U.S. Fish and Wildlife Service

# STATUS OF THE 2010 LAKE STURGEON SPAWNING POPULATION IN THE BAD AND WHITE RIVERS, WISCONSIN

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Lake Superior

CONSERVING AMERICA'S Fisheries U.S. Fish & Wildlife Service

Great Lakes RESTORATION

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*On the cover*:

Fish Biologists Mark Luehring (Great Lakes Indian Fish and Wildlife Commission – GLIFWC) and Joshua Schloesser (U.S. Fish and Wildlife Service) pose with a Bad River lake sturgeon.

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# EXECUTIVE SUMMARY

The population of lake sturgeon *Acipenser fulvescens* in the Bad and White rivers, WI, was sampled during April 14 – 30, 2010 to assess abundance of spawning adults, size structure, growth, age composition, and mortality rates. A pair of 25.4 or 30.5 cm stretch mesh gill nets that were 30.5 to 61 m long by 2.4 m high was set in each river to capture lake sturgeon, and dip nets were also used to capture spawning fish at the Lower Falls of the Bad River. A total of 278 lake sturgeon were collected in gill nets and an additional 58 fish were captured using dip nets. Of the 278 sturgeon captured in gill nets, 196 had no previous marks or tags, whereas 82 did have a previous tag indicating they were previously handled by researchers or managers prior to 2010. The overall sex ratio of all fish captured was 21.5% females, 48.5% males, and 30% unknown. The total adult spawning population size was estimated at 844; 666 (496-836) adults in the Bad River and 178 (111-245) in the White River. The total length of lake sturgeon ranged from 883 to 1,684 mm, with a mean of 1,436 mm and 1,290 mm for females and males, respectively. A greater proportion of lake sturgeon was female when total length exceeded 1,400 mm. The total length-weight relationship was $W = 0.000001149L^{3.236542}$ ($R^2 = 0.87$). The von Bertalanffy length at age model parameters were $L_\infty$ = 1,849 mm, $K$ = 0.0288, and $t_0$ = -10.4803, and predict that the Bad/White River lake sturgeon population is expected to grow approximately 22 mm per year at around age 20, but slowing in growth to only 12 mm per year at around age 40. Total length at age 20 and 40 was predicted to be at 1,080 mm and 1,417 mm, respectively. Weight at age 20 and 40 were predicted to be around 8,139 g and 19,614 g, with an approximate annual gain in weight of 540 g and 560 g per year, respectively. Ages for adult lake sturgeon ranged from 24 to 49 (mean of 34 years) after a correction factor for age estimation error was applied. Instantaneous mortality was estimated at 0.17 and total annual mortality was 0.11 (survival = 0.89). Weak age classes were apparent for age 32, 36, and 44 (1978, 1974, and 1966 year classes, respectively). This report of the 2010 Bad and White River assessment addresses research needs as outlined in the lake sturgeon rehabilitation plan for Lake Superior.

## INTRODUCTION

Lake sturgeon *Acipenser fulvescens* were historically abundant in Lake Superior, but have declined in abundance due to over exploitation, spawning habitat and water quality degradation, and construction of dams that altered flow regimes and impeded spawning migrations (Auer 1999). Since stocks collapsed in the early 1900s, Lake Superior's lake sturgeon populations have not fully recovered. Currently, only two Lake Superior tributaries in the United States (the Bad River, WI and Sturgeon River, MI) support spawning lake sturgeon populations out of six that historically supported self-sustaining populations (Auer 2003). A rehabilitation plan has been established for Lake Superior's lake sturgeon that outlines population goals, management strategies, and assessment and research needs (Auer 2003). Acknowledged in that plan is the need to assess population abundance and biological characteristics to better develop rehabilitation and management strategies (Auer 2003).

Studies have assessed lake sturgeon population dynamics in Lake Superior (Auer 1999) and other systems (Threader and Brousseau 1986; Thuemler 1997; Bruch 1999; Haxton 2002; Hughes et al. 2005; Smith and Baker 2005; Haxton 2006; Bruch 2008; Elliott and Gunderman 2008; Dieterman et al. 2010), but there are no published studies specific to the Bad River population. Comprehensive fishery management practices include assessments of age, growth, size, abundance, recruitment, mortality, and harvest to understand the population dynamics of the species and the effect that exploitation may have on efforts to rehabilitate lake sturgeon.

The Bad River enters Lake Superior approximately 10 km east of the city of Ashland, WI, on the Bad River Indian Reservation. Fish that enter the Bad River also utilize the White River to spawn, a tributary of the Bad River. The genetic structure of the Bad and White River spawning population was found to be similar between each other, but highly differentiated from all other spawning populations in Lake Superior (Welsh et al. 2008). Auer (1999) did report that tagged lake sturgeon moved between the Bad River and the Sturgeon River, MI, in Lake Superior and Schram (2007) found stocked lake sturgeon in the St. Louis River moved as far as the western Apostle Islands. Based on Welsh et al. (2008) and Homola et al. (2010) there is minimal evidence that stocks mix during reproduction, therefore, it may be possible to manage the Bad River population independently from other stocks.

The Bad River Band of Lake Superior Chippewa historically and currently is the primary steward and manager of the Bad River lake sturgeon spawning population. However, the Bad River Natural Resources Department cooperates with the Great Lakes Indian Fish and Wildlife Commission, Red Cliff Natural Resources Department, U.S. Fish and Wildlife Service, and Wisconsin Department of Natural Resources to collect biological and population data on lake sturgeon that spawn or are produced in the Bad River. The Bad River lake sturgeon population is utilized by tribal subsistence, tribal commercial, and state licensed sport fishermen. Tribal subsistence harvest typically occurs in the tributaries during spawning runs, whereas tribal commercial harvest occurs as by-catch from other targeted fisheries when mortalities occur. Wisconsin's licensed anglers are restricted to one fish greater than 127 cm (50 inches) per tag in Lake Superior waters. Current recreational anglers in Minnesota, Michigan, and Ontario are not permitted to harvest lake sturgeon in Lake Superior or its tributaries. The exploitation rate (i.e., subsistence and sport fish harvest combined) is currently unknown due to incomplete reporting of all fishing related mortality. Consequently, the effects of fishing related mortality on population sustainability are unknown, limiting the ability of fishery managers to formulate comprehensive management strategies and rehabilitation plans.

The lake sturgeon is significant ecologically to the Lake Superior aquatic ecosystem and culturally to the people of the region, warranting conservation efforts to protect its sustainability. The objective of this research was to assess the status of the 2010 lake sturgeon spawning population in the Bad and White rivers to help guide future restoration and management efforts. Specifically, we estimated the abundance of spawning adults, size structure, growth, age composition, and mortality rates.

## METHODS

*Study area*.—The lower 65 river kilometers (rkm) of the Bad River and 19 rkm of the White River flow though the Bad River Indian Reservation, offering a relatively undisturbed riparian zone with little development (Figure 1). The Bad River has no man-made barriers to impede migrating fish from reaching historic spawning grounds, but fish migration is limited by natural barriers at Brownstone and Copper falls, located 73 rkm upstream from Lake Superior. The White River has a dam constructed 49 rkm from Lake Superior, 40 rkm from the confluence with the Bad River, prohibiting fish movement upstream of the dam. However, it is uncertain whether lake sturgeon would historically ascend past the current dam site during spawning runs, as suitable spawning habitats are not present upstream of the dam.

Lake sturgeon spawn in two primary locations in the Bad River system, the first of which is the lower falls on the Bad River (36 rkm upstream of Lake Superior). The spawning habitat at the Bad River lower falls, located on the Bad River Indian Reservation, has remained relatively pristine with little human disturbance. Spawning lake sturgeon disperse their eggs below a series of sandstone ledges on large cobble and boulders that collectively make up the lower falls. The Bad River is unique among other lake sturgeon spawning tributaries in the Great Lakes in that lake sturgeon spawn at a location that is not the upstream limit of access for fish migration. The Bad River watershed is composed of mainly sandy soils.

In the White River, spawning typically occurs within 1 rkm downstream of the White River powerhouse, located 0.5 km downstream from the dam. A natural falls used to exist at the site of the present day dam. Suitable spawning substrate and flow conditions for lake sturgeon are located 1-2 km downstream of the White River dam. Downstream of the White River dam the substrate composition, natural flow regime, and thermal regime have been altered, implicating the dam in degrading spawning and nursery habitat that may be limiting reproductive success. The White River watershed contains a primarily clay substrate that is responsible for turbidity levels greater than observed in the Bad River.

One sample site was selected in both the Bad and White rivers to capture migrating lake sturgeon. The Bad River sample site was located at rkm 13, approximately 23 rkm below the lower falls spawning area. The White River sample site was at rkm 11, approximately 29 rkm below the White River dam.

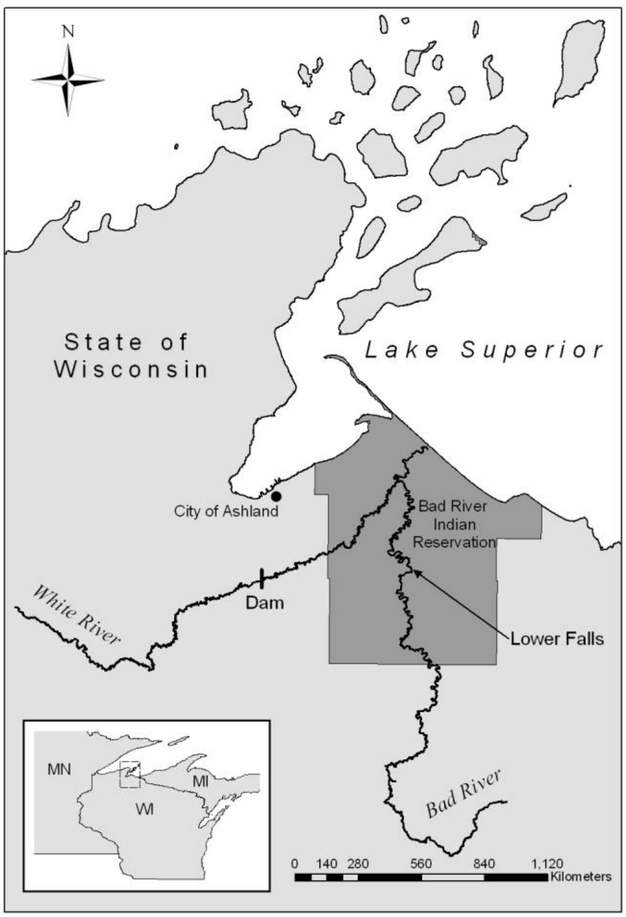


Figure 1.—Location of lake sturgeon spawning areas immediately below the lower falls of the Bad River and the dam on the White River, Wisconsin.

*Sampling methods*.—At each sample site, two gill nets spaced approximately 75 m apart were set across the river, perpendicular to the current, so as to maximize encounters with migrating lake sturgeon. The gill nets set at the Bad River site were 61 m long and 2.4 m tall with either a 25.4 or 30.5 cm stretch multifilament mesh. Gill nets set in the White River were the same dimensions except they were only 30.5 m long, as the river was narrower. Gill nets were set from April 14 through April 30, 2010 for a total of 16 sampling nights.

Dip net sampling also occurred during five occasions at the lower falls of the Bad River between April 30 and May 6, 2010. Two to three dip netters waded in the river and attempted to capture lake sturgeon on the spawning grounds using large dip nets.

All gill nets were checked for lake sturgeon daily, and captured lake sturgeon were removed from the net and measured for total and fork length, girth, and weight. If gametes were expelled from the fish with pressure applied to the abdomen, sex was determined. Each fish was given a uniquely numbered t-bar anchor tag inserted at the base of the dorsal fin, as well as a passive integrated transponder (PIT) tag inserted underneath the skull plate near the dorsal posterior of the right side of the head. On a subset of 10 fish per 50 mm group (Neumann and Allen 2007), a 1 cm section of the leading pectoral fin ray was removed nearest the fish's body for age estimation.

The body condition and condition of the gonads (e.g., ripe, hard, or spent) were inspected to determine if the fish was migrating towards or away from the spawning grounds. Fish with bruises, scrapes, or a concave abdomen were indications that the fish had already spawned. Fish determined to be spent were released approximately 1 rkm downstream of the gill nets to return to Lake Superior. Fish that were unblemished and "fresh", or with hard gonads were released approximately 1 rkm upstream of the nets to continue the assumed upstream migration towards the spawning grounds. After fish were processed, gill nets were cleaned of debris, repaired, and immediately reset in the same locations.

All fish captured in dip nets were measured the same as fish caught in gill nets, except during April 30 when sampling was opportunistic and length, girth, and weight were not measured as not all equipment was available.

Pectoral fin rays were allowed to air dry for four weeks before being sectioned for age estimation. A 0.25- to 0.30-mm section was cut using a low-speed Isomet saw. Digital imaging software was used to amplify the fin ray section to estimate the number of annuli. Ages for each fish were determined independently by three readers. When the readers did not agree on an age, an additional experienced reader also read the age structure and a collaborative session was held until a final age was agreed upon, similar to that of Copeland et al. (2007).

*Statistical methods*.—Population size was estimated using the POPAN formulation of the Jolly-Seber model implemented through Program MARK. Individual capture histories were compiled for each individual fish that was composed of a series of sixteen 1's or 0's for each sampling occasion to indicate whether the fish was captured (1) or not captured (0). A fish was counted as a recapture if it was at large for at least three days. Therefore, fish that were captured within one or two days of the initial capture date were not counted as a recaptured fish and given a 0 for those occasions. Only fish captured in gill nets were used to estimate population size.

The POPAN model was used to estimate apparent survival between sampling occasions (φ), capture probability (*p*), probability of entry (PENT) into the study area from a larger super-population, and abundance (N; Schwarz and Arnason 1996). For our modeling purposes, survival can be referred to as the proportion of the population that remains in the study area and 1 – φ equals the probability of a lake sturgeon that returned to Lake Superior, out of our effective study area. Likewise, PENT refers to the probability of a lake sturgeon entering into the effective study area from Lake Superior after the first sampling occasion.

Assumptions of the Jolly-Seber class of models specify that animals retain their tags throughout the experiment, tags are identified correctly, sampling is instantaneous, marked and unmarked animals have equal survival probabilities, catchability is the same for marked and unmarked animals at each sampling occasion, and the study area is constant (Seber 1982). Program RELEASE was used to test for violations of assumptions; equal survival probability among all animals (Test 3) and for equal probability of recapture among all animals (Test 2).

Model parameters were estimated as constant (.), group (*g*; Bad River and White River populations), time (*t*; 16 sampling occasions), and group by time interaction (*g*t*). The candidate set of models included all formulations for survival (., *g*, *t*, *g*t*), capture probability (., *g*), probability of entry (., *g*, *t*, *g*t*), and population size (*g*). We hypothesized that either a time or group by time model would best represent the migratory behavior (φ and PENT parameters) of spawning lake sturgeon, but concerns of estimating too many parameters prompted us to fit constant and group models as well (even though they do not make much biological sense). Candidate models were ranked using Akaike Information Criterion corrected for small sample sizes (AICc; Burnham and Anderson 2002). The top models and candidate models with an AICc value ≤2 of the top model were considered to be equally well supported by the data (Burnham and Anderson 2002). All candidate models contributing some weight ($w_i$) of evidence they support the data, were used in a model averaging procedure to derive final parameter estimates.

Length frequency histograms (all reported lengths are total length) were constructed using 50mm bins as recommended by Neumann and Allen (2007). The distribution in lengths between rivers was tested for differences for each sex using Kolmogorov-Smirnov tests in SAS (SAS Institute 2008). A Bonferroni correction of P = 0.017 (0.05/3) was applied to correct for multiple-tests. The length-weight relationship was fit to the standard allometric equation;

$$W = \alpha L^{\beta},$$

where $\alpha$ and $\beta$ are coefficients determined by a regression of Log total length ($L$; mm) on Log weight ($W$; g). Fish that had already expelled all their gametes were excluded from development of the length-weight relationship because the weight loss can be up to 15% for males and 30% for females. The length at age relationship was determined by constructing an age-length key from the subset of fish where an age structure was taken (Isely and Grabowski 2007). Bruch et al. (2009) recognized that age estimation error existed when pectoral fins spines were used and provides a correction equation;

$$Corrected\ age = Estimated\ age^{1.054796},$$

which was applied to all age related analyses for lake sturgeon greater than 14 years old. The proportion of individuals in each length class of a certain age was extrapolated to the entire sample of lake sturgeon to estimate the fish's age from its length. Growth in length was fit to the von Bertalanffy model;

$$L_t = L_\infty(1 - e^{-K\ t - t_0}\ ),$$

where $L_t$ is the length at time $t$, $L_\infty$ is the asymptotic length, $K$ is a growth coefficient, and $t_0$ is a time coefficient at which length would theoretically be 0 (Isely and Grabowski 2007). Model parameters $L_\infty$, $K$, and $t_0$ were derived by minimizing the residual sum of squares using the solver tool in Microsoft Excel. Growth in weight was also fit to the von Bertalanffy weight at age model;

$$W_t = W_\infty(1 - e^{-K\ t - t_0}\ )^{\beta},$$

where $W_t$ is the weight at time t, $K$ and $t_0$ were derived from the length at age model, and $\beta$ was derived from the length-weight relationship. Weight infinity ($W_\infty$) was estimated from the model;

$$W_\infty = \alpha L_\infty{}^{\beta}.$$

Instantaneous total mortality ($Z$) was estimated through catch curve regression models. The age-length key previously developed was used to assign each fish an age. A weighted regression analysis was then performed using SAS (SAS Institute 2008) to estimate instantaneous total mortality from the descending limb of the catch curve (Miranda and Bettoli 2007). Only the descending limb of the catch curve was used to estimate mortality to include only those ages that were fully recruited to capture in gill nets and to make a spawning run. Constant recruitment is preferred with the use of catch curves, but moderate and random variations in recruitment can still produce reasonable estimates of mortality (Miranda and Bettoli 2007). Total annual survival ($S$) and mortality ($A$) were deduced from the estimate of $Z$.

# RESULTS

A total of 278 individual lake sturgeon were collected in gill nets during the study period; 196 were new fish with no marks or tags to indicate that it was previously captured by researchers or managers and 82 fish did have some previous uniquely numbered tag (e.g., Floy, PIT, or Monel tag). In the field, it became obvious to us that gill nets reached a saturation point when approximately 10 fish were caught in the Bad River nets and 7 to 8 fish in the White River nets. A total of 58 fish were captured during dip net efforts. The sex ratios for lake sturgeon captured in the Bad River were 26% females, 47% males, and 27% fish of unknown sex, a male to female ratio of 1.8:1. The White River was composed of 17% females, 50% males, and 33% of unknown sex, a male to female ratio of 2.9:1.

*Population size*.—Out of the 278 total lake sturgeon captured, 54 were recaptured during the study period. For the POPAN model, goodness-of-fit tests indicated our data did not violate the assumption of equal survival probability among all animals ($P = 0.9818$) or equal probability of recapture among all animals ($P = 0.2954$). However, both tests indicated data were sparse as the number of marked fish was relatively low compared to the number of unmarked fish. Several (<5) lake sturgeon were recaptured with missing t-bar anchor tags, but the PIT tag allowed for positive identification of each fish.

The candidate models that ranked highest were the simplest models (i.e., least number of estimated parameters), where $\phi$, $p$, and PENT varied as either a constant or group function (Table 1). Parameters modeled as a function of time or group by time interaction were not well supported. Estimation of an additional 15 and 30 parameters for time and group by time functions, respectively, imposed a large penalty on the AICc score, resulting in complex models ranking less favorable than simpler models. The top four approximating models incorporated a group effect in apparent survival and either a constant or group effect for capture probability and probability of entry.

The top four models accounted for nearly 90% of the weight during model averaging. Model averaged parameter estimates for $\varphi$ were 0.8655 and 0.9882, $p$ were 0.0640 and 0.0588, and PENT were 0.0278 and 0.0306 for the Bad and White Rivers, respectively (Table 2). The $\varphi$ parameter can be interpreted as 86.55% of lake sturgeon already present in the study area will stay in the study area each sampling occasion (13.45% will leave). Similarly, the PENT parameter can be interpreted as 2.78% (3.06% for White River) of lake sturgeon returned to spawn each sampling occasion. By deduction, this means that 58.3% of lake sturgeon had already entered the Bad River before sampling began and 54.1% entered the White River. The estimated adult lake sturgeon population size for the Bad River was 666 (496-836) and 178 (111-245) for the White River (Table 2).

Table 1.—Candidate models ranked according to lowest AICc values. Apparent survival (φ), capture probability (*p*), probability of entry (PENT), and population size (N) were modeled as a constant probability (.), function of group (g; Bad and White Rivers), time (t), and a group by time interaction (g*t).

| Model | AICc | Delta AICc | AICc Weights | Model Likelihood | Number of parameters |
|---|---|---|---|---|---|
| { φ (g), *p*(.), PENT(.), N(g)} | 908.6702 | 0.0 | 0.36654 | 1.0 | 6 |
| { φ (g), *p*(g), PENT(.), N(g)} | 909.1822 | 0.5120 | 0.28375 | 0.7741 | 7 |
| { φ (g), *p*(.), PENT(g), N(g)} | 910.5516 | 1.8814 | 0.14308 | 0.3904 | 7 |
| { φ (g), *p*(g), PENT(g), N(g)} | 911.2563 | 2.5861 | 0.10059 | 0.2744 | 8 |
| { φ (.), *p*(g), PENT(g), N(g)} | 912.2267 | 3.5565 | 0.06192 | 0.1689 | 7 |
| { φ (.), *p*(.), PENT(g), N(g)} | 913.0751 | 4.4049 | 0.04051 | 0.1105 | 6 |
| { φ (.), *p*(.), PENT(.), N(g)} | 918.8510 | 10.1808 | 0.00226 | 0.0062 | 5 |
| { φ (.), *p*(g), PENT(.), N(g)} | 919.9460 | 11.2758 | 0.00130 | 0.0035 | 6 |
| { φ (g), *p*(g), PENT(t), N(g)} | 927.2180 | 18.5478 | 0.00003 | 0.0001 | 21 |
| { φ (t), *p*(.), PENT(g), N(g)} | 930.0393 | 21.3691 | 0.00001 | 0 | 20 |
| { φ (t), *p*(g), PENT(.), N(g)} | 936.7070 | 28.0368 | 0 | 0 | 20 |
| { φ (g*t), *p*(.), PENT(.), N(g)} | 937.8420 | 29.1718 | 0 | 0 | 34 |
| { φ (g), *p*(.), PENT(t), N(g)} | 939.8899 | 31.2197 | 0 | 0 | 20 |
| { φ (t), *p*(g), PENT(g), N(g)} | 940.3115 | 31.6413 | 0 | 0 | 21 |
| { φ (g*t), *p*(.), PENT(g), N(g)} | 940.9761 | 32.3059 | 0 | 0 | 35 |
| { φ (g*t), *p*(g), PENT(g), N(g)} | 945.0722 | 36.4020 | 0 | 0 | 36 |
| { φ (g), *p*(g), PENT(g*t), N(g)} | 948.1939 | 39.5237 | 0 | 0 | 36 |
| { φ (g*t), *p*(g), PENT(.), N(g)} | 949.6925 | 41.0223 | 0 | 0 | 35 |
| { φ (.), *p*(.), PENT(g*t), N(g)} | 950.5782 | 41.9080 | 0 | 0 | 34 |
| { φ (g), *p*(.), PENT(g*t), N(g)} | 950.9408 | 42.2706 | 0 | 0 | 35 |
| { φ (.), *p*(.), PENT(t), N(g)} | 958.8890 | 50.2188 | 0 | 0 | 19 |
| { φ (.), *p*(g), PENT(t), N(g)} | 960.4801 | 51.8099 | 0 | 0 | 20 |
| { φ (t), *p*(.), PENT(.), N(g)} | 960.7959 | 52.1257 | 0 | 0 | 19 |
| { φ (.), *p*(g), PENT(g*t), N(g)} | 965.7670 | 57.0968 | 0 | 0 | 35 |
| { φ (t), *p*(g), PENT(t), N(g)} | 971.0749 | 62.4047 | 0 | 0 | 34 |
| { φ (g*t), *p*(.), PENT(t), N(g)} | 971.4377 | 62.7675 | 0 | 0 | 48 |
| { φ (t), *p*(.), PENT(t), N(g)} | 973.7305 | 65.0603 | 0 | 0 | 33 |
| { φ (t), *p*(g), PENT(g*t), N(g)} | 973.9879 | 65.3177 | 0 | 0 | 49 |
| { φ (g*t), *p*(g), PENT(t), N(g)} | 979.8133 | 71.1431 | 0 | 0 | 49 |
| { φ (t), *p*(.), PENT(g*t), N(g)} | 988.0330 | 79.3628 | 0 | 0 | 48 |
| { φ (g*t), *p*(g), PENT(g*t), N(g)} | 998.8008 | 90.1306 | 0 | 0 | 64 |
| { φ (g*t), *p*(.), PENT(g*t), N(g)} | 1000.3336 | 91.6634 | 0 | 0 | 63 |

Table 2.—Model averaged parameter estimates and 95% confidence intervals for apparent survival (φ), capture probability (*p*), probability of entry (PENT), and population size (N).

| | Bad River | | White River | |
|---|---|---|---|---|
| Parameter | Estimate | 95% C.I. | Estimate | 95% C.I. |
| φ | 0.8655 | 0.7963-0.9138 | 0.9882 | 0.0384-0.9999 |
| *p* | 0.0640 | 0.0444-0.0913 | 0.0588 | 0.0384-0.0889 |
| PENT | 0.0278 | 0.0173-0.0443 | 0.0306 | 0.0175-0.0530 |
| N | 666 | 496-836 | 178 | 111-245 |

*Size metrics*.—Lake sturgeon lengths ranged from 883 to 1,684 mm total length, with all but two fish greater than 1,000 mm (Figure 2). The Kolmogorov-Smirnov tests indicated length frequency distributions were similar between rivers for each sex; female $P = 0.7590$, male $P = 0.4396$, and unknown $P = 0.9888$. Mean total length of females, males, and unknowns in both rivers combined was 1,436 mm, 1,290 mm, and 1,313 mm, respectively. Over 98% of females captured in the Bad River and 92% in the White River were greater than 1,300 mm. A disproportionate number of lake sturgeon were females when total length exceeded 1,400 mm, whereas males represented a greater proportion of the spawning adults when total lengths were less than 1,400 mm (Figure 3). No males were captured ≥ 1,650 mm total length.

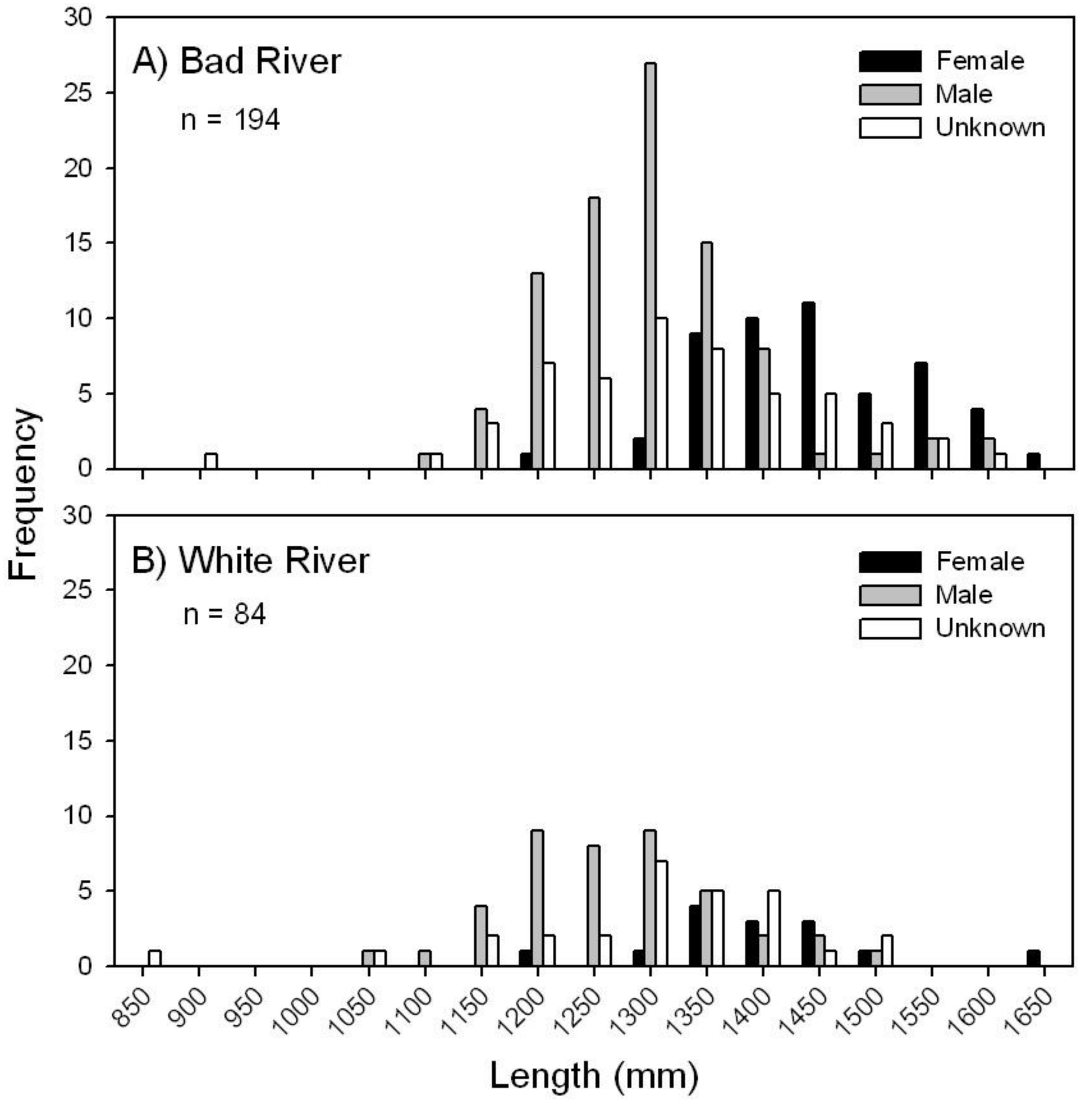


Figure 2.—Length frequency distributions for female, male, and unknown sex lake sturgeon captured in gill nets in the Bad (A) and White Rivers (B) during April 15-30, 2010.

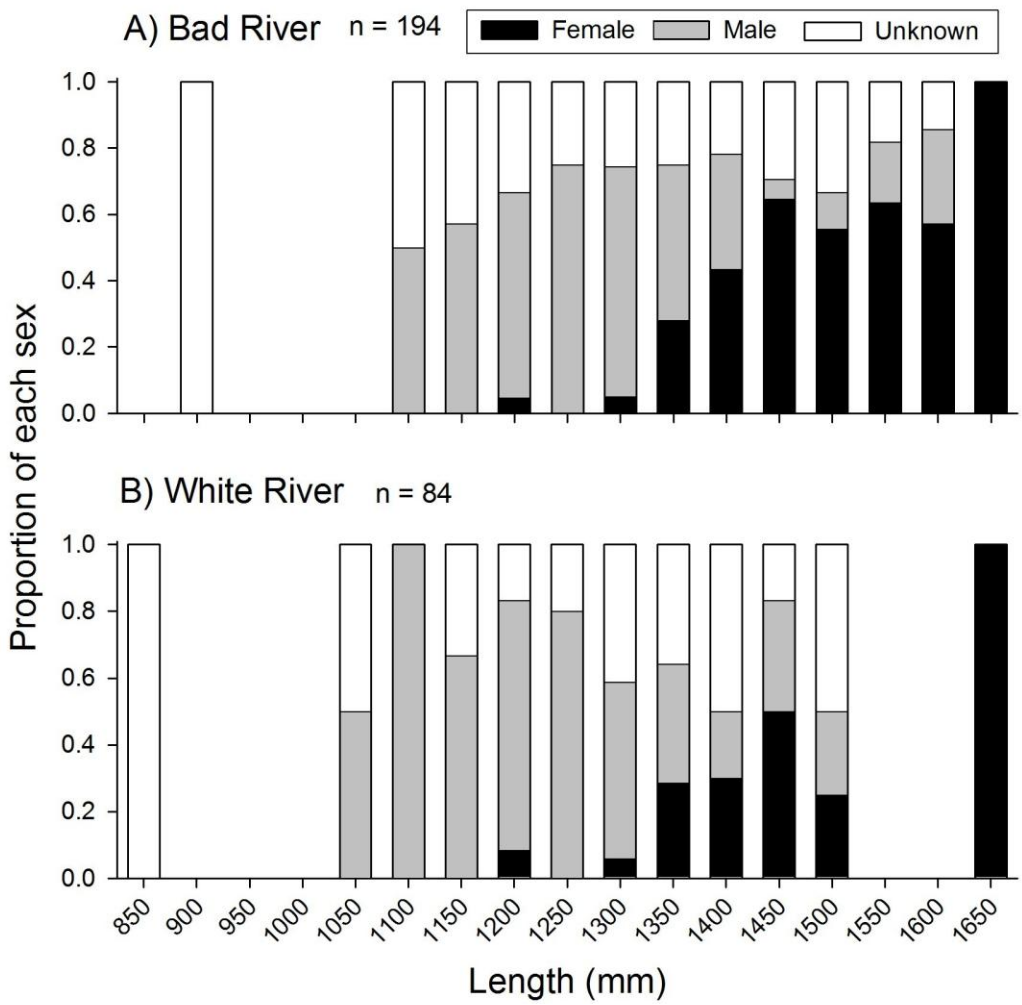


Figure 3.—Proportion of female, male, and unknown sex lake sturgeon in each length category captured in gill nets in the Bad (A) and White Rivers (B) during April 15-30, 2010.

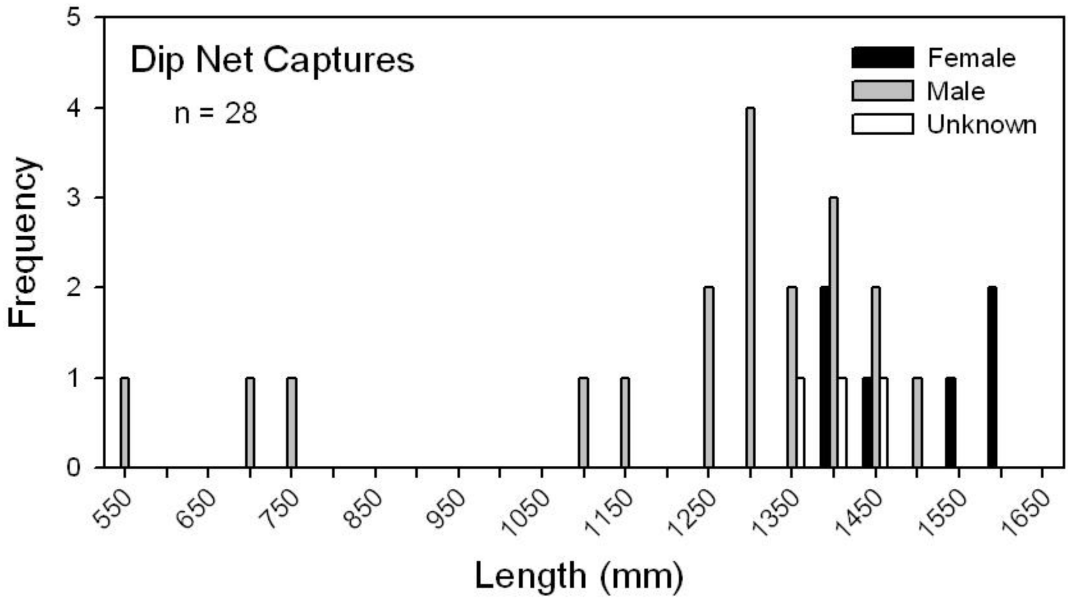


Figure 4.—Length frequency distributions for female, male, and unknown sex lake sturgeon captured in dip nets in the Bad River during May 3-6, 2010.

*Growth*.—Combined data of all sexes and both rivers (N = 212) gave the total length-weight relationship $W = 0.000001149L^{3.236542}$ ($R^2 = 0.87$; Figure 5). This model represents lake sturgeon at their heaviest weight just prior to spawning while full of gametes. At a length of 1,200 mm, weight was expected to be 10.6 kg. Lake sturgeon were expected to grow approximately 22 mm per year around age 20, but slowed growth to only 12 mm per year around age 40, reaching a theoretical maximum length ($L\infty$) of 1,849 mm (Figure 6). Total length at age 20 and 40 was predicted to be at 1,080 mm and 1,417 mm, respectively (growth of 337 mm in 20 years). Length at age model parameters were estimated at $K = 0.0288$ and $t_0 = -10.4803$. Growth in weight exhibited a nearly linear relationship with age reaching a theoretical maximum weight of 46,540 g (103 lbs). Weight at age 20 and 40 were predicted to be around 8,139 g and 19,614 g, with an approximate annual gain in weight of 540 g and 560 g per year, respectively. The mean observed weight of lake sturgeon tended to deviate more (greater residuals) from the predicted value of the weight at age model with increased age. Growth of female and male lake sturgeon could not be estimated separately due to the small sample size of age structures taken. One lake sturgeon of unknown sex tagged by GLIFWC during 1994 measured 715 mm in length was recaptured during the 2010 population assessment and measured 1,300 mm in length, a growth of 585 mm in 16 years (mean of 36.6 mm per year).

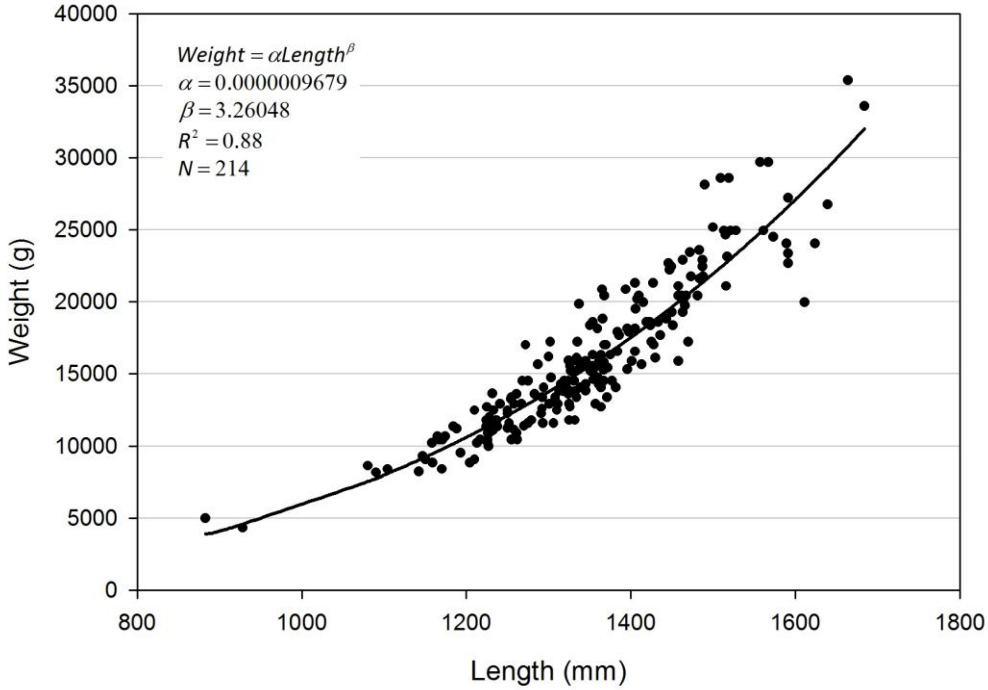


Figure 5.—Length-weight relationship for lake sturgeon prior to spawning during the 2010 spring spawning run in the Bad and White Rivers, Wisconsin.

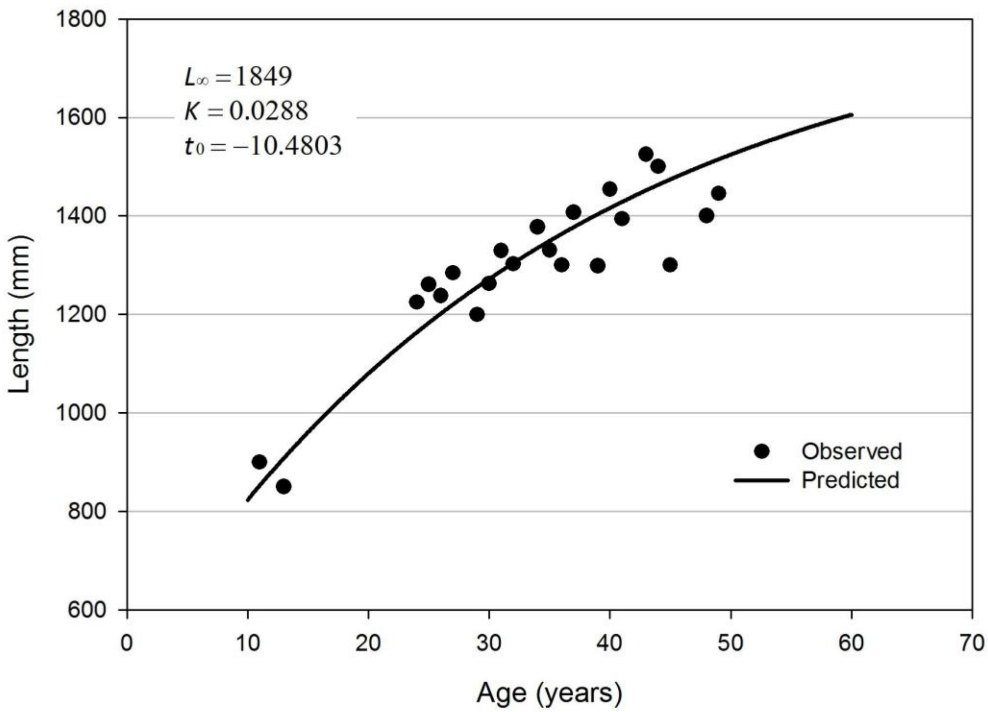


Figure 6.—Growth in total length (mm) for adult lake sturgeon in the Bad and White Rivers, Wisconsin.

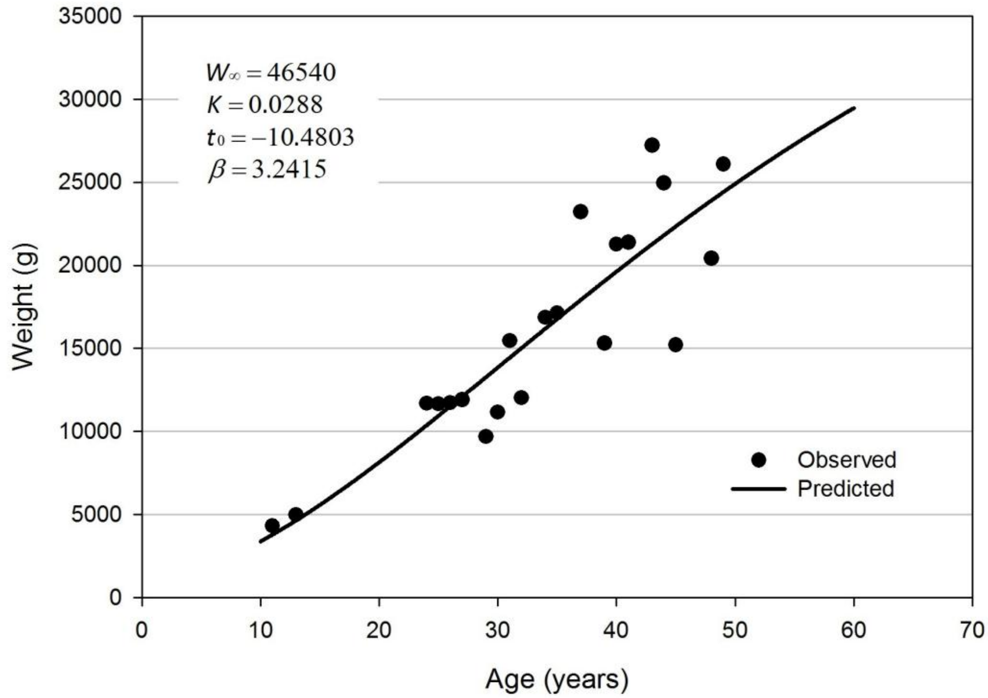


Figure 7.—Growth in weight (g) for adult lake sturgeon in the Bad and White Rivers, Wisconsin.

*Age composition and mortality*.—Lake sturgeon ages estimated from pectoral fin spines were expected to be under-estimated by 4 years from a spine read at 20 years old and by 9 years from a spine read at 40 years old (Table 3). When the correction factor was applied over the entire range of spines read, rounding errors inherent in the correction equation excluded ages 33, 38, 42, and 47 from being represented in the entire sample of lake sturgeon.

Corrected ages for adult lake sturgeon ranged from 24 to 49, but two fish of unknown sex were also caught and aged at 11 and 13 years old. Mean age of all lake sturgeon was 34 years. The catch curve was developed from lake sturgeon in the range of 31 to 49 years old which defined the descending limb of the catch curve. No age 46 fish were captured, therefore 1 was added to the catch in each age class to accommodate the zero catch during the natural log transformation to perform the weighted regression. The ages not represented as a result of the age correction factor (33, 38, 42, and 47) were excluded from the weighted regression. Instantaneous mortality was estimated at $Z$ = 0.11647 and total annual mortality was estimated at $A$ = 0.10994 ($S$ = 0.89006; Figure 7). Weak age classes were apparent for age 32, 36, and 44 (1978, 1974, and 1966 year classes, respectively) as indicated by large negative residuals from the catch curve regression.

Table 3.—Adjusted ages used to correct for age estimation error from lake sturgeon pectoral fins spines from the equation $Corrected\ age = Estimated\ age^{1.054796}$.

| Estimated age | Corrected age | Estimated age | Corrected age | Estimated age | Corrected age | Estimated age | Corrected age |
|---|---|---|---|---|---|---|---|
| 15 | 17 | 25 | 30 | 35 | 43 | 45 | 55 |
| 16 | 19 | 26 | 31 | 36 | 44 | 46 | 57 |
| 17 | 20 | 27 | 32 | 37 | 45 | 47 | 58 |
| 18 | 21 | 28 | 34 | 38 | 46 | 48 | 59 |
| 19 | 22 | 29 | 35 | 39 | 48 | 49 | 61 |
| 20 | 24 | 30 | 36 | 40 | 49 | 50 | 62 |
| 21 | 25 | 31 | 37 | 41 | 50 | 51 | 63 |
| 22 | 26 | 32 | 39 | 42 | 52 | 52 | 65 |
| 23 | 27 | 33 | 40 | 43 | 53 | 53 | 66 |
| 24 | 29 | 34 | 41 | 44 | 54 | 54 | 67 |

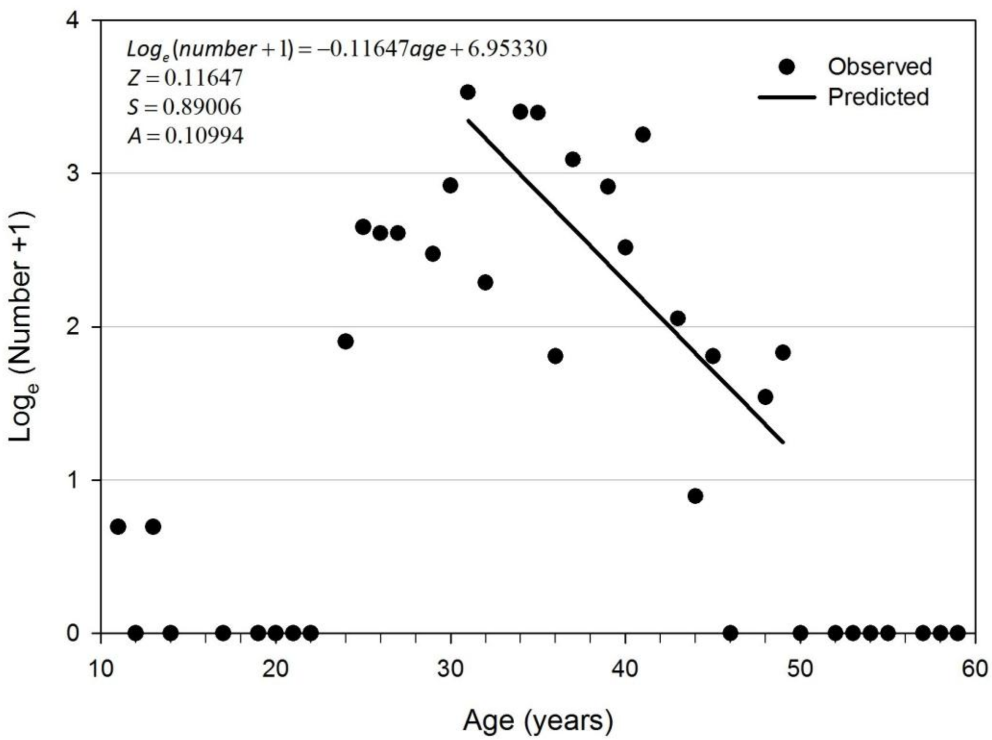


Figure 7.—Catch curve of lake sturgeon in the Bad and White Rivers, Wisconsin. Ages 31 to 49 years defined the descending limb of the catch curve used to estimate mortality rates.

# DISCUSSION

The estimated size of the 2010 spawning lake sturgeon population in the Bad and White Rivers has increased since population assessments in the 1990s. In 1992 and 1994 a total of 34 and 13 adult lake sturgeon were captured in the Bad River system, respectively (Slade and Rose 1994). A mark-recapture effort estimated the 1999 spawning run at 250-350 individuals (USFWS Ashland, WI, unpublished data). While the 1999 estimate is significantly lower than the 2010 estimate, sampling effectiveness was low during the 1999 survey (i.e., high discharge, in-stream debris) which may have contributed to a lower estimate.

Auer (2003) set a restoration goal of 1,500 mature adults that could ascend a tributary to spawn as a minimum benchmark for a self-sustaining population. The 2010 spawner population estimate of nearly 850 was approximately half of the minimum goal of mature adults in the system. This estimate does not include adult lake sturgeon in the recovery or developmental phases of spawning that remained in Lake Superior during the spawning run, and thus were not incorporated into the current years population estimate. Based on an adult population goal of 1,500 mature individuals and the intermittent nature of the lake sturgeon spawning cycle, it is likely the Bad River lake sturgeon population has reached at least 1,500 adults. However, it would be premature to conclude the Bad River population has recovered from the stock collapse of the 20$^{th}$ century because this was only a single year spawner estimate. Additionally, the goal outlined in the rehabilitation plan was developed on little data from the Sturgeon River, MI and may need to be adjusted to be tributary specific to be biologically meaningful.

Tagged lake sturgeon marked and recaptured from 1997-2010 in the Bad and White rivers suggests that males spawn every 2-3 years and females spawn on a 4-6 year cycle. A few fish have been recaptured after more than 6 years at large, but it is possible these fish were undetected during prior spawning runs. A definitive understanding of spawning periodicity specific to the Bad River population would better enable the ability to estimate total stock size in Lake Superior. Auer (1999) observed male lake sturgeon returning to spawn in the Sturgeon River, MI after 2 to 6 years at large and females returned after 3 to 7 years, but this study did not address the probability of missed detections.

The estimated population sizes of lake sturgeon spawning from other Lake Superior tributaries are smaller than the estimated population size of the Bad River. In the Sturgeon River, MI, the spawning population was estimated at 350-400 fish (Auer and Baker 2007). In the Black Sturgeon River, ON, the population size utilizing the river as a spawning site was estimated at 89 during 2003 and 96 during 2004 (Friday 2004). The Kaministiquia River, ON experienced spawning runs of 160-188 individuals between 1998 and 2001 (Friday and Chase, draft report). Holey et al. (2000) summarized estimated annual spawning run size from populations throughout the Great Lakes and St. Lawrence River. At the time, the Bad River spawning run estimate was 250-350 and that ranked second among Great Lakes basin sites, well behind the Wolf River, WI estimate of 22,000. In Lake Michigan, tributaries of the Bay of Green Bay had lake sturgeon spawning runs of 25 to ≥200 fish (Elliott and Gunderman 2008).

The POPAN model fits well with the biology and behavior of spawning lake sturgeon populations because it is an open population model and can specifically estimate the rate at which fish enter and leave the system for spawning. Our results suggested that lake sturgeon enter and leave the spawning grounds of the Bad and White Rivers at nearly a constant rate. However, we hypothesized that entry to and exit from the spawning grounds would be a function of water temperature (e.g., a time parameterization of φ and PENT). Sex of fish may also determine entry and survival probabilities, with males entering the system earlier and departing later than females. Inspection of model outputs indicated that models parameterized by time were generally over-parameterized given the number of fish captured, resulting in less favorable models than constant or group models. Model results also suggested that more than half the spawning population was already present in the study area before sampling had begun. While ideal sampling conditions (i.e., consistent flows, little debris) were present during the study period, an early and warm spring triggered a rapid increase in water temperatures that may have resulted in early spawning migrations. The first sampling occasion yielded a total of 25 lake sturgeon. Ideally, catch rates at the start and end of the study period would have been near or at zero with the greatest catch rates corresponding to the peak of the spawning migration.

Low capture probabilities observed during the study could be a result of net saturation. At the saturation point, tangled lake sturgeon reduced the effective sampling area to a point where migrating fish could easily swim over or under the twisted nets. We estimated a net saturation point of roughly 10 fish per 61 m of gill net in the Bad River and 6-7 fish per 30.5 m of gill net in the White River. In future efforts additional nets could be added to the paired net design to overcome net saturation issues and hopefully increase capture probabilities. An increase in capture probabilities should reduce confidence intervals for all parameter estimates.

Similarity among length distributions between the Bad and White Rivers indicates both rivers could be managed with similar length restrictions for fishing harvest. We found that most spawning females were greater than 1,300 mm in length and that any lake sturgeon ≥1,400 mm harvested in the Bad or White River has a greater likelihood of being a female than a male. Likewise, the likelihood of a fish being female increases as length increases. Therefore, in order to protect spawning females it would be beneficial to limit the harvest of longer fish with the understanding that they are likely females. The Sturgeon River, MI had a similar length distribution of spawning females to the Bad and White Rivers, where the minimum size of females observed was 1,300 mm and once fish reached a length of 1,450 mm there was a greater likelihood it was a female (Auer 1999). Auer (1999) did observe spawning females up to the 1,800 mm length class, where the maximum size observed in the Bad River during 2010 was 1,684 mm. Stephenson (1999) reported the mean total length of lake sturgeon was 1,201 mm on the Kaministiquia River, ON, and lake sturgeon in the St. Clair system averaged 1,334 mm in length with a maximum of 1,876 mm (Boase and Hill 2002). In the Black Sturgeon River, ON, the average length of adult lake sturgeon utilizing the river as a spawning site was 1,098 mm during 2002-2004 (Friday 2004).

Sex ratios of the Bad and White Rivers were similar to other Lake Superior spawning runs. During five years of natural flows in the Sturgeon River, MI, a sex ratio of 1.25:1 to 2.7:1 males to females was observed (Auer 1999), and earlier data from the Bad River, WI showed a 2:1 ratio (Quinlan 2007). Harkness and Dymond (1961) commented that the percent of lake sturgeon greater than 1,524 mm was more than 95% females in Lake Winnebago, WI, but the sex ratios were more similar for lake sturgeon less than 1,245 mm. In the Rehabilitation Plan for Lake Superior, a goal of a roughly equal sex ratio was identified (Auer 2003), but we believe this goal may need to be analyzed more thoroughly and be specific to the Bad River population.

The length-weight relationship for lake sturgeon has been found to be consistent among different populations and that the slopes of the logarithmic relationship vary little from 3.3 (Beamish et al. 1996). The Bad River population falls in line with this observation that lake sturgeon exhibit disproportionate increases in weight with length. In relation to other Great Lakes populations, the Bad River exhibits a similar length-weight relationship. For the Upper St. Clair River system, a sturgeon that was 1,200 mm total length was expected to be 10.3 kg (Boase and Hill 2002), whereas Bad River lake sturgeon were expected to be 10.6 kg. Compared to an earlier study on the Bad River in the early 1990s, the length-weight relationship has remained relatively unchanged from when Slade and Rose (1994) reported a length-weight relationship of $W = 0.00000086L^{3.298}$, which was developed from 30 fish.

Growth in length has been shown to vary in response to environmental variables and location within the species range (Harkness and Dymond 1961; Fortin et al. 1996). Auer (1999) estimated that males may be 1,340 mm at 22 years old and females 1,530 mm at about 30 years old, but Bad River lake sturgeon were estimated to be 1,123 mm and 1,272 mm at the same ages, respectively, after the age correction factor was applied. In the Upper St. Clair River system, total length at age 20 and 40 was predicted to be 1,337 mm and 1,709 mm, which was 257 mm and 292 mm greater than what was observed in the Bad River, respectively (Boase and Hill 2002). A possible explanation for the apparent slower growth rates of Bad River lake sturgeon could be a product of applying an age correction factor to all our age estimates. Other studies did not account for age estimation error in their growth calculation, which would likely decrease growth rate estimates as ages are typically underestimated for lake sturgeon. Bruch (1999) observed a decrease in growth for males once they reached 20 years old, but we did not develop sex specific growth curves with our data.

We attempted to validate the growth model we developed to assess whether it actually matched the biological response of lake sturgeon. When comparing expected lengths from the growth model to the actual growth from recaptured fish over the prior 16 years worth of lake sturgeon surveys, we suspect the age corrected growth model still overestimates length at age. This means that the age correction equation developed by Bruch et al. (2009) still underestimates the true age for lake sturgeon in Lake Superior. It is suspected that different environmental conditions (i.e., colder water temperatures, lower ecosystem productivity) and population genetic structure in Lake Superior compared to the Lake Winnebago system are primary factors driving slower growth in Lake Superior. To resolve issues with age estimation errors, it is recommended that a correction factor be developed specifically for Lake Superior's lake sturgeon. This may be achieved by marking known age fish when they are young (i.e., age can be accurately estimated) and recapturing them at later time periods.

Few old individuals (>40 years) were captured during the 2010 assessment. The maximum age observed was 49 years. Historic records cite lake sturgeon living up to 154 years in Lake of the Woods, ON (MacKay 1963) and reaching weights that exceed 300 pounds in Lake Superior and Lake Michigan (Harkness and Dymond 1961). The potential should exist for Bad River lake sturgeon to live many years and reach large sizes in Lake Superior, especially because of the close proximity to the more productive waters in Chequamegon Bay. However, we did not observe any excessively large fish. It may be possible that we are just starting to see the population rebound from its collapse during the early 1900s. Restoration activities implemented over the last 50 years such as passage of the Clean Water Act, sea lamprey control, reduction of recreational and commercial fishing harvest, and stocking efforts (Schram et al. 1999) may have been effective, and it is only now that we are seeing the effects of past restoration efforts. In support of this speculation, abundance of juvenile lake sturgeon captured near the mouth of the Bad River has increased over the last 15 years (Quinlan et al. 2010) and Thomas and Haas (2004) observed a higher frequency of cohorts present since 1973 in the St. Clair River system.

The age when lake sturgeon first return to spawn has been well studied, and most studies generally accept that males first return to spawn at age 12-15 and females at age 18-27 (Peterson et al. 2007). The smallest female captured in the Bad River during 2010 was a 1,231 mm female whose age was estimated at 29 years with the correction factor applied (24 years read from the pectoral fin ray) and one of the smallest ripe males collected was 1,143 mm total length and 20 years old (17 years read from the pectoral fin ray). What this means is that the age at first spawn for the Bad River population may tend towards the upper end of the range, but comparing additional sampling years would help validate this observation.

When catch curves are used to estimate steady state total mortality rates, similar recruitment among years must be assumed, but variation in recruitment can be detected through residuals of the catch curve regression (Maceina 1997). Three weak year classes and one that was absent indicate that recruitment may vary among years, although inspection of residuals appears to have had a minimal effect on the slope of the regression (the parameter representing mortality). Age 31 was the start of the descending limb of the catch curve indicating that not all fish were vulnerable to capture up to age 30. It is likely that males were fully vulnerable to capture by age

30, but all females may not have been mature by age 30, an observation that further supports our conclusion of a late age at maturity. It would be highly beneficial to add additional years to the catch curve since all age classes were not represented during the 2010 assessment (e.g., age 46 was absent). During our assessment, only five age samples were taken per 50 mm length class, and it is likely that five or more age classes were represented within each 50 mm length class. To eliminate bias when assigning fish to an age class, especially at older ages, it would be beneficial to take age samples from all fish ≥1,500 mm. With future assessments, it may become possible to develop sex specific catch curves that will aid in formulating sustainable harvest levels.

Our attempt to minimize age estimation error resulted in a total annual mortality being lower than what it would have been had we not applied the correction factor. If our speculation that the correction factor reported by Bruch et al. (2009) still underestimates the true age of Lake Superior lake sturgeon, total annual mortality may in fact be lower than what we reported. One method to avoid problematic issues when using catch curve mortality estimates (e.g., variable recruitment, sex-specific mortality at older ages), would be to use mark-recapture demographic models to estimate apparent survival ($S$) and derive estimates of annual mortality (mortality = 1-$S$; e.g., Dieterman et al., 2010).

We were unable to find mortality estimates for other Lake Superior tributaries in the literature. It is likely that low catches of lake sturgeon in other Lake Superior tributaries (presumably due to low abundance) prohibit development of mortality estimates. In the St. Clair system total annual mortality of lake sturgeon ranged between 0.09 and 0.14 (Thomas and Haas 2004). Elliott and Gunderman (2008) reported a total annual mortality of 0.0506 ($Z = 0.052$) for open water trap net assessments in Green Bay of Lake Michigan. Extensive studies on the Lake Winnebago system over a 40 year period have shown the total annual mortality rate to range from 10%-22%, which included years of intensive harvest (Bruch 1999).

The Lake Sturgeon Rehabilitation Plan for Lake Superior has set a maximum exploitation rate of 5% for populations lake-wide (Auer 2003). However, unavailable or incomplete reporting of lake sturgeon harvest limits biologist's ability to verify that exploitation is below the goal of 5%. Incomplete reporting also impedes the ability to safely set maximum harvest levels that would minimize the risk of overexploiting a population being rehabilitated.

*Future management needs*.—The need to acquire information on population size and biological characteristics of recovering lake sturgeon populations was highlighted in the lake sturgeon rehabilitation plan for Lake Superior (Auer 2003) and this report addresses some of those needs for the Bad and White river lake sturgeon population. We addressed gaps in information related to population size, length distribution, growth, sex ratios, and total annual mortality. However, continued assessments are needed to further develop biological models for growth, mortality, population size, and spawning periodicity that are sex specific and representative of the entire

Bad River population. Annual population assessments could also affirm population stability or reveal an increasing or decreasing population trend. Assessment activities could also include young of year to ensure adequate numbers of lake sturgeon will recruit to adult sizes and contribute to future progeny, as recruitment is generally recognized as limiting population growth and sustainability. Additionally, continually marking lake sturgeon with uniquely numbered PIT tags will allow for modeling a variety of demographic processes that will aid to improved management strategies and determine appropriate harvest levels (e.g., Dieterman et al. 2010). A critical need is accurate reporting of lake sturgeon harvest from all sources to ensure the risk of overexploitation is minimized and the population is sustainable.

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Appendix 1. Capture histories for lake sturgeon of a known sex recaptured in 2010 during fishery assessments on the Bad River, WI. Total length (mm) is listed under capture year.

| PIT Tag | Sex | Capture Year | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 |
| 421C18096F | M | | | 1430 | | | 1432 | | | 1440 | | | 1447 |
| 421C21135B | M | | | 1220 | | | 1250 | | | | | | 1325 |
| 421C262743 | M | | 1135 | | | | | | | | | | 1458 |
| 421C2C4127 | M | | 1340 | | | | | | | | | | 1339 |
| 421C363A2E | M | | 1389 | | | | | | | | | | 1450 |
| 4225681261 | M | 1116 | | | | | | | | | | | 1230 |
| 4226022544 | M | | | | | 1093 | | | | | | | 1181 |
| 42262A2730 | M | 1460 | | | | | | | | | | | 1515 |
| 42287C1841 | M | | | | | 1325 | | | | | | | 1384 |
| 4229071938 | M | | | 1520 | | | 1553 | | | | | | 1602 |
| 42290A152B | M | 1441 | | | | | | | | | | | 1488 |
| 422E16125E | M | | | | | | 1141 | | | | | | 1258 |
| 4234502923 | M | | | | | 1280 | | | | | | | 1368 |
| 423A4A3920 | M | | | | 1360 | | | | | | | | 1433 |
| 423A56377F | M | | | | 1470 | | | | | | | | 1513 |
| 430E50446E | M | | | | | | 1164 | | | | | | 1262 |
| 4310470E71 | M | | | | | | 1332 | | | | | | 1360 |
| 43104B7923 | M | | | | | | 1271 | | | | | | 1334 |
| 4310535838 | M | | | | | | 1268 | | | | | | 1327 |
| 43105E6E24 | M | | | | | | 1313 | | | 1354 | | | 1370 |
| 43106C7723 | M | | | | | | 1313 | | | | | | 1361 |
| 4311217250 | M | | | | | | 1185 | | | | | | 1233 |
| 4311480E3D | M | | | | | 1215 | | | | | | | 1335 |
| 43152E2C4B | M | | | | | | 1413 | | | | | | 1412 |
| 43153D465C | M | | | | | | 1245 | | | 1280 | | | 1345 |
| 4315563107 | M | | | | | 1415 | | | | | | | 1467 |
| 4315571F78 | M | | | | | 1164 | | | | | | | 1236 |
| 435F554B26 | M | | | | | | 1323 | | | | | | 1353 |
| 435F70683D | M | | | | | | 1205 | | | | | | 1210 |
| 4446100700 | M | | | | | | | | 1246 | | | | 1293 |
| 421C234949 | F | | 1490 | | | | | | | | | | 1635 |
| 421C3C5C4A | F | | | 1580 | | | | | | | | | 1611 |
| 42261D3C1B | F | 1250 | | | | | | | | | | | 1357 |
| 4310394E2E | F | | | | | | 1323 | | | | | | 1406 |