Thermal maxima for juvenile shortnose sturgeon acclimated to different temperatures

Jeffrey R. Ziegeweid · Cecil A. Jennings · Douglas L. Peterson

Abstract Many populations of shortnose sturgeon, *Acipenser brevirostrum*, in the southeastern United States continue to suffer from poor juvenile recruitment. High summer water temperatures, which may be exacerbated by anthropogenic activities, are thought to affect recruitment by limiting available summer habitat. However, information regarding temperature thresholds of shortnose sturgeon is limited. In this study, the thermal maximum method and a heating rate of 0.1°C min^{-1} was used to determine critical and lethal thermal maxima for young-of-the-year (YOY) shortnose sturgeon acclimated to temperatures of 19.5 and 24.1°C. Fish used in the experiment were 0.6 to 35.0 g in weight and 64 to 140 days post hatch (dph) in age. Critical thermal maxima were 33.7°C (±0.3) and 35.1°C (±0.2) for fish acclimated to 19.5 and 24.1°C, respectively. Critical thermal maxima significantly increased with an increase in acclimation temperature ($p<0.0001$).

Lethal thermal maxima were 34.8°C (±0.1) and 36.1°C (±0.1) for fish acclimated to 19.5 and 24.1°C, respectively. Lethal thermal maxima were significantly affected by acclimation temperature, the log_{10} (fish weight), and the interaction between log_{10}(fish weight) and acclimation temperature ($p<0.0001$). Thermal maxima were used to estimate upper limits of safe temperature, thermal preferences, and optimal growth temperatures of YOY shortnose sturgeon. Upper limits of safe temperature were similar to previous temperature tolerance information and indicate that summer temperatures in southeastern rivers may be lethal to YOY shortnose sturgeon if suitable thermal refuge cannot be found.

Keywords Survival · Mortality · *Acipenser brevirostrum* · Ontogenetic · Weight · Hematocrit

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Introduction

Many populations of shortnose sturgeon, *Acipenser brevirostrum*, are severely depleted throughout the sturgeon's native range, from the Saint John River in New Brunswick, Canada to the St. Johns River, Florida (Vladykov and Greeley 1963). Commercial fishing in the late nineteenth century decimated many populations of shortnose sturgeon (Dadswell et al. 1984) and led to the species' protection under the

Endangered Species Act (Kynard 1997). However, the complex life history of shortnose sturgeon makes managing the species difficult; as a result, many populations remain severely depleted. Degradations of habitat and water quality are believed to contribute to reduced juvenile recruitment (Smith and Collins 1996; Collins et al. 2000); however, a lack of field studies has resulted in a poor understanding of habitat requirements for young-of-the-year (YOY) shortnose sturgeon (Kynard 1997).

Hydrologic alterations, such as the construction of dams, dredging, and water removal for waste treatment, agriculture, and drinking water all reduce river discharges and alter thermal regimes of rivers (Baxter 1977; Lydeard and Mayden 1995; Poff et al. 1997; Bunn and Arthington 2002; Pringle 2003). Thermal effluents, such as those released by power plants, cause further increases in water temperatures (Baxter 1977; Pringle 2003). River discharges may decline in summer periods of increased temperatures and reduced precipitation. As a result, summer water temperatures in coastal rivers of the southeastern United States may exceed 31°C for up to 2 months (July and August) during low-discharge years (Dyar and Alhadeff 1997; DeVries 2006). Such high water temperatures may be extremely stressful and potentially lethal to YOY shortnose sturgeon, which would be ≤200 days old and ≤200 mm TL at the time of exposure to these high temperatures (Ziegeweid 2006).

Studies that examine the effects of temperature on sturgeon populations are limited. High temperature and hypoxia have been shown to reduce growth rates, increase mortality, and reduce swimming activities of white sturgeon, *Acipenser transmontanus* (Cech et al. 1984; Crocker and Cech 1997). Respiration and survival rates decreased for juvenile Atlantic sturgeon, *Acipenser oxyrinchus*, exposed to hypoxia and high temperatures (Secor and Gunderson 1998). The effects of temperature on green sturgeon, *Acipenser medirostris*, growth and bioenergetics have also been examined (Mayfield and Cech 2004; Allen et al. 2006). Mayfield and Cech (2004) also used thermal preference data to estimate lethal temperatures for green sturgeon. Studies of shortnose sturgeon have examined effects of temperature on spawning activity, egg development, and seasonal movements (Hall et al. 1991; Collins and Smith 1993; Kynard 1997; Collins et al. 2002; Hardy and Litvak 2004; DeVries 2006).

Despite the threats that summer water temperatures may pose to southern populations of shortnose sturgeon, few studies have examined temperature thresholds for shortnose sturgeon. Ziegeweid (2006) conducted laboratory experiments to determine LC_{50} temperatures for YOY shortnose sturgeon that ranged from 68 to 128 mm total length (TL) and were acclimated to a temperature of 19°C. Temperature LC_{50} values ranged from 28.2°C (±1.8°C) to 30.7°C (±0.8°C) (Ziegeweid 2006). Because acclimation temperature has been shown to affect thermal tolerance (Brett 1952; Becker and Genoway 1979; Jobling 1981; Kilgour and McCauley 1986; Young and Cech 1996), the results of Ziegeweid (2006) need to be re-evaluated with fish acclimated to a range of temperatures.

In this study, thermal maximum experiments were conducted with artificially propagated fish to examine how temperature tolerances of YOY shortnose sturgeon change with changes in acclimation temperature (Becker and Genoway 1979; Young and Cech 1996). Furthermore, thermal maximum data were used to estimate upper limits of safe temperature (Bridges 1971; Young and Cech 1996), final thermal preferences, and optimum growth temperatures for YOY shortnose sturgeon (Jobling 1981; Young and Cech 1996). Upon completion of experiments, total length, weight, and hematocrit levels of the fish at each acclimation temperature were measured to evaluate physiological condition of the fish in each treatment.

Materials and methods

Fish culture

Hatchery-produced young-of-the-year (YOY) shortnose sturgeon of the 2006 year class were raised at the Warm Springs National Fish Hatchery in Warm Springs, Georgia. Fish were raised in two 120-l cylindrical, flow-through tanks. The tanks were supplied with un-chlorinated spring water via polyvinyl chloride (PVC) pipes elevated about 15 cm above the tank. From this height, the falling water sufficiently mixed and oxygenated the water inside the tank. Suitable hardness, alkalinity, and pH were maintained in the source water with a chemical injection system (Hickson et al. 2001). Fish were fed a 3.0% body weight day^{-1} ration of Rangen® Soft-Moist commercial pellet feed (44%

protein, 18% fat, <5% fiber, <8% ash, ~23% moisture). Tanks were siphoned at least once daily to remove accumulated waste and scrubbed at least once per week to remove algal growth on tank surfaces. A 14 h light:10 h dark photoperiod was maintained throughout the study.

Water in the two holding tanks was kept at two different experimental temperatures. Water in the first tank was maintained at 19.5°C, with an approximate flow rate of 85 ml s^{-1}. The second tank was equipped with a 250-W Won® titanium aquarium heater and kept at a flow rate of 10 ml s^{-1} to maintain an average temperature of 24.1°C. This tank was further equipped with an airstone (connected to a central blower system) to help maintain suitable oxygen levels (Jenkins et al. 1993; Campbell and Goodman 2004) at lower flow and a higher temperature. The difference in flow rates was necessary to maintain the acclimation temperatures in the two treatments. However, because water was released straight down into the tanks, the incoming water did not create a current for the fish to swim against and thus should not have affected the results of the experiments. Dissolved oxygen and temperature were checked daily with a YSI-85® multi-parameter meter; other water quality variables such as hardness, alkalinity, and pH were checked weekly with colorimetric test kits (Aquarium Pharmaceuticals, Inc.).

Experimental setup

Thermal maximum experiments were conducted in two 38-l glass aquaria. Each aquarium was wrapped in a layer of clear plastic and a layer of 1.3-cm Styrofoam to minimize heat loss during experimental trials. Each aquarium was equipped with a 250-W Won® titanium aquarium heater, and water in each aquarium was circulated and oxygenated with an AquaClear Mini® biofiltration unit. Aquaria were elevated on 10-cm cinder blocks placed inside a 550-l cylindrical flow-through tank, which was used as a water bath to maintain desired water temperatures. The building housing the tanks was not temperature-controlled; therefore, the water bath was necessary to prevent the experimental aquaria from equilibrating with the ambient air. One of the 38-l aquaria was maintained at a temperature of 19.9°C, the approximate tempera-ture of the source water. The other aquarium was maintained at 24.7°C with the aquarium heater. Both

aquarium tanks were within 0.6°C of the acclimation holding tanks.

Experimental protocol

Juvenile shortnose sturgeon were held at their acclimation temperature for at least 7 days and starved for 24 h prior to use in thermal maximum experi-ments. In preparation for each trial, one fish from each holding tank was randomly selected and placed in the corresponding experimental aquarium. Fish were given 15 h to acclimate to the new tank conditions and recover from handling stress.

At the start of each trial, the water bath was drained, and both heaters were turned on. Water in the tanks was heated at a consistent rate of 0.1°C min^{-1} (Becker and Genoway 1979; Young and Cech 1996). Temperatures in each tank were continuously moni-tored with one of two YSI® meters, models 85 and 58. There was a dedicated meter for each tank so that experiments could be conducted for each acclimation temperature simultaneously. Prior to beginning ther-mal maximum testing, the two meters were compared against each other and consistently read within 0.1°C of each other. The starting temperature of each tank was recorded, and temperatures were recorded every 10 min and at designated endpoints (loss of equilibrium and death).

Because shortnose sturgeons are demersal, both loss of equilibrium (LOE) and death were designated as endpoints. Fish were considered to have lost equilibrium when they were unable to right them-selves within 10 s of first losing equilibrium. Fish were declared dead when opercular movements ceased and the fish did not respond to tactile stimulus. In accordance with Becker and Genoway (1979), LOE endpoints are referred to as critical thermal maxima (CT_{max}), and death endpoints are lethal thermal maxima (LT_{max}).

Upon completion of each trial, mortalities were removed from the experimental tanks, total lengths and weights were recorded, and tank water quality measurements were recorded. Dissolved oxygen concentrations were measured with a YSI-85® multi-parameter meter, and hardness, alkalinity, pH, ammo-nia, nitrite, and nitrate levels were determined by using colorimetric test kits (Aquarium Pharmaceuticals, Inc.). Finally, the exchange rate of the biofiltration unit was estimated by using a 1.0-l beaker to collect

and measure the water leaving the unit for a period of 10 s.

Once the trials for fish at both acclimation treatments were completed, the equipment was turned off, the aquaria were cleaned with a mild disinfectant, rinsed, and refilled, and the equipment was reset in preparation for the next trial. Trials were repeated throughout the summer as the fish grew and developed. A total of 32 fish, ranging in age from 64 to 140 dph, were tested at each acclimation temperature. Weights ranged from 0.6 to 35.0 g, and total lengths ranged from 54 to 215 mm.

Blood analysis

At the conclusion of all thermal maximum experiments, remaining fish in the holding tanks were removed, anesthetized in 75 mg l^{-1} MS-222 (Hickson et al. 2001), and measured for total length (mm) and wet weight (g). Blood was collected in heparinized 75-μl microcapillary tubes through caudal puncture. The tubes were sealed and centrifuged at 11 500 rpm for 10 min in an International Equipment Company (IEC) microcapillary centrifuge, model MB®. Hematocrit values were determined with a microhematocrit reader.

Statistical analysis

The normality of the distributions and the equality of the variances for the LOE and mortality data were examined using Shapiro–Wilkes and F_{max} tests, respectively (Sokal and Rohlf 1981). Results indicated that the data were normally distributed and that variances were not significantly different between treatments ($\alpha=0.05$). In addition, sample sizes were relatively large ($n\geq29$). Therefore, parametric statistical tests were used to analyze the data. Lethal thermal maximum data were compared using ANCOVA, with acclimation temperature as the categorical predictor variable and the log$_{10}$ (fish weight) as the continuous predictor variable. Weight data were linearized with log transformations because the rapid weight gain of YOY sturgeon skewed the distribution of the data. Upper limits of safe temperature (ULST) were determined by subtracting a safety factor of 5°C from the lethal and critical thermal maxima data (Bridges 1971; Young and Cech 1996). Final thermal preferences (FTP) and thermal growth optima (TGO) were estimated from CT$_{max}$ data with regressions modified from Jobling (1981):

$$FTP = (CT_{max} - 16.43)(0.66^{-1}) \qquad (1)$$

$$TGO = (CT_{max} - 13.81)(0.76^{-1}) \qquad (2)$$

Critical thermal maxima, holding tank water quality, experimental water quality, and post-experiment length, weight, and hematocrit data were compared between the two acclimation groups with two-sample t-tests ($\alpha=0.05$).

Results

Water quality

Water quality variables were maintained at adequate levels in the holding tanks. Temperatures were significantly different between holding tanks ($p<0.0001$), with mean temperatures of 19.5°C (SE= 0.1, $n=91$) and 24.1°C (SE=0.1, $n=91$). Dissolved oxygen concentrations were significantly higher for the low acclimation temperatures ($p<0.0001$), but the concentrations were adequate for both the low (8.3 mg l^{-1}, SE=0.1, $n=79$) and high (7.4 mg l^{-1}, SE=0.1, $n=79$) acclimation temperature treatments (Jenkins et al. 1993; Campbell and Goodman 2004). Mean hardness, alkalinity, and pH values for the holding tanks were 102.9 ppm (SE=4.2, $n=60$), 64.7 ppm (SE=2.4, $n=52$), and 6.9 (SE=0.0, $n=60$), respectively.

For thermal maxima trials, water quality variables were similar between experimental tanks for each acclimation temperature (Table 1). Furthermore, water quality variables in experimental tanks were maintained at levels that would not cause additional stress to the experimental fish (Table 1) (Piper et al. 1989). Ammonia, nitrite, and nitrate were rarely detected; if detected, concentrations did not exceed 0.25, 0.25, and 5.0 ppm, respectively.

Fish condition

Total length ($p=0.6847$) and weight ($p=0.5703$) of experimental fish were not significantly different between acclimation temperature treatments. The mean total length and weight of fish used in thermal

Table 1 Water quality variables for experimental tanks used to conduct thermal maximum experiments with YOY shortnose sturgeon

| Variable | 19.5°C | | 24.1°C | | |
	Mean	SE	Mean	SE	*p*-value
Dissolved oxygen (mg l^{-1})	6.6	0.1	6.3	0.1	<0.0001
Hardness (ppm)	101.2	6.7	100.7	6.7	0.9530
Alkalinity (ppm)	62.7	2.8	63.8	2.9	0.7814
Ammonia (ppm)	0.0	0.1	0.0	0.1	1.0000
Nitrite (ppm)	0.0	0.1	0.0	0.1	1.0000
Nitrate (ppm)	0.0	0.0	0.2	0.2	0.3212
Exchange rate (ml s^{-1})	62.5	1.2	64.5	1.1	0.8916
pH	7.6	0.0	7.6	0.0	0.2895

Water quality variables were compared between acclimation temperatures using two-sample *t*-tests, and values were based on experiments conducted with 32 fish at each acclimation temperature.

maxima trials were 135 mm (SE=5, *n*=64) and 10.7 g (SE=1.2, *n*=64), respectively. Furthermore, total lengths (*p*=0.8809) and weights (*p*=0.8638) of remaining holding tank fish were not significantly different between acclimation temperatures, with averages of 182 mm (SE=2, *n*=46) and 21.1 g (SE= 0.8, *n*=46). Finally, hematocrit levels of remaining holding tank fish were not significantly different between acclimation temperatures (*p*=0.9896), which demonstrated that oxygen requirements and general physiological condition were not affected by acclimation temperature.

Thermal maxima

The mean CT_{max} for fish acclimated to 24.1°C was significantly (*p*<0.0001) higher (35.1°C, SE=0.2, *n*= 32) than the mean CT_{max} for the fish acclimated to 19.5°C (33.7°C, SE=0.3, *n*=29) (Table 2). For LT_{max} data, the effects of acclimation temperature and the $\log_{10}$(fish weight), as well as the interaction between acclimation temperature and $\log_{10}$(fish weight), were significant (R^2=0.87, *p*<0.0001), and the following

equations describe the relationships of the predictor variables:

$$\text{Low Temperature } (19.5°C) LT_{max} \quad (3)$$
$$= 35.19 + 0.30[\log_{10}(\text{fish weight})]$$

$$\text{High Temperature } (24.1°C) LT_{max} \quad (4)$$
$$= 35.82 + 0.49[\log_{10}(\text{fish weight})]$$

The distribution of LT_{max} data for fish at each acclimation temperature is shown in Fig. 1. Mean LT_{max} values were 36.1°C (SE=0.1, *n*=32) and 34.8°C (SE=0.1, *n*=32) for YOY shortnose sturgeon acclimated to temperatures of 24.1 and 19.5°C, respectively (Table 2). The sample size for the CT_{max} estimates is different for fish acclimated to 19.5°C because three of the fish in the low temperature trials died without first losing equilibrium. Estimated final thermal preferences and thermal growth optima were 26°C for the low acclimation temperature fish and 28°C for the high temperature fish (Table 2). Estimated upper limits of safe temperature ranged from 28.7°C to 31.1°C across critical and lethal thermal maximum data (Table 2).

Table 2 Lethal thermal maxima (LT_{max}), upper limits of safe temperature (ULST), critical thermal maxima (CT_{max}), final thermal preferences (FTP), and thermal growth optima (TGO) for YOY shortnose sturgeon

Temp (°C)	N_{LT}	LT_{max} (°C)	$ULST_{LT}$	N_{CT}	CT_{max} (°C)	$ULST_{CT}$	FTP	TGO
19.5	32	34.8 (0.1)	29.8	29	33.7 (0.3)	28.7	26.2	26.2
24.1	32	36.1 (0.1)	31.1	32	35.1 (0.2)	30.1	28.3	28.0

Fish were acclimated to two different temperatures, and ages ranged from 64 to 140 days post hatch (dph). The LT_{max} and CT_{max} were significantly higher at the higher acclimation temperature (*p*<0.0001). Standard errors are listed in parentheses.
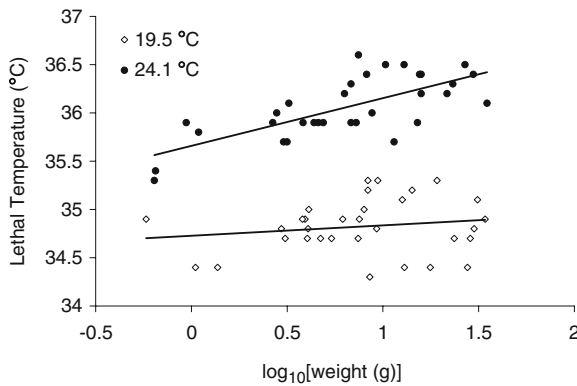
Fig. 1 Lethal thermal maxima distribution for YOY shortnose sturgeon raised at two different acclimation temperatures

Discussion

Thermal tolerances of YOY shortnose sturgeon were significantly affected by acclimation temperature and body weight. A 4.6°C increase in acclimation temperature resulted in a 1.4°C increase in mean CT_{max}. A 4.6°C increase in acclimation temperature also resulted in a 1.3°C increase in mean LT_{max}, which indicated that death occurred at a relatively constant interval following LOE. In addition to acclimation temperature, LT_{max} values also were significantly affected by $\log_{10}$(fish weight) and by the interaction of $\log_{10}$(fish weight) and acclimation temperature. The LT_{max} increased with increasing weight, although the magnitude of this increase was greater for fish acclimated to the higher temperature (24.1°C).

Visual observations suggest that fish exhibited similar behaviors with increasing temperature regardless of acclimation temperature. As temperatures increased, fish activity appeared to increase. About 5–6°C prior to the lethal endpoint, fish began frantically swimming around the tank, presumably looking for an escape route. As fish began to lose equilibrium, their activity level decreased dramatically, and at about 0.3°C before the lethal endpoint, most fish were completely incapacitated.

The results of this study were similar to results of LC_{50} experiments for fish acclimated to a temperature of 18.8°C (Ziegeweid 2006). In the three LC_{50} experiments (Ziegeweid 2006), the average lengths of the fish were 68 mm TL, 106 mm TL, and 128 mm TL. In the LC_{50} experiments, the highest temperatures at which mortalities did not occur increased with size

and were 26.5, 28.5, and 30.0°C, respectively. The lowest temperatures at which mortalities did occur were 30.1, 30.0, and 31.5°C, respectively. The averages of these described values create an interval of (28.3°C, 30.5°C) that can approximate an upper limit of safe temperature (ULST) for YOY shortnose sturgeon within the tested size range. Although the estimated interval is a function of the test temperatures, the narrow spacing of the test temperatures (1.5–3.5°C) and the abrupt change in mortality between test temperatures facilitate comparison to the ULST data from this study. Upper limits of safe temperature based on LOE data in this study were 28.7 and 30.1°C for fish acclimated to 19.5 and 24.1°C, respectively. Upper limits of safe temperature based on mortality data in this study were 29.8 and 31.1°C for fish acclimated to 19.5 and 24.1°C, respectively. Upper limits of safe temperature between the present study and Ziegeweid (2006) were very similar, despite differences in acclimation temperatures, measured endpoints, and methodologies.

The present study further illustrates the importance of acclimation temperature in evaluating thermal tolerance, which was not evaluated in the previous study of shortnose sturgeon thermal tolerance (Ziegeweid 2006). Thermal tolerance of YOY shortnose sturgeon increased with increasing acclimation temperature, which is similar to results of the euryhaline splittail, *Pogonichthys macrolepidotus* (Young and Cech 1996). However, the increase in thermal tolerance was not as pronounced in shortnose sturgeon. In this study, a 4.6°C increase in acclimation temperature only resulted in a 1.3°C increase in lethal temperature, whereas a comparable increase in splittail acclimation temperature (5°C) resulted in an 8°C increase in LOE temperature (Young and Cech 1996).

Although the thermal maximum method can be used to produce consistent, cost-effective results, the method has limitations. Final tolerances are influenced by acclimation temperature, thermal history, and heating rate (Becker and Genoway 1979; Jobling 1981; Kilgour and McCauley 1986), and the results of this study demonstrate that acclimation temperature significantly affects thermal tolerance. A heating rate that is too fast will result in thermal shock, whereas a heating rate that is too slow may result in partial acclimation of the fish, biasing the tolerance limit upward. The heating rate should be just fast enough to allow deep-body temperatures to parallel test temper-

atures without a significant time lag (Becker and Genoway 1979). The time lag for deep-body temperatures depends on the size of the test fish, but a heating rate of <1°C min^{-1} typically will not result in a significant time lag (Becker and Genoway 1979).

Concerns about heating rates in thermal maximum experiments can be addressed by conducting studies with a variety of heating rates. Studies of juvenile coho salmon, *Oncorhynchus kisutch* and pumpkinseed sunfish, *Lepomis gibbosus*, heated at a variety of rates ranging from 0.017 to 1.0°C min^{-1}, suggest an optimum heating rate of 0.3°C min^{-1} (Becker and Genoway 1979); however, a heating rate of 0.1°C min^{-1} did not significantly bias the thermal maxima upward (Becker and Genoway 1979). Because coho salmon and pumpkinseed sunfish differ substantially in life history and body shape, a heating rate ranging from 0.1 to 0.3°C min^{-1} should be adequate for most small fish. Therefore, we assumed that the heating rate of 0.1°C min^{-1} used in this study did not affect the thermal tolerances of YOY shortnose sturgeon.

Published equations were used to estimate final thermal preferences (FTP) and thermal growth optima (TGO) for YOY shortnose sturgeon (Jobling 1981; Young and Cech 1996). The FTP estimates were similar to TGO estimates of fish acclimated to the same temperature, with values of approximately 26 and 28°C for fish acclimated to 19.5 and 24.1°C, respectively. The FTP and TGO estimates were close to the estimated upper limits of safe temperatures of 28.7 and 30.1°C for fish acclimated to 19.5 and 24.1°C, respectively. Similar results were observed for YOY splittail (Young and Cech 1996). Warmer temperatures may increase YOY metabolism and conversion of prey into somatic growth, as long as the cost of maintenance metabolism does not significantly increase (Brown 1957).

Temperature optima of many fishes are highest during early life history stages and decrease with ontogeny (Brett and Groves 1979; Kitchell 1979; Lankford and Targett 1994). For example, CT$_{max}$, ULST, FTP, and TGO decreased with increasing age for splittails acclimated to 17°C (Young and Cech 1996). In addition, juvenile green sturgeon grew better at 24°C compared to 19°C (Allen et al. 2006), even though a previous study had estimated an upper temperature limit of 27°C and reported significant transport-related mortality for fish acclimated to 25°C (Mayfield and Cech 2004). Similar trends in thermal tolerance are possible for shortnose sturgeon, although thermal maximum experiments with older juveniles are needed to confirm this relationship.

The thermal tolerance results of this study have important implications for wild populations of shortnose sturgeon, especially in southern rivers where summer water temperatures may limit habitat availability. Summer water temperatures in Georgia's coastal rivers frequently exceed 31°C (Dyar and Alhadeff 1997; DeVries 2006), which would be potentially lethal according to the results presented in this study. Furthermore, at high temperatures, food availability may not be able to keep up with the metabolic needs of YOY shortnose sturgeon. Therefore, availability of thermal refugia in southeastern rivers may be critical in assessing shortnose sturgeon habitat in southeastern rivers. As such, identification of thermal refugia may be an important study component for management plans that seek to improve shortnose sturgeon recruitment.

Conclusion

The results of this study further demonstrate the importance of acclimation temperature in assessing thermal tolerances of fishes. Although the oxygen requirements and growth of YOY shortnose sturgeon were not affected by differences in acclimation temperature, thermal tolerances increased with increasing acclimation temperature. Estimated upper limits of safe temperature (ULST) ranged from 28.7 to 31.1°C and varied with acclimation temperature and measured endpoint. Final thermal preference and thermal growth optima were nearly identical for fish at each acclimation temperature and ranged from 26.2 to 28.3°C. Thermal maxima ranged from 33.7 to 36.1°C and varied with acclimation temperature and designated endpoint. The thermal tolerances identified in this study suggest a range of physiological limits on suitable habitats of YOY shortnose sturgeon in coastal rivers of the southeastern United States. This information should help to structure future investigations of YOY shortnose sturgeon that evaluate the hypotheses advanced in this discussion. Field collections of YOY shortnose sturgeons should be used to facilitate identification of critical habitats for YOY shortnose sturgeon in southeastern rivers. Furthermore, results of this study may be used to help

determine appropriate mitigation measures for future hydrologic modifications that alter thermal regimes of southeastern rivers.

References

Allen PJ, Nicholl M, Cole S, Vlazny A, Cech JJ Jr (2006) Growth of larval to juvenile green sturgeon in elevated temperature regimes. Trans Am Fish Soc 135:89–96

Baxter RM (1977) Environmental effects of dams and impoundments. Ann Rev Ecol Syst 8:255–283

Becker CD, Genoway RG (1979) Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. Env Biol Fish 4(3):245–256

Brett JR (1952) Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. J Fish Res Board Can 9:265–323

Brett JR, Groves TDD (1979) Physiological energetics. In: Hoar WS, Randall DJ, Brett JR (eds) Fish physiology, vol 3. Academic, New York, pp 599–677

Bridges DW (1971) The critical thermal maximum of juvenile spot, *Leiostomus xanthurus*, Lacepede. Water Resource Research Institute of the University of North Carolina, Publication 17, Chapel Hill, NC

Brown ME (1957) Experimental studies on growth. In: Brown ME (ed) The physiology of fishes, vol 1. Academic, New York, pp 361–398

Bunn SE, Arthington AH (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manage 30(4):492–507

Campbell JD, Goodman LR (2004) Acute sensitivity of juvenile shortnose sturgeon to low dissolved oxygen concentrations. Trans Am Fish Soc 133:772–776

Cech JJ Jr, Mitchell SJ, Wragg TE (1984) Comparative growth of juvenile white sturgeon and striped bass: effects of temperature and hypoxia. Estuaries 7(1):12–18

Collins MR, Smith TIJ (1993) Characteristics of the adult segment of the Savannah River population of shortnose sturgeon. Proc Ann Conf SEAFWA 47:485–491

Collins MR, Rogers SG, Smith TIJ, Moser ML (2000) Primary factors affecting sturgeon populations in the southeastern United States: fishing mortality and degradation of essential habitats. Bull Mar Sci 66(3):917–928

Collins MR, Post WC, Russ DC, Smith TIJ (2002) Habitat use and movements of juvenile shortnose sturgeon in the Savannah River, Georgia-South Carolina. Trans Am Fish Soc 131:975–979

Crocker CE, Cech JJ Jr (1997) Effects of environmental hypoxia on oxygen consumption rate and swimming activity in juvenile white sturgeon, *Acipenser transmontanus*, in relation to temperature and life intervals. Environ Biol Fish 50:383–389

Dadswell MJ, Taubert BD, Squiers TS, Marchette D, Buckley J (1984) Synopsis of biological data on shortnose sturgeon, *Acipenser brevirostrum* LeSueur 1918. FAO Fisheries Synopsis No 40

DeVries RJ (2006) Population dynamics, movements, and spawning habitat of the shortnose sturgeon, *Acipenser brevirostrum*, in the Altamaha River system, Georgia. Master's Thesis, University of Georgia

Dyar TR, Alhadeff SJ (1997) Stream-temperature characteristics in Georgia. USGS Water Resources Investigations Report 96-4203

Hall JW, Smith TIJ, Lamprecht SD (1991) Movements and habitats of shortnose sturgeon, *Acipenser brevirostrum* in the Savannah River. Copeia 3:695–702

Hardy RS, Litvak MK (2004) Effects of temperature on the early development, growth, and survival of shortnose sturgeon, *Acipenser brevirostrum*, and Atlantic sturgeon, *Acipenser oxyrinchus*, yolk-sac larvae. Environ Biol Fish 70:145–154

Hickson B, Ware K, Mohead M (2001) Feeding trial to determine the maintenance diet requirement, optimal feeding rate, and maximum feeding rate for juvenile shortnose sturgeon (*Acipenser brevirostrum*) at 17 and 20°C. Final Report. Florida Marine Research Institute, Florida Fish and Wildlife Commission

Jenkins WE, Smith TIJ, Heyward LD, Knott DM (1993) Tolerance of shortnose sturgeon, *Acipenser brevirostrum*, juveniles to different salinity and dissolved oxygen concentrations. Proc Ann Conf SEAFWA 47:476–484

Jobling M (1981) Temperature tolerance and the final preferendum – rapid methods for the assessment of optimum growth temperatures. J Fish Biol 19:439–455

Kilgour DM, McCauley RW (1986) Reconciling the two methods of measuring upper lethal temperatures in fishes. Env Biol Fish 17(4):281–290

Kitchell JF (1979) In search of an optimal environment. In: Clepper H (ed) Predator–prey systems in fisheries management. Sport Fishing Institute, Washington, DC, pp 31–33

Kynard B (1997) Life history, latitudinal patterns, and status of the shortnose sturgeon, *Acipenser brevirostrum*. Environ Biol Fish 48:319–334

Lankford E, Targett TE (1994) Suitability of estuarine nursery zones for juvenile weakfish (*Cynoscion regalis*): effects of temperature and salinity on feeding, growth, and survival. Estuarine Biol 119:611–620

Lydeard C, Mayden RL (1995) A diverse and endangered aquatic ecosystem of the southeast United States. Conserv Biol 9(4):800–805

Mayfield RB, Cech JJ Jr (2004) Temperature effects on green sturgeon bioenergetics. Trans Am Fish Soc 133:961–970

Piper RG, McElwain IB, Orme LE, McCraren JP, Folwer LG, Leonard JR (1989) Hatchery requirements. Fish hatchery management. US DOI, FWS, Washington, DC, pp 3–55

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: a paradigm for river conservation and restoration. BioScience 47(11):769–784

Pringle C (2003) What is hydrologic connectivity and why is it ecologically important? Hydrol Process 17:2685–2689

Secor DH, Gunderson TE (1998) Effects of hypoxia and temperature on survival, growth, and respiration of juvenile Atlantic sturgeon, *Acipenser oxyrinchus*. Fish Bull 96(3):603–613

Smith TIJ, Collins MR (1996) Shortnose sturgeon stocking success in the Savannah River. Proc Ann Conf SEAFWA 50:112–121

Sokal RR, Rohlf FJ (1981) Biometry, 2nd edn. Freeman, New York, 859pp

Vladykov VD, Greeley JR (1963) Order Acipenseroidei. In: Olsen VH (ed) Fishes of the Western North Atlantic, Part 3. Memoirs of the Sears Foundation of Marine Research. Yale University, New Haven, CT, pp 24–60

Young PS, Cech JJ Jr (1996) Environmental tolerances of splittail. Trans Am Fish Soc 125:664–678

Ziegeweid JR (2006) Ontogenetic changes in salinity and temperature tolerances of young-of-the-year shortnose sturgeon, *Acipenser brevirostrum*. Master's Thesis, University of Georgia