0 paddlefish. Increased age-0 recruitment to adulthood resulting from warmer Spring temperatures would increase adult abundance, in turn increasing catch rates, as in a previous study that found relationships between water temperature and paddlefish catch rates (Lein & Devries, 1998). Since paddlefish spawning success (Runstrom et al., 2001) and spawning timing in late May early June (Ruelle & Hudson, 1977) is related to discharge, and suitable preferred habitat (i.e., water depth 6–18 m; Budnik et al., 2014) requires moderate flows (Phelps et al., 2009), dam operations providing these flows may benefit the Gavins Point paddlefish population.

Like adult movement, local discharge negatively affects catch rates and harvest (Scholten & Bettoli, 2005). Local discharge affects both age-0 and adult paddlefish. For example, age-0 paddlefish recruitment in Lewis and Clark Lake was positively related to high spring flows of a local tributary, the Niobrara River (Pracheil et al., 2009). Similarly, in Kentucky Lake, a main channel impoundment on the Tennessee River, the number of paddlefish caught was negatively related to river discharge (Scholten & Bettoli, 2005). However, paddlefish movement was positively related to February–April gauge height, and upstream movement was positively related to catch rates (Schwinghamer et al., 2019). For example, change in

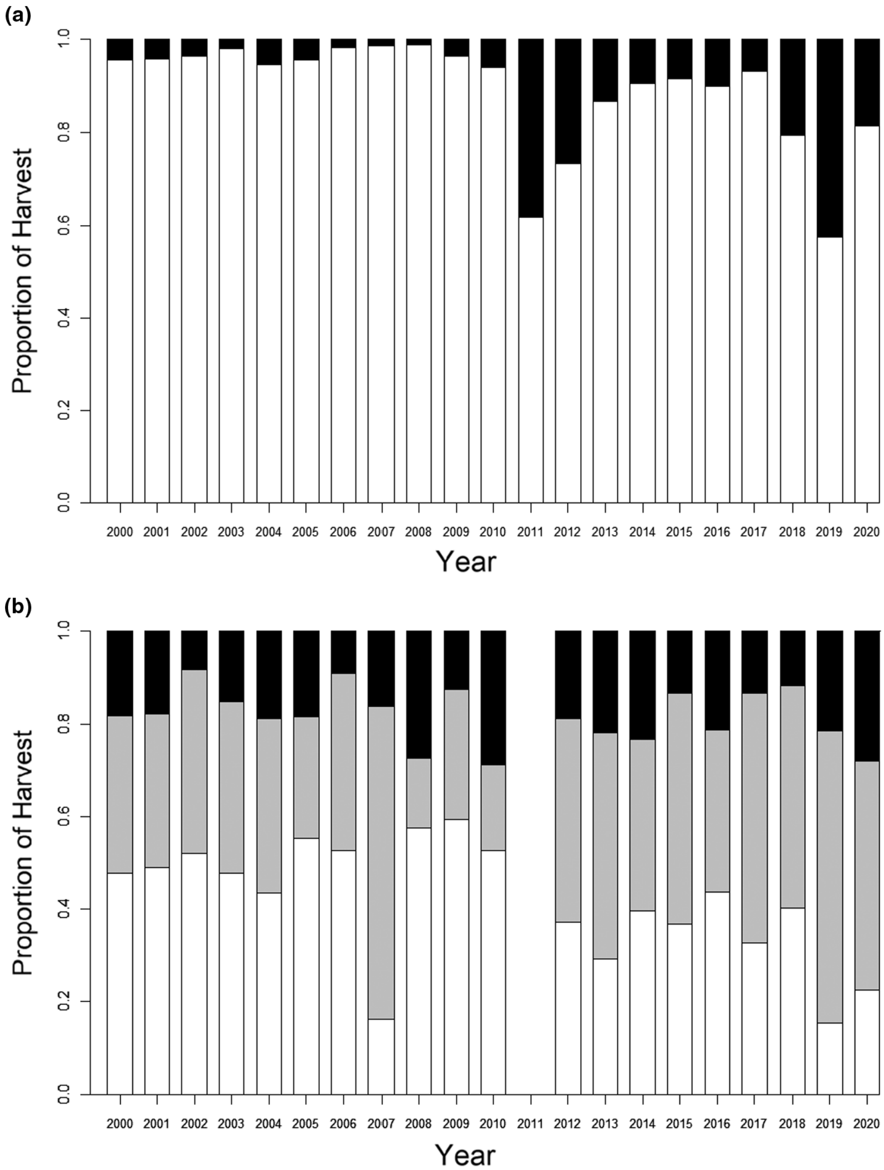

FIGURE 3 Proportion of harvest for (a) snagging and (b) bowfishing below a 889 mm slot (white), in a 889–1143 mm slot (grey), and above a 1143 mm slot (dark) for paddlefish *Polyodon spathula* (Walbaum) collected in the Missouri River below Gavins Point Dam between 2000 and 2020. For bowfishing harvest, 2011 is omitted because the season was closed for the year due to a large flood.

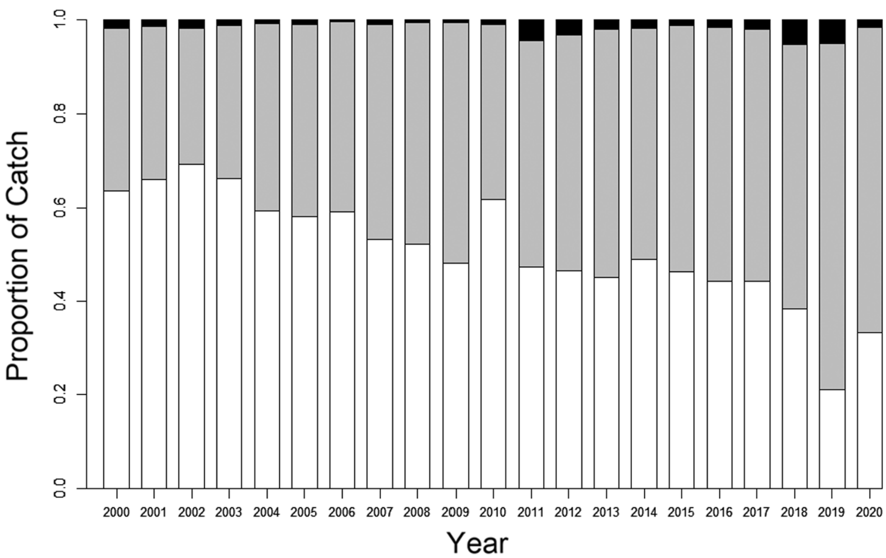

FIGURE 4 Proportion of catch (both released and harvested cumulatively) for snagging below a 889 mm slot (white), in a 889–1143 mm slot (grey), and above a 1143 mm slot (dark) for paddlefish *Polyodon spathula* (Walbaum) collected in the Missouri River below Gavins Point Dam between 2000 and 2020.

TABLE 3 The number of estimated parameters (K), 2nd order Akaike's information criterion (AIC_c), difference in AIC values relative to the best model (Δ AIC_C), log-likelihood (LL), Akaike weights (weights), and trend ("+" denotes an increasing trend), "±" denotes a stable trend, and ("−" denotes a decreasing trend) for the top-5 models from 11 candidate models predicting paddlefish *Polyodon spathula* (Walbaum) snagging catch rates below Gavins Point Dam, South Dakota, during 2000–2020

Model	K	AICc	Δ AIC_C	LL	Weights	Trend
SD_Oct_GH	3	27.48	0.00	1.00	0.52	−
SD_Oct_PT_SD_Oct_GH	5	28.56	1.08	0.58	0.30	±
Global	9	32.26	4.79	0.09	0.05	±
SD_Oct_P	3	32.77	5.30	0.07	0.04	±
Discharge_Diff	3	32.92	5.44	0.07	0.03	±

Note: Model parameter descriptions can be found in Table 1.

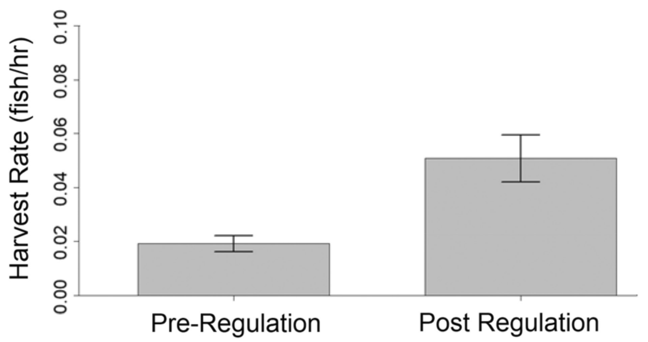

FIGURE 5 Mean bowfishing harvest rates pre- (2000–2015) and post- (2016–2020) regulation change moving the season from July 1 to July 31 and from to June 1 to June 30 for paddlefish *Polyodon spathula* (Walbaum) in the Missouri River below Gavins Point Dam between 2000 and 2020. Error bars represent one standard error.

river stage was not related to direction of paddlefish movement, which suggested that other factors (i.e., water temperature) affected paddlefish movement and catch rates (Moen et al., 1992). Further, episodic recruitment, or typical recruitment of weaker year classes intermingled with recruitment of intermittent stronger year classes, confounds management of paddlefish (Scarnecchia et al., 2014).

Similar to other paddlefish fisheries lacking age structure data, knowledge gaps in recruitment variation patterns (i.e., episodic recruitment) pose concerns for the fishery below Gavins Point Dam (Scarnecchia et al., 2014). The age structure of paddlefish harvested below Gavins Point Dam during 1972–1990 suggests that recruitment was episodic in this system (Mestl & Sorensen, 2009). Harvest of age-0 to age-5 paddlefish varied from under 40% during 1972–1980 to over 60% during 1987–1988, before returning to 40% in 1990 (Mestl & Sorensen, 2009). Because female paddlefish take 10–12 years to mature (Russell, 1986), high-water in 1993, 1995, and 1997 may have been responsible for peak catch rates in 2001–2008. If true, then high water years in 2010, 2011, 2014, 2017, and 2018 may cause peak catch rates during 2023–2030. However, snagging catch rates decreased, perhaps because of nascent population decline. Concerns over episodic recruitment in paddlefish fisheries elsewhere (i.e., Oklahoma; Scarnecchia et al., 2014) may be warranted below Gavins Point Dam, because current protected slot regulations may not be adequate for sustaining catch rates in years with typical recruitment. Although snagging catch rates decreased, bowfishing harvest rates increased.

4.2 | Harvest rates

Like catch rates (Paukert & Fisher, 2001a), harvest rates are linked to adult paddlefish movement patterns (Devine et al., 2020), most of which are linked to flow or water temperature (Mestl et al., 2005). We found that temperature and precipitation were both related to bowfishing harvest rates, perhaps because water temperature and precipitation dictate timing of paddlefish spawning and movement (Roush et al., 2003; Stancill et al., 2002). In Kansas reservoirs, surface water temperature was positively related to catch per unit effort; Paukert & Fisher, (2001a). We found that local flows were more important than remote discharge for explaining bowfishing harvest rates, perhaps because year-class strength of paddlefish is associated with high flows, as in Lake Sakakawea, North Dakota (Scarnecchia et al., 2009).

In addition to management of local flows, continued regulation of paddlefish harvest below Gavins Point Dam is prudent. Changes in the size structure may be due to either harvest or movement, with an increasing proportion of snagging and bowfishing harvests consisting of larger individuals. Current harvest regulations protect mature fish within the protected slot for 7–9 years, thereby allowing several spawning events before becoming susceptible to harvest. Harvest of larger individuals may cause harvest of smaller fish in the future, to mirror population size structure. Larger individuals are more fecund than smaller individuals (Leone et al., 2012; Scarnecchia et al., 2022) and smaller (younger) fish may have fewer viable eggs than older fish (Larkin, 1978), so harvest focused on larger individuals may disproportionately affect recruitment of age-0 paddlefish. Harvest rates increased significantly since 2016, possibly due to a move of the bowfishing season from July to June.

Due to significant increases in harvest rates coincident with a regulation change, we were able to evaluate abiotic factors influencing bowfishing harvest rates during 2000–2020 and 2000–2015. However, post-regulation change (2016–2020) analysis was not possible due to the number of years of data available. Bowfishing total harvest increased, specifically numbers of paddlefish 889–1143 mm

TABLE 4 The number of estimated parameters (K), 2nd order Akaike's Information Criterion (AIC_c), difference in AIC values relative to the best model (Δ AIC_C), log-likelihood (LL), Akaike weights (weights), and trend ("+" denotes an increasing trend, "±" denotes a stable trend, and ("−" denotes a decreasing trend) for the top-5 models from 11 candidate models predicting paddlefish *Polyodon spathula* (Walbaum) bowfishing harvest rates below Gavins Point Dam, South Dakota, during 2000–2020

Model	K	AICc	Δ AIC_C	LL	Weights	Trend
Global	9	−104.60	0.00	1.00	0.57	±
SD_Jun_T	3	−102.65	1.95	0.38	0.21	+
SD_Jun_PT	4	−100.74	3.87	0.14	0.08	±
SD_Jun_PT_SD_Jun_GH	5	−100.49	4.12	0.13	0.07	±
Discharge_Diff	3	−96.56	8.04	0.02	0.01	±

Note: Model parameter descriptions can be found in Table 1.

TABLE 5 The number of estimated parameters (K), 2nd order Akaike's Information Criterion (AIC_c), difference in AIC values relative to the best model (Δ AIC_C), log-likelihood (LL), Akaike weights (weights), and trend ("+" denotes an increasing trend, "±" denotes a stable trend, and ("−" denotes a decreasing trend) for the top-5 models from 11 candidate models predicting paddlefish *Polyodon spathula* (Walbaum) bowfishing harvest rates below Gavins Point Dam, South Dakota, during 2000–2015

Model	K	AICc	Δ AIC_C	LL	Weights	Trend
SD_Mean_Annual_Temp	3	−92.97	0.00	1.00	0.26	+
SD_Mean_Annual_Precip+SD_Mean_Annual_Temp	4	−92.30	0.67	0.72	0.19	±
SD_Mean_Annual_Precip	3	−92.15	0.82	0.67	0.18	−
Discharge_Diff	3	−91.37	1.60	0.45	0.12	±
SD_Jun_T	3	−90.81	2.16	0.34	0.09	±

Note: Model parameter descriptions can be found in Table 1.

during 2000–2020. However, bowfishing harvest typically makes up <10% of total harvest, while snagging harvest comprises greater than 90% of total harvest, so increased bowfishing harvest is likely less important than decreased snagging harvest in relation to total mortality. Peak bowfishing harvest rates in 2016–2020 were likely due to changes in season dates from July 1–31 to June 1–30 in 2016, because water clarity is greater in June than July.

4.3 | Management implications

Limited-entry snag fisheries in both Lake Francis Case (Sorensen et al., 2017) and below Gavins Point Dam are both effective at regulating harvest rates. Gavins Point Dam protected slot limits may be effective at protecting mature paddlefish, similar to higher minimum length limits (i.e. to 864 mm) that increased the proportion of trophy-sized paddlefish in three Missouri reservoirs (Hupfeld et al., 2018). Mandatory catch and release within a protected slot (889–1143 mm) for the snagging fishery may protect reproductive year classes of paddlefish, and likely do not affect most angling participation because anglers that dislike the regulation still participate (Cha & Melstrom, 2018). Our results can inform local management of the paddlefish harvest by increasing angler satisfaction (Neely et al., 2014). However, age structure of the paddlefish population and harvest below Gavins Point Dam is needed to assess episodic recruitment.

Paddlefish fisheries are often managed locally, without consideration of state-wide or nation-wide population impacts. For example, Kansas paddlefish populations required a state-wide management plan that was the product of consolidating institutional knowledge and internal documents in order to set a paddlefish snagging season and associated permit system in place (Neely et al., 2015). By contrast, Nebraska and South Dakota have been successful at interstate management of paddlefish fisheries, including regulations and stocking (Mestl et al., 2005). Because paddlefish are highly migratory, local harvest may be influenced by emigration and immigration (Devine et al., 2020), and interstate management may be necessary (Pracheil et al., 2012; Tripp, Phelps, et al., 2019). For example, paddlefish in Missouri moved through 14 different states, each with its own harvest regulations (Devine et al., 2020). Historically, interstate paddlefish management was coordinated among 28 states through the Mississippi Interstate Cooperative Resource Association (Jennings & Zigler, 2009). Presently, paddlefish management varies among states despite paddlefish moving into stretches of river where locally prohibited actions (i.e., commercial harvest below Gavins Point Dam) are permitted.

Paddlefish face enhanced mortality by moving out of areas where commercial harvest is prohibited into areas open to commercial harvest (Timmons & Hughbanks, 2000). For example, 45% of wild paddlefish tagged and recaptured in the lower Missouri River sub-basin were harvested by commercial fishers in Mississippi or Illinois (Mestl et al., 2005). Similarly, commercial harvest led to exploitation rates of 30% in Ozark Lake, Arkansas (Donabauer et al., 2009). Paddlefish stocked in South Dakota moved out of the state (36% of 1244 adult paddlefish recaptures), where they were subject to varying recreational fishing pressure in different states (Pracheil et al., 2012). Similarly, sturgeon (family *Acipenseridae*) harvest regulations currently vary among nations (Pikitch et al., 2005).

In addition to varying regulations among states and nations impacting paddlefish fisheries, both paddlefish and shovelnose sturgeon (*Scaphirhynchus platorynchus*; Rafinesque) fisheries in the Missouri River are in danger of a market switch from foreign caviar to American caviar. Worldwide catch rates of sturgeons have decreased to 15%–30% of historical catch rates from 1960 to 2002 (Pikitch et al., 2005). As sturgeon caviar becomes increasingly rare, a market switch and increased demand for lucrative ($923–$1539/kg) paddlefish caviar may similarly threaten North American paddlefish fisheries (Pappalardo et al., 2019; Pikitch et al., 2005). The market already switched from lake sturgeon (*Acipenser fulvescens*; Rafinesque) to paddlefish caviar in the Mississippi River at the turn of the 20th century (Carlson & Bonislawsky, 1981). Although current regulations prohibit commercial harvest of paddlefish in the Missouri River (Hupfeld et al., 2016), political pressure is increasing to open or reopen previously closed commercial paddlefish fisheries in Alabama and Mississippi (Rider et al., 2019).

Migratory adult paddlefish below Gavins Point Dam are thought to move up the river when discharge is greatest at the confluence of the Mississippi and Missouri Rivers. Remote discharge dictating whether paddlefish ascend the Missouri or Mississippi River is supported by findings in Fort Peck, Montana, where paddlefish select the river they ascend by each river's discharge (Firehammer & Scarnecchia, 2006). We found limited support for remote discharge affecting bowfishing harvest rates, possibly because only a portion of the paddlefish population below Gavins Point Dam migrates. Further, movement may be sex-specific (Scarnecchia et al., 2007). Local environmental factors influenced snagging catch rates and bowfishing harvest rates below Gavins Point Dam, thereby highlighting the need for consideration of intra-jurisdictional management of local factors and inter-jurisdictional management of remote factors to manage paddlefish populations. By considering local and remote factors and conducting intra- and inter-jurisdictional management, our findings allow for a measure of predictive power regarding paddlefish snagging catch rates (i.e., shallower water in October may increase catch rates) and bowfishing harvest rates (i.e., warmer and dryer year may increase harvest rates).

5 | CONCLUSION

Similar to other large-bodied, native fish species, paddlefish in Missouri River reservoirs are likely affected by a variety of abiotic factors, including natural flow regime disruption, alteration of floodplain connectivity, loss of overall systemic connectivity related to the construction of impoundments, and annual variation in seasonal temperature and precipitation (Diaz et al., 2015; Jennings & Zigler, 2000). Dams and habitat degradation (i.e., by siltation) have restricted the historical range of paddlefish in South Dakota (Hoagstrom et al., 2006), and paddlefish are restricted to the Missouri and Platte Rivers in Nebraska due to dewatering (Carlson & Bonislawsky, 1981). Future management should focus on standardising state laws, considering the role of global factors (i.e., growing paddlefish caviar markets), and expanding existing knowledge regarding paddlefish. Future research using acoustic telemetry for population estimation (Hale et al., 2003), habitat selectivity (Stancill et al., 2002; Zigler et al., 2003), and movement (Schwinghamer et al., 2019; Tripp, Neely, & Hoxmeier, 2019) will inform paddlefish management by providing greater insight into paddlefish life history. Research into age-0 paddlefish natal environments below Gavins Point Dam (and elsewhere) using dentary (Rude & Whitledge, 2019; Schooley et al., 2021) microchemistry will help determine important nursery habitats. Research after a few years have passed since the 2016 regulation change may allow for a more robust assessment of abiotic factors driving bowfishing harvest rates after the regulation changed. Current management prioritizing local abiotic factors is prudent until a post-regulation change assessment can be made.

AUTHOR CONTRIBUTIONS

WJR conceptualised and drafted the manuscript, performed data analysis and solicited edits, SF conceptualised and drafted the manuscript and performed data analysis, JS edited the manuscript and provided the data that was used, and CML edited the manuscript and provided the data that was used.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

William J. Radigan https://orcid.org/0000-0003-1803-8659

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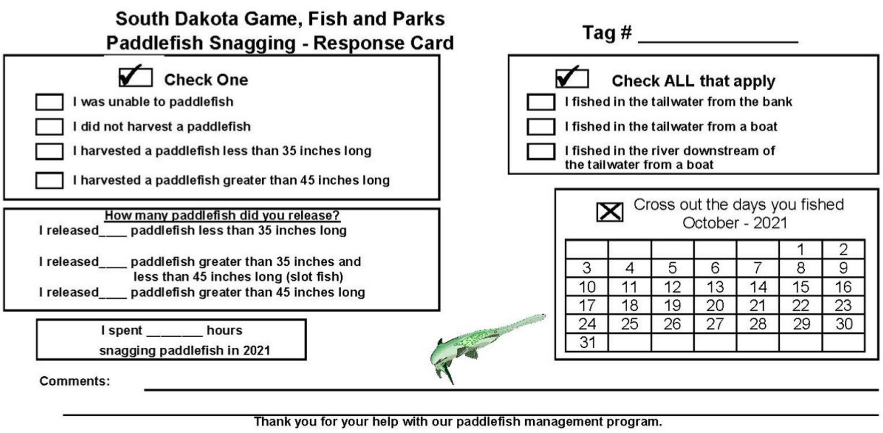
APPENDIX A

Creel cards provided to successful South Dakota snagging applicants (top) and South Dakota (middle) and Nebraska bowfishing paddlefish applicants (bottom) for the paddlefish fishery below Gavins Point Dam in South Dakota, between 2016 and 2020.



South Dakota Game, Fish and Parks
Paddlefish Snagging - Response Card

Tag # ______________

☑ Check One
☐ I was unable to paddlefish
☐ I did not harvest a paddlefish
☐ I harvested a paddlefish less than 35 inches long
☐ I harvested a paddlefish greater than 45 inches long

☑ Check ALL that apply
☐ I fished in the tailwater from the bank
☐ I fished in the tailwater from a boat
☐ I fished in the river downstream of the tailwater from a boat

How many paddlefish did you release?
I released____ paddlefish less than 35 inches long
I released____ paddlefish greater than 35 inches and less than 45 inches long (slot fish)
I released____ paddlefish greater than 45 inches long

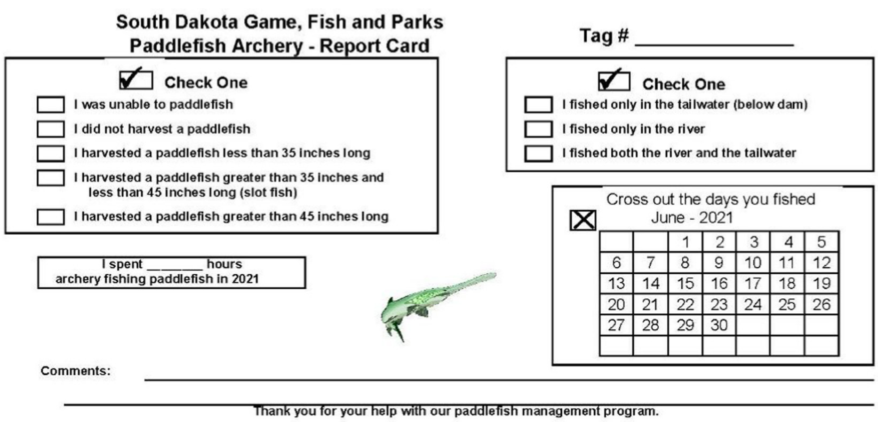
☒ Cross out the days you fished
October - 2021

					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

I spent ______ hours snagging paddlefish in 2021

Comments: ____________________

Thank you for your help with our paddlefish management program.



South Dakota Game, Fish and Parks
Paddlefish Archery - Report Card

Tag # ______________

☑ Check One
☐ I was unable to paddlefish
☐ I did not harvest a paddlefish
☐ I harvested a paddlefish less than 35 inches long
☐ I harvested a paddlefish greater than 35 inches and less than 45 inches long (slot fish)
☐ I harvested a paddlefish greater than 45 inches long

☑ Check One
☐ I fished only in the tailwater (below dam)
☐ I fished only in the river
☐ I fished both the river and the tailwater

☒ Cross out the days you fished
June - 2021

		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

I spent _______ hours archery fishing paddlefish in 2021

Comments: ____________________

Thank you for your help with our paddlefish management program.

NEBRASKA GAME PARKS

Nebraska Game and Parks Commission

Paddlefish Archery - Response Card Tag # ___________

33-448 / rev. 1-2022

☑ Check One

- ❑ I fished but did not harvest a paddlefish
- ❑ I harvested a paddlefish less than 35 inches
- ❑ I harvested a paddlefish between 35 and 45 inches (slot fish)
- ❑ I harvested a paddlefish greater than 45 inches long
- ❑ I did not fish during the paddlefish season

______ Approximate number of Asian Carp taken

☑ Check One

- ❑ I fished only in the tailwater (*From the dam to the boat ramp on the north bank*)
- ❑ I fished only in the river
- ❑ I fished both the river and the tailwater

I spent ______hours archery fishing paddlefish in 2022

☑ Check the days you fished
June 1 - June 30, 2022

Sun	Mon	Tue	Wed	Thur	Fri	Sat
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

Comments: ________________________________

____

____

____

Please mail in this card. If you harvest a paddlefish with a jaw tag, please record the number above. Thanks