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[Article]

Effect of Temperature on Growth, Condition, and Survival of Juvenile Shovelnose Sturgeon

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Abstract.—Water temperature plays a key role in determining the persistence of shovelnose sturgeon *Scaphirhynchus platorynchus* in the wild and is a primary factor affecting growth both in the hatchery and in natural waters. We exposed juvenile shovelnose sturgeon to temperatures from 8°C to 30°C for 87 d to determine the effect of temperature on growth, condition, feed efficiency, and survival. Growth occurred at temperatures from 12°C to 30°C; the optimal temperature predicted by regression analysis was 22.4°C, and the minimum temperature needed for growth was greater than 10.0°C. The maximum feed efficiency predicted by regression analysis was 24.5% at 21.7°C, and condition factor was highest in the 18°C treatment. Mortality was significantly higher at 28°C and 30°C than at lower temperatures but less than 10% across the thermal regimes tested and 0% at 14–18°C. Mortality was observed at and below 12°C, suggesting that extended periods of low temperature may deplete energy reserves and lead to higher mortality. Rearing juvenile shovelnose sturgeon at temperatures above 24°C reduced the growth rate and feed efficiency and increased mortality. Temperatures in the range 18–20°C appeared to maximize the combination of condition, growth, and feed efficiency while not increasing thermal stress. This study corroborates field studies suggesting that altered temperature regimes in the upper Missouri River reduce the growth of shovelnose sturgeon. This information may help protect the thermal habitat critical to the species and guide restoration efforts by delineating temperature regime standards for regulated rivers and those affected by hydroelectric facilities and suggesting new criteria for conservation propagation.

Shovelnose sturgeon *Scaphirhynchus platorynchus* remains one of the most widespread and abundant sturgeon species in North America, but its range and numbers were substantially reduced in the 20th century (Keenlyne 1997). Shovelnose sturgeon have decreased in number from overharvest and anthropogenic habitat alterations (Carlson et al. 1985; Hesse 1987; Quist et al. 2002). A significant amount of the historic Mississippi and Missouri rivers' riverine habitats once available to shovelnose sturgeon has been impounded, channelized, and regulated by dams (Keenlyne 1989; USFWS 2000). Reports from 1997 to 2005 have stated that the remaining upper Mississippi and lower Missouri rivers' shovelnose sturgeon populations were considered stable (Keenlyne 1997; Williamson 2003; Pikitch et al. 2005), but new information from Colombo et al. (2007) and Bajer and Wildhaber (2007) suggests that the populations in these areas may be declining, possibly because of overharvest. Shovelnose sturgeon populations are abundant in the upper Missouri River and its tributaries in Montana. While exploitation from fishing harvest is low in these areas, concerns over the effect of hypolimnetic discharge from reservoirs formed by Missouri River main-stem dams on the productivity of shovelnose sturgeon populations inhabiting these areas have become elevated in recent years (Everett et al. 2003; Braaten and Fuller 2004, 2005, 2006). Examples of dramatically altered river thermal profiles caused by hypolimnetic releases from main-stem dams can be found in the Missouri River downstream of Fort Peck and Garrison dams (Everett et al. 2003; Braaten and Fuller 2005, 2006).

Water temperature plays a key role in determining the persistence of fish (Fry 1971). Temperature influences resistance to diseases and parasites and affects spawning, embryo development, growth, and survival (Armour 1991). The effect of thermal regime

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changes, caused by land use practices (i.e., dams, channelization, and irrigation) and the specific thermal optima and tolerances for all life stages (i.e., embryo, larvae, juvenile, and adult) of shovelnose sturgeon have not been defined. The historic distribution of shovelnose sturgeon suggests that they have the ability to inhabit a broad range of thermal habitat (Keenlyne 1997). Anthropogenic alterations to the physical characteristics of the Missouri River (e.g., flow, water temperature, and turbidity) are being investigated to determine their effects on shovelnose sturgeon and other biota (Braaten and Fuller 2004, 2005, 2006). Our study was designed to investigate the effects of altered thermal conditions on shovelnose sturgeon growth and survival using standard laboratory experiments. The results can be used to develop thermal criteria that when used in combination with current field investigations will provide thermal protection standards for shovelnose sturgeon.

Sturgeon species possess life history characteristics that are adapted to the natural thermal regimes of the lakes and rivers they inhabit. North American sturgeon in the family Acipenseridae spawn in the spring within a range of 10–20°C, with 14–16°C considered optimal for embryo development in many sturgeon species (McCabe and Tracy 1994; Chapman and Carr 1995; NMFS 1998; Bruch and Binkowski 2002; Van Eenennaam et al. 2005). North American sturgeon species undergo relatively short incubation and prelarval phases during a period when water temperatures are generally increasing with the onset of summer. Cooler spring temperatures, generally optimal for embryo and prelarval development, are followed by a seasonal increase in temperature that typically promotes growth in larvae and juvenile sturgeon (Lutes et al. 1990; Mayfield and Cech 2004; Allen et al. 2006). Though less information is available for the North American sturgeon genus *Scaphirhynchus*, it appears that shovelnose sturgeon in the upper Missouri River do not differ extensively from other acipenserids with respect to their spawning cycles. *Scaphirhynchus* spawn in the spring and early summer, with warmer water conditions available for larvae and juvenile growth throughout late summer and early fall. Observations of spawning individuals and embryo and larval collections support that shovelnose sturgeon spawn within a range of 12–24°C (Moos 1978; Keenlyne 1997; Braaten and Fuller 2004). In the relatively natural thermograph present in the upper Missouri River (upstream of Fort Peck Dam) and Yellowstone River, larvae and juvenile shovelnose sturgeon are exposed to increasing temperatures from spring to summer, with cooling temperatures beginning in late fall (Everett et al. 2003; Braaten and Fuller 2004). The reported range of temperatures for the relatively natural thermograph in the upper Missouri River (upstream of Fort Peck Dam) and Yellowstone River are from a low near 0°C in January to a high of 28°C in July (Gardner and Stewart 1987; Everett et al. 2003; Braaten and Fuller 2007).

The thermal requirements for the growth and survival of many sturgeon species have been widely studied (Cech et al. 1984; Lutes et al. 1990; Hung et al. 1993; Power and McKinley 1997; Mayfield and Cech 2004). Information on the temperature range that promotes juvenile sturgeon growth and survival in laboratory experiments can be used to make inferences into ecological conditions affecting sturgeon in the wild and reveal the influence of thermal habitat changes (Armour 1991; McCullough et al. 2001; Mayfield and Cech 2004; Allen et al. 2006). Fish size and growth rate affect time to maturation, fecundity, feeding behavior, and recruitment (Houde 1987) and thus ultimately determine the populations' productivity and robustness. The thermal conditions that provide optimal growth and maximize survival of juvenile shovelnose sturgeon are of interest to managers and researchers working to protect this species, improve and maintain habitat, and manage sustainable fisheries.

Determining the optimal and threshold temperatures for the growth and survival of juvenile shovelnose sturgeon should also benefit hatchery managers using conservation propagation to reintroduce extirpated populations or supplement existing populations. Although culture of shovelnose sturgeon has been performed for many years, propagation methods, specifically the effects of different temperatures on feed efficiency (defined as weight gain [kg]/feed consumed [kg]), growth rate, and nutrient retention (percentage of dietary protein and lipid retained in the body), have not been defined. Consequently, the cost and physiological effectiveness of culture regimes (feed, water temperature, and captive conditions) may be less than optimal and thus limit fish growth and condition. Determining the optimal water temperature at which to rear juvenile shovelnose sturgeon will reduce thermal stress, increase growth, decrease incidence of disease and infection, and produce healthier fish for conservation propagation programs.

Laboratory methods have commonly been used to define the thermal requirements of fish species at different life stages (Brett 1956; Jobling 1981; Zale 1984; Kilgour and McCauley 1986; Armour 1991). We used a modification of the acclimated chronic exposure (ACE) method (Zale 1984; Selong et al. 2001) to define the thermal requirements for juvenile shovelnose sturgeon. The objective of this study was to examine the effects of water temperature on the survival, growth, condition, and feed efficiency of juvenile shovelnose sturgeon within the range of temperatures to which shovelnose sturgeon are currently exposed in the upper Missouri River basin and within propagation programs.

Methods

Fish collection, spawning, and rearing.—The study was conducted at the U.S. Fish and Wildlife Service (USFWS) Bozeman Fish Technology Center (BFTC) in Bozeman, Montana. Adult shovelnose sturgeon were collected from the upper Missouri River near Loma, Montana, and transported to BFTC in spring 2005. Shovelnose sturgeon were held at BFTC in 3-m-diameter circular tanks on flow-through water at 16 ± 1°C. Shovelnose sturgeon were sexed, staged, and spawned using methods described for sturgeon species (Webb et al. 1999; Van Eenennaam et al. 2001; Pallid Sturgeon Propagation Committee 2005). Embryos were incubated and hatched and larvae were reared at 16°C using methods described for pallid sturgeon *S. albus* (Pallid Sturgeon Propagation Committee 2005).

Experimental design.—We used the ACE method with modifications that included extending the exposure period to treatment temperature to approximately 90 d and gradually adjusting (decreasing and increasing) water temperatures from a midrange temperature (i.e., 18°C) within the thermal regime tested. The temperature modification maintained the effect of an environmentally realistic rate change of ±1°C per day that allowed fish to acclimate to changing conditions (Selong et al. 2001) but still provided a rapid approach to acquiring test temperatures. The extended exposure period allowed us to observe an increased effect of different water temperatures on growth and survival. A flow-through system designed to provide water at 12 different temperatures was used in the study (Selong et al. 2001). Water from cold- and warmwater springs was disinfected by ultraviolet light and heated by three 40,000-Btu water heaters to provide our 12 test temperatures (8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, and 30°C). Both cold and warm water were degassed in head columns before mixing in 12 head tanks. Warm spring water and heated water had pure oxygen added continuously to decrease nitrogen supersaturation and increase oxygen saturation. Water from each of the 12 head tanks was randomly assigned to each of three test tanks. Three replicates of each of the 12 treatment temperatures were maintained in 75-L, rectangular, aluminum test tanks measuring 120 × 35 × 25 cm. Tank covers were in place at all times except during maintenance and periodic observations. The maximum test temperature of 30°C was 2°C higher than the reported high temperature for the upper Missouri River (Gardner and Stewart 1987; Everett et al. 2003; Braaten and Fuller 2002, 2003, 2004, 2007) and the minimum temperature of 8°C was 4°C lower than the temperature reported by a hatchery manager where juvenile shovelnose sturgeon feeding stopped (M. Toner, personal observation). Flow-through water (pH 7.6–7.8; alkalinity, 140–180 mg/L; and hardness, 180–220 mg/L) from the 12 head tanks was supplied at approximately 3 L/min to each of the 36 tanks. Tank turnover rate was approximately 2.81 times per hour and was sufficient to maintain adequate dissolved oxygen levels and flush metabolites.

On 21 December 2005, 30 age-0 shovelnose sturgeon (140–170 d posthatch [dph]) from multiple male × female crosses were randomly selected from two 1.8-m (6-ft) tanks (water temperature, 18°C) and placed in each of the 36 tanks (also at 18°C). Fish length ranged from 65 to 258 mm fork length (FL), weight ranged from 0.90 to 67.0 g, and average weight was 22.9 g. All fish were held at 18°C for 5 d to ensure normal feeding continued and allow acclimation to the tanks. Mortalities during the 5-d tank acclimation period were replaced, but during the thermal acclimation period (temperature ramping) and thereafter, mortalities were removed and weighed, but not replaced. We initiated feeding at 5% of fish body weight per tank (32 g/tank) of #3 Silver Cup feed (Nelson & Sons, Murray, Utah). The cleaning and feeding schedule was generally 5 d per week. Fish were not fed on weekends or 2 d before periodic batch-weighing. Feed was dispensed from an automatic belt feeder placed near the head of each test tank. The thermal acclimation period was initiated on 26 December 2005. Treatment tanks were acclimated by adjusting the temperature ±1°C per day until treatment temperatures were obtained. We visually monitored uneaten feed and waste daily, and adjusted ration levels when necessary to ensure fish were fed to excess. During the ramping period, feed was adjusted incrementally (1% increments) from 5% to 10% of fish body weight per tank. We determined that 7–8% of fish body weight per tank was needed to ensure fish were fed to excess in all temperature treatments. Feed was calculated and adjusted for each tank 2 d after batch-weighing by using the most recent weight information to calculate feed adjustments. All tanks reached their treatment temperatures on 6 January 2006 (day 1), 12 d after temperature acclimation began. Fish were counted and batch-weighed on day 1. There were no statistical differences between the mean batch weight of treatments at the 12 temperature regimes ($P = 0.58$), and the range of means across the treatments was 0.603–0.735 kg. Fish were batch-weighed (0.01 g) four times during the experiment on days 1, 29, 56, and 87. Individual fish were also weighed and measured (FL; mm) on day 87. Fish were fed for a total of 53 d, 10 d at 7% and 43 d at 8% body weight per tank.

Water temperature was monitored multiple times daily by visual observation of digital thermometers and recorded at 24-min intervals with data loggers in each of the 12 head tanks. The average temperatures in the test tanks for the entire study duration calculated from data logger readings were within 0.3°C of the treatment temperatures. The average daily water temperature in the test tanks was within 1°C for all days in all tanks. The daily temperature fluctuation for all tanks from 8 to 22°C was less than 1°C for the entire test period except for a 92-min fluctuation that occurred on 10 January 2006, which resulted in a 4°C decrease in the most affected tank (22°C tank). The daily fluctuation in tanks from 24°C to 30°C was typically less than 1°C but exceeded 1°C briefly (for <4 h) on 5 d owing to source water fluctuations. We monitored percent saturation of dissolved oxygen, total dissolved gases, and nitrogen plus argon (N + Ar) using a Common Sensing Model TBO-DL6 meter (Common Sensing, Clark Fork, Idaho). The common sensing unit was placed in one of the 12 individual head boxes, on a 12-d rotation, with gas parameters in a single head tank logged every 10 min for 24 h. For all treatment tanks and throughout the duration of the experiment, the mean daily values for dissolved oxygen ranged from 99% to 108% saturation (minimum and maximum recorded values for dissolved oxygen were 96% and 111% saturation), mean daily values for total dissolved gases ranged from 100% to 104% saturation (minimum and maximum recorded values for total gas were 97% and 105% saturation), and mean daily values for N + Ar ranged from 99% to 104% saturation (minimum and maximum recorded values for N + Ar were 97% and 104% saturation). We provided the minimum and maximum values for all treatments and conditions throughout the duration of the experiment in an effort to acknowledge the potential of a short-term spike in any variable.

Proximate analysis.—The body composition (protein, lipid, moisture, and ash) was calculated by means of standard proximate analysis. Body composition was measured at the end of 87 d from three randomly selected fish from each tank. Fish were pooled by temperature treatment (three fish per tank) and frozen until analysis. The treatment sample was partially thawed and homogenized with an equivalent weight of distilled water. Protein content was determined by thermal oxidation (Leco TruSpec, Leco Corp., St. Joseph, Missouri) following the Association of Official Analytical Chemists method 992.15 (AOAC 1990). Lipid was measured using a petroleum ether extraction (Ankom XT 10; Ankom Technology, Macedan, New York). Tissue moisture was measured by freeze-drying a 2-g sample (Labconco Freezone 12; Labconco Corp., Kansas City, Missouri) until no mass change occurred, and ash content was determined by heating a 2-g subsample in a muffle furnace (Barnstead/Thermolyne 30400; Barnstead International, Dubuque, Iowa) at 555°C for 12 h.

Data analyses.—Batch weights for each tank were calculated at 1, 29, 56, and 87 d. Analysis of variance (ANOVA) with Bonferroni mean comparisons were used to compare weights among temperature treatments at 1, 29, 56, and 87 d, and total mortality (all fish that died throughout the course of the study) among temperature treatments at 87 d. Condition factor (K = body weight/fork length^3; Ricker 1975) was calculated for all surviving fish on day 87 and compared among treatments by ANOVA with Bonferroni mean comparisons. Growth rates were calculated as absolute daily mean body weight gains (AGR) and specific growth rate (SGR). Absolute growth rate was calculated according to the formula AGR = $(W_2 - W_1)/t$, where W_2 and W_1 are the final (e.g., 29, 56, or 87 d) and initial average weights of the fish per tank, respectively, and t is the number of days of the experiment (Ricker 1979).

Specific growth rate (percent body weight increase per day) was calculated for each treatment according to the formula SGR = $([\log_e W_2 - \log_e W_1]/t) \times 100$ (Ricker 1979). Feed efficiency for each treatment was calculated as grams of wet weight gain of fish at time per gram of feed fed (Ricker 1979), and treatments were compared by ANOVA. Regression analysis was used to determine the temperature for maximum weight gain, the minimum temperature needed to maintain weight, feed efficiency, and length–weight relationships at 8–30°C. The latter took the form weight = $a \times$ FL^b, where a and b are the coefficients of the regression model (Ricker 1979). Body constituents measured by proximate analysis were compared among treatments by ANOVA with Bonferroni mean comparisons. The accepted significance level for all statistical tests was $\alpha = 0.05$. Unless otherwise specified, all values are reported as means ± SEs.

Results

Growth

Fish growth varied significantly among temperature treatments at 29 ($P < 0.0001$), 56 ($P < 0.0001$), and 87 d ($P < 0.0001$). Increases in growth were observed at temperatures from 12°C to 30°C and the weight difference among treatments increased over time

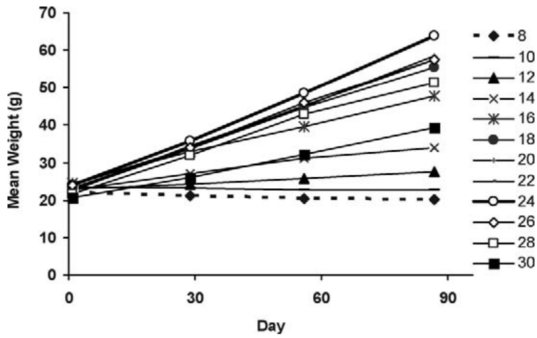

FIGURE 1.—Mean wet weights of juvenile shovelnose sturgeon reared for 29, 56, and 87 d at temperatures of 8°C to 30°C.

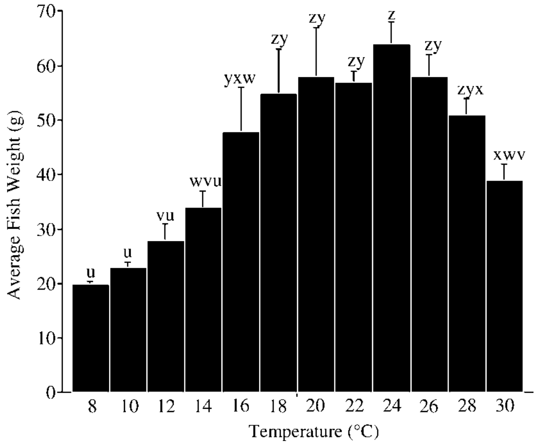

FIGURE 2.—Mean weights of shovelnose sturgeon exposed to temperatures ranging from 8°C to 30°C for 87 d. Different letters denote statistically significant differences among treatments.

except in the 8°C and 10°C treatments. Mean individual weight gain at 87 d ranged from −1.6 g at 8°C to +39.8 g at 24°C (Figure 1). Growth was roughly linear across the temperature regimes (Figure 1).

After 87 d of exposure to the thermal regimes, the mean individual fish weights (wet weight) at 8°C and 10°C were significantly lower than the mean individual fish weights in all temperature treatments except 12°C and 14°C (Figure 2). Within the treatments and at all dates, the highest mean individual weight was seen at 24°C, but the mean individual weight of treatments between 18°C and 28°C did not differ significantly at 87 d (Figure 2).

The predicted temperature for no growth under these conditions is 10.0°C, and the peak or maximum temperature for mean daily individual percent weight gain is 22.4°C (Figure 3). The percent daily individual weight gain ranged from −0.087% at 8°C to +1.09% at 24°C (Figure 3). Using the curvilinear weight gain function shown in that figure, a fish at 24°C would double its weight every 62 d, whereas a fish at 12°C would double its weight once in 315 d.

Feed efficiency was very low because fish were fed to excess (Figure 4). Mean feed efficiency was 15% or higher for temperatures of 16–30°C but decreased substantially at temperatures of 16°C or less (i.e., to values 40, 60, and 80% less than the maximum at 16, 14, and 12°C, respectively). The regression model for feed efficiency shown in Figure 4 predicted a maximum feed efficiency of 24.5% at 21.7°C and a minimum feed efficiency of 0% at 10.3°C.

Survival

Mortality differed significantly between treatment temperatures ($P = 0.004$; Figure 5). Mortality was significantly higher at 28°C and 30°C than at 14, 16, and 18°C, with no significant differences among treatments from 8°C to 12°C and from 20°C to 26°C. Mortality was highest at 28°C and 30°C, was first observed at 2 and 5 d, respectively, and continued until 75 and 69 d, respectively, in the 87-d study. No mortality occurred at 14, 16, and 18°C. Survival between 8°C and 22°C was greater than 95% and survival was at least 90% in all treatments.

Condition and Length–Weight Regression

The values of the condition factor at the end of the 87-d exposure differed significantly across the temperature regimes ($P < 0.0001$; Figure 6). The highest value occurred at 18°C, though the value at this temperature did not differ significantly from those at 12–16°C, 20°C, and 26°C. The length–weight relationships are given in Table 1.

Proximate Analysis

The effect of water temperature on body composition in shovelnose sturgeon juveniles exposed to temperatures from 8°C to 30°C (as reflected through proximate analysis) was significantly different for lipid ($P = 0.0001$) and moisture ($P = 0.0001$) but not for protein ($P = 0.5874$) and ash ($P = 0.0617$; Table 1). Lipid concentrations were highest in fish exposed to 16°C and 18°C, though these lipid levels only differed significantly from those in fish exposed to 8°C and 10°C. Body lipid levels were lowest at 8, 10, and 22°C. Owing to the outlying nature of the lipid level found at 22°C relative to more similar temperatures, we analyzed a second sample from this treatment and determined there was not a laboratory processing error. The percent lipid content for the two samples was 6.0

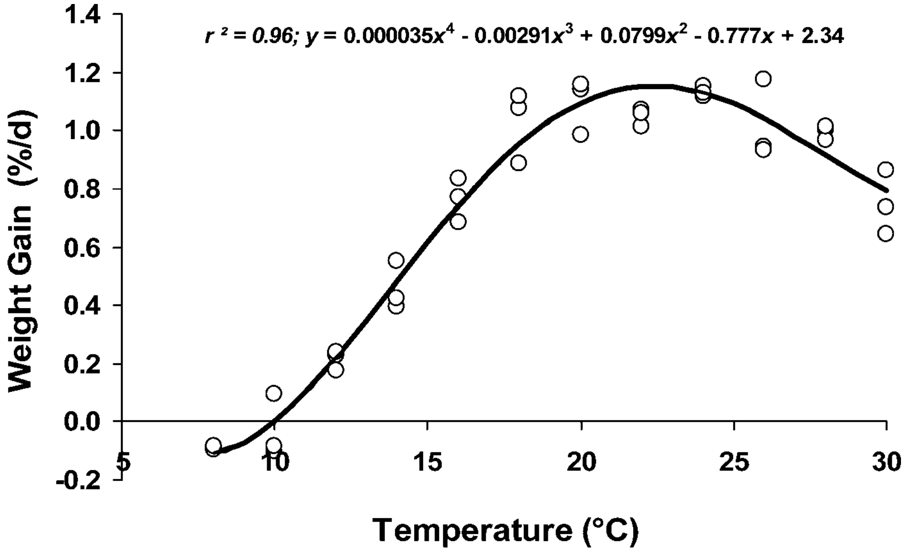

FIGURE 3.—Growth of shovelnose sturgeon in relation to temperature. Each circle represents the mean daily individual percent weight gain per temperature treatment (8–30°C; three tanks per temperature) over a period of 87 d. The maximum weight gain predicted by the regression line shown was 1.15% per day at 22.4°C; the predicted temperature for zero weight gain was 10.0°C.

± 0.3% and 6.6 ± 0.3%. The low concentration of lipids found in fish reared at 22°C cannot be explained at this time. Body moisture and lipid levels were inversely related in juvenile shovelnose sturgeon exposed to these temperatures, with the lowest moisture levels observed at 16°C and 18°C.

Discussion

Our results show that juvenile shovelnose sturgeon have a broad temperature range for growth and an extensive tolerance for prolonged exposure to thermal stress. The relatively similar condition we observed in juvenile shovelnose sturgeon reared from 12°C to 26°C

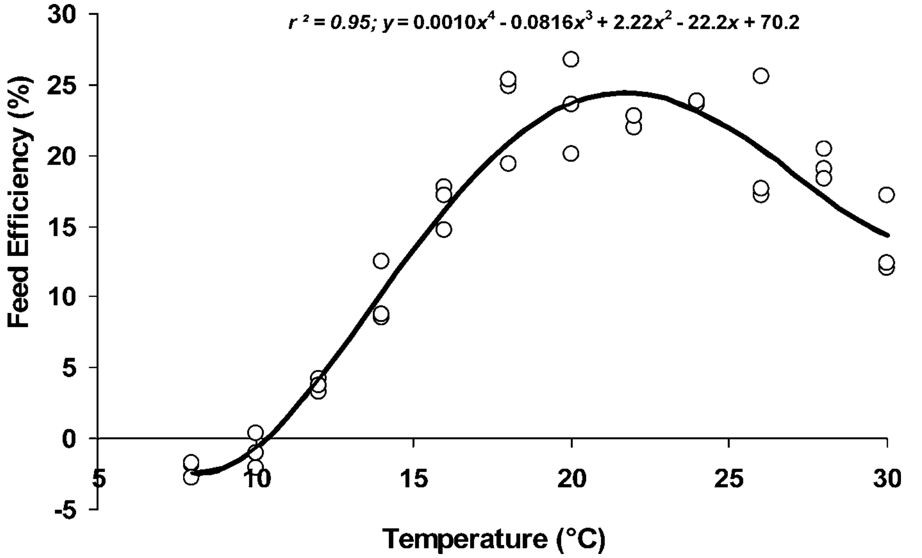

FIGURE 4.—Feed efficiency (increase in wet weight [g] divided by the amount of food needed to maintain satiation [g]) of shovelnose sturgeon in relation to temperature. Each circle represents the mean efficiency per temperature treatment (8–30°C; three tanks per temperature). The maximum feed efficiency predicted by the regression line shown was 24.5% at 21.7°C. The predicted temperature for zero feed efficiency was 10.3°C.

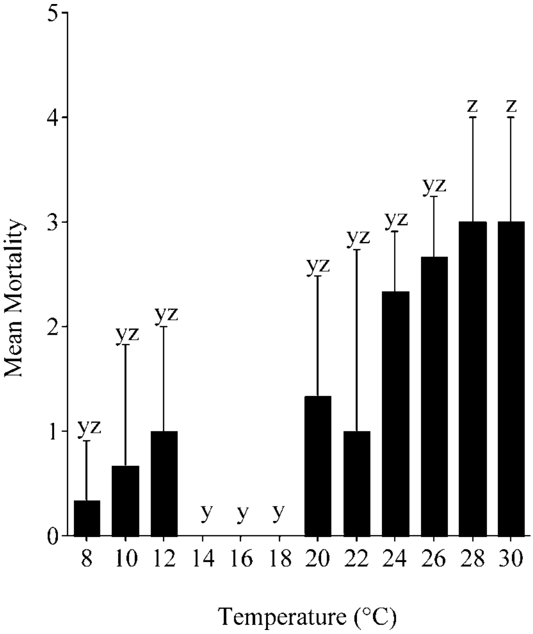

FIGURE 5.—Mean + SD mortality (%) of shovelnose sturgeon exposed to temperatures ranging from 8°C to 30°C for 87 d. Different letters denote statistically significant differences among temperatures.

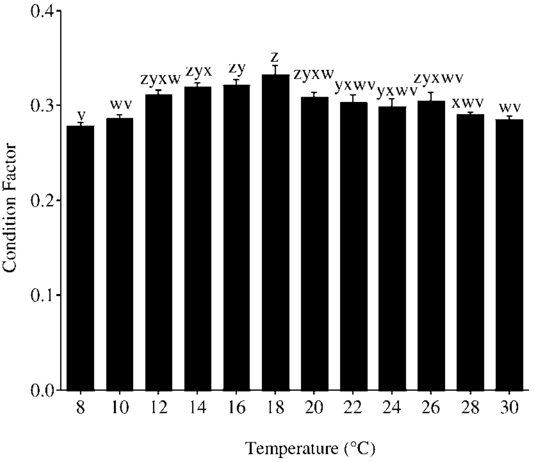

FIGURE 6.—Condition factors of shovelnose sturgeon exposed to temperatures ranging from 8°C to 30°C for 87 d. Different letters denote statistically significant differences among temperatures.

illustrates the species' robustness to a range of thermal habitat. In our experiment with juvenile shovelnose sturgeon, a temperature of 16°C or greater resulted in a substantially higher mean weight gain than a temperature of 14°C or lower with the highest predicted growth at 22.4°C. This indicates that shovelnose sturgeon in the wild may experience significant growth with extended periods of exposure to warm water (i.e., 16–24°C) and adequate food resources. If shovelnose sturgeon in the wild were to respond to temperature in a manner similar to the fish in our experiment, fish experiencing water temperatures from 12°C to 14°C for extended periods would exhibit reduced growth rates and those experiencing temperatures below 12°C for extended periods would lose weight and exhaust their energy reserves regardless of the amount of food present. Temperatures above 16°C did not influence survival at statistically significant levels up to 26°C, suggesting that warm temperatures are generally beneficial and that increased growth may provide shovelnose sturgeon a survival advantage (e.g., allowing them to avoid predation or reach sexual maturity earlier) that has been observed in other fish species (Houde 1987). Conversely, it is important to note that though there was no statistical difference among mortality at temperatures from 8°C to 26°C, there may be a biologically relevant effect of increased mortality, in that small incremental increases in annual mortality may have a significant effect on population abundance overtime.

Similar observations of increased growth at warmer temperatures and feeding ad libitum have been made for other sturgeon species. Lake sturgeon *Acipenser fulvescens* experienced higher growth at temperatures ranging from 7°C to 23°C (the % body weight gain/d ranged from 0.71 at 10°C to 1.52 at 23°C; Wehrly 1995). White sturgeon *A. transmontanus* experienced higher growth at temperatures ranging from 15°C to 20–25°C (the % body weight gains/d were 1.6, 2.6, and 2.9, respectively; Cech et al. 1984). Similarly, green sturgeon *A. medirostris* experienced higher growth at temperatures ranging from 11°C to 15–19°C (the % body weight gains/d were 1.3, 1.8, and 2.1, respectively; Mayfield and Cech 2004). In these investigations and an additional investigation by Allen et al. (2006), the authors determined that the laboratory conditions that produced maximum growth corresponded closely to the natural thermal regime present in the native rearing habitat or prealtered rearing habitat of the species and life stage studied. Juvenile lake sturgeon (~16.3 g) grew faster at 23°C, which is near the high temperature range found in inland lakes in the summer (Wehrly 1995). Juvenile green sturgeon (15 dph, ~0.1–10 g) grew faster at 24°C, near the temperature historically found in the spawning rivers (before dam construction) during that age and size (Allen et al. 2006), and age-0 green sturgeon (144 dph; ~150 g) grew faster at temperatures of 15°C and 19°C (Mayfield and Cech 2004). Juvenile white sturgeon

TABLE 1.—Weight gain, specific growth rate, weight–length regression parameters, and results of proximate analysis for shovelnose sturgeon during 87-d temperature trials at 8–30°C based on three replicates per temperature treatment. The weight–length relationships are of the form $W = a \cdot FL^b$, where W is weight in grams and FL is fork length in millimeters. The proximate analysis data are means ± SDs; within columns values with the same letter are statistically equivalent ($P \leq 0.05$).

Temperature (°C)	Mean weight (g)	Specific growth rate[a]	Weight–length equation a	b	r^2	Protein (%)	Lipid (%)	Moisture (%)	Ash (%)
8	20.3	−0.09	1.635×10^{-6}	3.102	0.962	13.3 ± 1.5	4.8 ± 1.4 x	77.7 ± 1.4 zy	3.2 ± 1.0
10	22.8	−0.03	1.545×10^{-6}	3.116	0.959	12.7 ± 0.4	5.1 ± 1.1 x	77.8 ± 0.9 z	2.6 ± 0.2
12	27.5	0.21	2.407×10^{-6}	3.046	0.949	13.1 ± 0.2	7.0 ± 2.5 wzyx	76.1 ± 2.9 zyxw	2.7 ± 0.2
14	33.9	0.44	1.188×10^{-6}	3.184	0.949	14.0 ± 0.4	8.9 ± 1.2 zy	73.8 ± 0.6 yxw	2.3 ± 0.1
16	47.7	0.74	5.464×10^{-7}	3.327	0.969	13.2 ± 0.4	10.8 ± 0.4 z	72.4 ± 0.7 w	2.5 ± 0.4
18	55.4	0.99	1.789×10^{-7}	3.526	0.978	13.5 ± 0.4	10.7 ± 1.5 z	72.7 ± 0.7 w	2.4 ± 0.3
20	58.4	1.06	3.570×10^{-7}	3.391	0.983	13.1 ± 1.0	9.9 ± 1.7 zy	74.0 ± 1.2 zyxw	2.2 ± 0.1
22	57.4	1.01	2.015×10^{-7}	3.486	0.982	12.6 ± 1.2	6.6 ± 0.3 yx	77.2 ± 0.5 zyx	2.0 ± 0.4
24	63.8	1.09	2.121×10^{-7}	3.469	0.979	13.9 ± 0.5	9.1 ± 0.2 zy	73.7 ± 0.6 xw	1.9 ± 0.6
26	57.6	0.98	1.093×10^{-6}	3.180	0.977	13.2 ± 0.9	8.1 ± 0.9 zyx	75.2 ± 1.6 zyxw	2.3 ± 0.2
28	51.3	0.96	9.487×10^{-7}	3.203	0.984	13.2 ± 0.6	8.6 ± 0.4 zyx	74.5 ± 1.2 zyxw	2.5 ± 0.3
30	39.4	0.71	4.610×10^{-7}	3.334	0.963	13.0 ± 0.6	7.7 ± 0.4 zyx	75.1 ± 0.4 zyxw	2.9 ± 0.3

[a] Percent increase in weight per day.

(~0.5 g) grew fastest at temperatures of at least 20°C, near the temperature found in native estuarine nursery habitat during the "growing season" (Cech et al. 1984). We conclude that there is a significant potential that anthropogenic alterations that decrease a rivers' natural thermal regime below the temperature indicated in our studies can result in a decrease in growth, an increase in mortality, and a decrease in production of shovelnose sturgeon.

In a comparison between populations of Yellowstone River and Missouri River shovelnose sturgeon, Everett et al. (2003) found that the growth of shovelnose sturgeon was greater in the relatively natural thermal regime of the Yellowstone River than in an altered Missouri River section with a significantly lower temperature regime. The authors hypothesized that thermal influence was the mechanism driving the growth differences between these populations. Unable to separate the altered temperature regime's influence on growth from other abiotic and biotic factors present in the river, Everett et al. (2003) suggested that further information was needed to clarify specific effects of habitat alteration on shovelnose sturgeon growth. Our laboratory study was not influenced by biotic and abiotic factors such as prey availability, competition for food, and river hydrology and supports the main hypotheses described by Everett et al. (2003). An evaluation of historic temperature data (Everett et al. 2003) showed that temperature was above the critical temperature (10.0°C) we identified for growth for approximately 1 month longer in the Yellowstone River than in the Missouri River section. Furthermore, temperatures in the section of the Missouri River studied by Everett et al. (2003) did not exceed 15°C on average at anytime during the year. Conversely, the temperature in the Yellowstone River exceeded 15°C (range, 15–23°C) for approximately 4 months (mean monthly water temperature from 1971 to 1996), a range we found to promote growth.

Further analysis shows that the fundamental thermal niche, described by Christie and Regier (1988) as −3°C and +1°C of the optimal growth temperature, does not exist for shovelnose sturgeon (optimal temperature, 22.4°C; niche range, 19.4–23.4°C) in this section of the Missouri River. Braaten and Fuller (2004, 2005, 2006) provided additional annual, monthly, and daily temperature information on relatively thermally homogenous sections of the Missouri River that have been affected by hypolimnetic water released from dams. We conclude from our findings that hypolimnetic releases that reduced the temperature in the Missouri River may be a leading cause of reduced growth in shovelnose sturgeon in the thermally altered section of the Missouri River studied by Everett et al. (2003), and may be having similar effects in other areas.

Natural resource managers in the Missouri River system need information on the effects of altered temperatures on native fish species. The information we present on shovelnose sturgeon, a species with a relatively broad thermal range, should inform the efforts of Missouri River managers who are working to manage this species and recover other native species that may be more sensitive to environmental perturbations. The knowledge derived from this study demonstrates the need for upper Missouri River water quality management plans that reduce the influence of hypolimnetic releases from main-stem dams and mimic a natural thermal regime similar to that found in the relatively natural area upstream from Fort Peck Dam. We recommend that researchers and river managers work together to refine the effects of thermal alterations on native species and develop Missouri River management plans that incorporate diel, seasonal, and naturally occurring rates of the thermal transitions necessary for shovelnose sturgeon and other native species at all life stages.

This study provides shovelnose sturgeon conservation propagation programs with needed thermal guidelines for rearing juvenile shovelnose sturgeon to improve their growth, survival, and condition. Based on our study results, we recommend hatchery managers rearing shovelnose sturgeon maintain water temperatures between 16°C and 20°C to provide optimal growth, condition, and survival of shovelnose sturgeon, noting that a low level of hatchery mortality may occur at 20°C. Managers with the ability to control temperature should perform cost-benefit analyses to determine the suitability of raising or lowering temperatures to increase growth and promote survival. We recommend that hatchery managers maintain a minimal temperature of 14°C throughout the year. Our study demonstrated that food intake and growth decreased at temperatures below 14°C. Growth is an obvious indicator of thermal stress. The reduction of feed intake may also reduce immune function (Lim and Webster 2001). Thermal stress may lead to reduced immunological function and increased incidence of disease (Lim and Webster 2001). Hatchery managers unable to maintain temperatures above 14°C (e.g., generally during the winter months) may be subjecting shovelnose sturgeon to additional stress that could make those fish more susceptible to bacterial or viral outbreaks.

Proximate analysis describes body composition, and an increase in one component results in the reduction in one or more of the other components. Fasted fish show low lipid content and high moisture (Burrows 1969). Our experiment demonstrates this effect (Table 1). The higher lipid content we observed in fish reared from 16°C to 20°C (Table 1) further supports that this temperature range is optimal for rearing shovelnose sturgeon. Our finding that high lipid levels and less moisture are associated with good growth among shovelnose sturgeon is consistent with the findings of white sturgeon studies that focused on effects of optimum feeding rations and diet composition (Hung et al. 1987, 1993; Hung and Lutes 1987; Stuart and Hung 1989). The similarities in the relationships between increased growth and high lipid content and optimum temperatures (in our study) and optimum rations and feed composition (in the white sturgeon studies) emphasize the influence of temperature as a factor in body composition and growth. As in the white sturgeon studies referenced, protein and ash content in shovelnose sturgeon were not affected by the range of temperatures we studied. Hung et al. (1993) states that protein level is affected only if growth is severely depressed, suggesting that even at our lowest temperatures growth was not suppressed for a long enough period to demonstrate a significant decrease in protein or ash content.

Feed efficiency for the shovelnose sturgeon in our study did not approach the rates reported by Hung et al. (1989) for juvenile white sturgeon (~30 g), which ranged from 86% to 102%. Though both shovelnose and white sturgeon were fed a manufactured diet, the differences between feeding rates within the studies make feed efficiency comparisons difficult. Hung et al. (1993) demonstrated that feed efficiency decreased linearly as feed rate was increased from a range of 2–3.5% body weight per day for white sturgeon at 23°C. Thus, it is not surprising that at the 7–8% body weight per day feeding rate that we used for shovelnose sturgeon, we observed dramatically lower feed efficiency at all temperatures. More important to our study than the comparatively low feed efficiency we observed, is that similar to white sturgeon (Hung et al. 1993) shovelnose sturgeon had higher feed efficiency at 22–23°C than at lower or higher temperatures (20°C and 26°C were tested in both studies). The thermal information we provide can be used in future studies of the optimal ration with respect to growth, condition, and survival. Incorporating the recommendations suggested by this study and future ones will promote the conservation of shovelnose sturgeon.

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