

ENVIRONMENTAL REQUIREMENTS, PREFERENCES, AND TOLERANCE LIMITS OF NORTH AMERICAN STURGEONS

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3.1 Introduction

Sturgeons are “living fossils” (Gardiner 1984) that have enormous value for studying vertebrate evolution, including physiological adaptations to the environment. Regrettably, human impacts have reduced their stocks to levels near extinction (Birstein et al. 1997). A more complete understanding of sturgeon environmental requirements and preferences will help protect their natural reproduction, properly manage the existing small fisheries, and develop sustainable aquaculture. The three genera (including paddlefish) of North American Acipenseriformes live in an amazing variety of habitats. Although all of them spawn in fresh water, the various species ($n = 8-9$), depending on where taxonomic lines are drawn) can be exposed to a wide range of light, environmental temperature, dissolved gas (oxygen and carbon dioxide), salinity, depth, and velocity conditions (Table 3-1). This chapter reviews these species’ environmental requirements, preferences, and tolerance limits.

3.2 North American Species

Eight species of Acipenseriformes inhabit rivers, lakes, estuaries, and coastal waters of the North America between the sub arctic and subtropics (Table 3-1). Four species are amphihaline (live in fresh and seawater), including anadromous Atlantic and green sturgeons and semi-anadromous shortnose and white sturgeons. The Atlantic and green sturgeons use freshwater habitat for spawning and for the first years of life (they do not have resident, freshwater populations); white and shortnose sturgeons reside mainly in the river estuaries and adjacent coastal areas, although the white sturgeon can migrate up to 1,000km along the Pacific coast (Kohlhorst et al. 1991). Four other North American species: lake, pallid, shovelnose sturgeons, and paddlefish, are inland freshwater fish, although lake sturgeon may occur in a tidal zone of the lower river

reaches. Sturgeons are long-lived and some species can reach very large sizes (Table 3-1).

Table 3- 1. Distributions and characteristics of North American sturgeon and paddlefish. Habitat: seawater (SW), brackish water (BW), freshwater (FW). Maximum age, length, and weight from Carey & Judge (2000, lake sturgeon), Cailliet et al. (2001, white sturgeon), and the FishBase (for other species)

Species	Habitat	Age (y)	Length (cm)	Weight (kg)	Status
<i>Atlantic Coast (from Hudson Bay to Mexican Gulf)</i>					
Atlantic & Gulf sturgeon <i>Acipenser oxyrinchus</i> & <i>A. o. desotoi</i>	SW, BW, FW	60	430	368	Fishery moratorium Gulf -threatened
Shortnose sturgeon <i>A. brevirostrum</i>	BW, FW	67	143	23	<i>Endangered</i>
<i>Pacific Coast (from Alaska to California)</i>					
White sturgeon <i>A. transmontanus</i>	SW, BW, FW	104	610	816	Harvested, One stock <i>endangered</i>
Green sturgeon <i>A. medirostris</i>	SW, BW, FW		213	159	Harvested
<i>Hudson-James Bay, St. Lawrence-Great Lakes, Mississippi-Missouri drainages</i>					
Lake sturgeon <i>A. fulvescens</i>	FW, BW	152	274	125	Harvested
Shovelnose <i>Scaphirhynchus platyrhynchus</i>	FW		100	5	Harvested
Pallid sturgeon <i>S. albus</i>	FW	41	168	45	<i>Endangered</i>
Paddlefish <i>Polyodon spathula</i>	FW	30	221	91	Harvested

Despite their high fecundity (up to 2 million eggs in Atlantic sturgeon), they have low, overall reproductive rates due to late sexual maturity, e.g. 10-25 years in females, and long breeding intervals (Boreman 1997). All the species spawn in rivers broadcasting their gametes on the river current, and they require specific water

velocities for egg dispersal, and a hard spawning substrate for the egg attachment. Unregulated commercial fisheries for caviar, and the dams that changed hydraulic regimes of sturgeon rivers rendered the rivers unsuitable for spawning fragmented sturgeon stocks and reduced their abundance to small fractions of historic levels (Waldman and Secor 1998).

3.2.1 LIGHT

Light intensity and day length (photoperiod) influence behaviour, growth, and reproduction of fish, yet light is the least studied environmental factor in sturgeon. Sturgeons generally prefer dimly lit, moderately turbid water. Cultured white sturgeon held outdoors in clean water seek shaded tank areas when exposed to sunlight, but swim undisturbed over the entire tank area during cloudy days or during early morning and late afternoon hours. Green sturgeon are more photophobic and exhibit a pronounced nocturnal behaviour, i.e. high swimming activity at night and sluggish, demersal behaviour during the day. Lankford et al. (2003) reported a more pronounced stress response (high plasma cortisol and lactate levels) in green sturgeon stressed at night, when compared with those stressed during the daytime. Studies on retinal photoreceptors of white sturgeon revealed one type of rods and three types of cones, with blue-sensitive, green-sensitive, and red-sensitive visual pigments (Loew and Sillman 1993). Shovelnose sturgeon and paddlefish retinas had a different type of long and tightly packed rods, which may have value for light intensity discrimination and orienting behaviour in dimly lit environments (Sillman et al. 1999).

Photoperiodicity appears to regulate sturgeon growth and reproduction, in a manner similar to that shown in salmonids. Juveniles of the Eurasian beluga (*Huso huso*) grew faster under a cyclic photoperiod (16L: 8D) compared to constant light (24L) condition (Trenkler and Semenkov 1995). White sturgeon, reared in outdoor tanks and raceways under year-round, constant temperature and feeding regime conditions, grew significantly faster during spring and summer compared to fall and winter (S. Doroshov, University of California, and R. Schneider, Clear Springs Food Co., Idaho, unpublished observations). All of the North American Acipenseriformes, studied so far, are long-day breeders, with a spawning season approximately between the spring equinox and summer solstice with the spawning run peak often coinciding with the maximal river flow. The majority of the Eurasian species also spawn during spring and summer (Dettlaff et al. 1993). However, there are ecotypes (stellate sturgeon in Kura and Sefid-Rud rivers, South Caspian Sea) and species (Chinese sturgeon in the Yangtze River) that have well-documented fall spawning during the September-November period, associated with river flooding (Berg 1948, Wei et al. 1997).

3.2.2 ENVIRONMENTAL TEMPERATURE

Environmental temperature controls metabolism, growth and reproduction in ectothermic fish (Brett 1979). Fishes have preferred and optimal temperature ranges (Neill et al. 1972, Neill and Magnuson 1974) which often coincide (Jobling 1981). While the distribution range of North American Acipenseriformes extends over a zone with the temperature variation up to 30°C, they generally prefer and perform optimally under cool (e.g., <25°C) temperature conditions. McKinley et al. (1998) studied lake sturgeon movements in the Mattagami River system (northern Ontario, Canada), using radio-telemetered fish. The lake sturgeon started an upstream migration in January

(water temperature: 3°C) to suspected spawning sites in May, when temperatures reached 8-10°C. They dispersed downstream as temperatures approached 13°C (McKinley et al. 1998). Gulf of Mexico sturgeon (subspecies of Atlantic sturgeon) adults and large juveniles swim upriver from the Gulf in the spring when the water temperature is 15–20°C (Chapman and Carr 1995, Sulak and Clugston 1998, Fox et al. 2000) and return to the Gulf in the fall when water temperatures range from 18 to 23°C. Adult white sturgeon migrate up the Sacramento River from San Francisco Bay during late fall and remain at low river temperatures (7-12°C) before spring spawning (optimal spawning temperature range: 14-16°C, Kohlhorst 1976). Adult female white sturgeon require exposure to cold (ca. 10°C) temperatures for oocyte development and ovulation to proceed normally (Webb et al. 1999, Linares-Casenave et al. 2002). Semi-anadromous shortnose sturgeon juveniles (<56 cm TL) moved down the Savannah River (Georgia - South Carolina, USA) when temperatures decreased to < 22°C, to Savannah Harbour and the mouths of the Front and Middle Rivers (Collins et al. 2002).

Activity and growth of young sturgeons generally increase with temperature increases until an optimal temperature is reached, usually below 25°C. Juvenile lake sturgeon tend to be more active at 19°C than at 6°C (Peake 1999) and juvenile white sturgeon were more active at 16°C than at 10 or 20°C, (near-air-saturated dissolved O₂ levels) (Table 3-2). Juvenile white sturgeon grew faster at 20-25°C than at 15°C under normoxic (Table 3-1) conditions (Cech et al. 1984), and juvenile Atlantic sturgeon reared for six months in a hatchery grew faster at 17°C, reaching up to 323mm TL, than when reared at 10°C, reaching a maximum of 156mm mean TL (Welsh et al. 2002). Finally, green sturgeon (mean wet weight: 150g) from the Klamath River grew faster at 15-19°C, compared with those at 11°C, when fed either full (repletion) or 50% of repletion rations (Mayfield and Cech 2004). Cultured white sturgeon reared in warm water of 18-22°C grew and matured much faster compared with their wild counterparts. Fully matured, cultured males and females reached 10 and 32kg live weights at ages 4 and 8 years, respectively (Doroshov et al. 1997).

Young life history stages may be the most temperature sensitive within sturgeon species. Laboratory studies show that Gulf of Mexico sturgeon eggs, embryos, and larvae have the highest survival rates in the 15 - 20°C range, and that survival decreased significantly at temperatures >25°C (Chapman and Carr 1995). The 14 - 17°C temperature range is optimal for the development and survival of white and lake sturgeons' embryos; hatching rates of both species decreased at 20°C and complete arrest of development occurred at 23°C in white sturgeon (Wang et al. 1985). Embryos of green sturgeon incubated over the 11-26°C range had high hatching rates at 11-19°C, low hatching rate at 20°C, high rates of abnormal embryos at 22°C, and did not hatch at 23°C (Van Eenennaam, Linares and Doroshov, unpublished observation). Another laboratory experiment showed that the development rate and dry matter losses during yolk resorption in larval white sturgeon increased directly with temperature within the 11-20°C range, and that larval survival decreased dramatically at temperatures >20°C (Wang et al. 1987). Larval paddlefish exhibited low survival to metamorphosis at 24°C and no survival at 28°C (Kroll et al. 1992). In general, the results of laboratory studies on early life stages are in good agreement with the field observations on spawning temperature ranges of several stocks (Kohlhorst 1976, McCabe and Tracy 1994, Bruch and Binkowski 2002, Perrin et al. 2003).

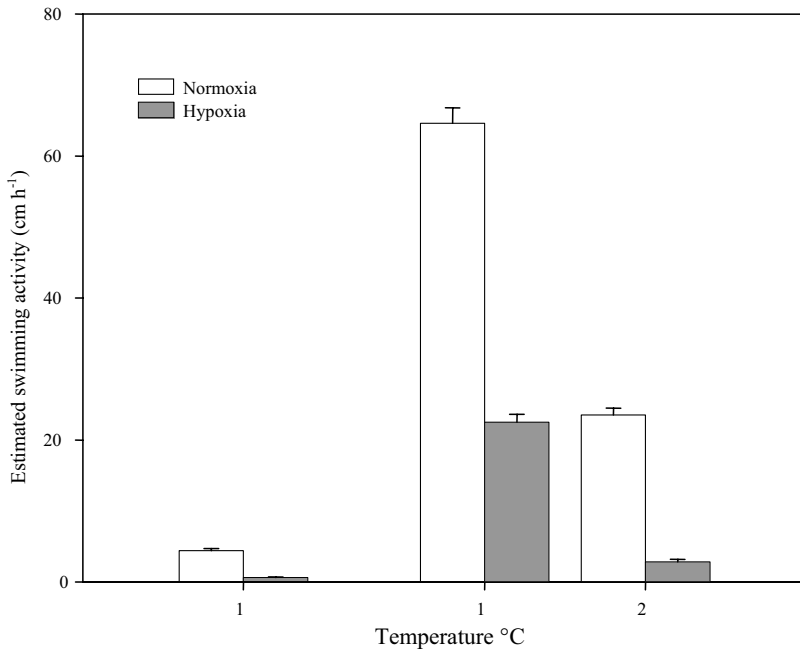


Fig. 3-1. White sturgeon estimated swimming activity at various temperatures, under normoxic and hypoxic conditions.

3.2.3 DISSOLVED OXYGEN (O₂)

Low dissolved O₂ conditions (hypoxia) typify eutrophic, nutrient-rich aquatic systems, where a high respiring biomass overwhelms O₂ inputs from inflowing water, photosynthesis, and atmospheric diffusion. Sturgeon are typically sensitive to dissolved O₂ decreases and hypoxic conditions impair their respiratory metabolism, foraging activity, and growth rates. Expressed as mg O₂ consumed per gram body weight per hour “small” (0.2g body weight at 10°C), “medium” (1.9g at 16°C), and “large” (63g at 20°C) juvenile white sturgeon all displayed significant O₂ consumption rate decreases with exposure to mild hypoxia, representing 51% of air-saturation levels, at temperatures typical for these life stages (Crocker and Cech 1997). This level of hypoxia also significantly decreased activity at these temperatures and at 25°C (Figure 3-2) (Cech et al. 1984) at least partially explaining their decreased O₂ consumption rates (Crocker and Cech 1997). In turn, the decreased activity level may account for decreased food consumption rates and/or decreased energy storage (although these were not quantified), and thus the significantly slower growth in juvenile white sturgeon found to occur under mild hypoxia (58% of air-saturated conditions) in comparison to the growth rate under normoxic conditions at 15, 20, and 25°C, (Cech et al. 1984). This hypometabolic response, seen also in adults (Burggren and Randall 1978), may benefit white sturgeon in natural habitats where decreased activity, at least

in the juveniles, would decrease oxygen demand, thereby conserving oxygen resources in hypoxic habitats until conditions improved.

In contrast, activity of Atlantic and shortnose sturgeon did not change with exposure to moderate hypoxia ($3\text{mg O}_2 \text{ l}^{-1}$) at 15°C (Daniel Baker, Dept. Biology, Univ. New Brunswick, Saint John, N.B. Canada; pers. comm.). Gill ventilatory frequencies increased by 50% in both species during this hypoxic exposure. Finally, plasma lactate concentrations, indicating a partial shift to anaerobic metabolism, increased in both species after exposure to $2\text{mg O}_2 \text{ l}^{-1}$ at 15°C , which is close to the minimum dissolved O_2 concentration ($1\text{mg O}_2 \text{ l}^{-1}$) measured in the Saint John River (Daniel Baker, Dept. Biology, Univ. New Brunswick, Saint John, N.B. Canada; pers. comm.). Shortnose sturgeon died, regardless of the life stage, at oxygen concentrations $< 2\text{mg l}^{-1}$ (Jenkins et al. 1993).

3.2.4 DISSOLVED CARBON DIOXIDE (CO_2)

Sturgeon are exposed to higher-than-atmospheric CO_2 (hypercapnic) conditions in some natural environments such as poorly circulated sloughs, and in high-density culture systems that employ O_2 injection (Wedemeyer 1996). In these culture systems, pure O_2 is injected carefully into the inflowing water, allowing the culture of higher densities of fish, which produce proportionately more CO_2 . Because CO_2 solubility in water is 25-30 times greater than that of O_2 , the CO_2 tends to stay dissolved, producing the hypercapnic conditions. Further, because much CO_2 hydrates in water, producing carbonic acid, water pH decreases with increasing CO_2 additions. Crocker and Cech (1996) measured significant decreases in the growth, apparently due to decreased food consumption, of juvenile white sturgeon, which were exposed to sturgeon-farm-production-tank CO_2 conditions ($45\text{-}75\text{mg CO}_2 \text{ l}^{-1}$, pH 7.0). The decreased growth rates were attributable to the CO_2 additions, rather than to the resulting pH decreases, from experiments using mineral acid (HCl) additions to simulate the "low" pH environment (pH 7.1) without the CO_2 additions (Crocker and Cech 1996).

Hypercapnia also affected white sturgeon blood gas, cardiovascular, and acid-base characteristics. In vitro studies showed that increasing CO_2 decreased white sturgeon blood O_2 affinity. The partial pressure of dissolved O_2 at which blood was half saturated ("arterial" P_{50}) decreased by 21mm Hg at 15°C and by 28mm Hg at 20°C at the "high-hypercapnic" levels associated with the high-density white sturgeon culture, compared with normocapnic levels (Crocker and Cech 1998). Thus, higher O_2 partial pressures ($\text{PO}_{2\text{s}}$) are needed to adequately saturate white sturgeon blood with oxygen for respiratory purposes under high hypercapnia, especially at the higher (20°C) temperature. In vivo studies showed that hypercapnic exposure induced stress as detected by significantly increased plasma norepinephrine, epinephrine, and cortisol concentrations, in white sturgeon (Crocker and Cech 1998). Furthermore, hypercapnic exposure increased white sturgeon struggling, when compared with those exposed to normocapnia. Although hypercapnic exposure, per se, did not affect gut blood flow, the struggling events significantly decreased it, possibly affecting nutrient absorption (Crocker et al. 2000). White sturgeon arterial CO_2 conditions directly reflected those in the water, while arterial PO_2 showed either no difference or a slight increase in the hypercapnic fish, presumably due to increased gill ventilation. As expected, arterial pH significantly decreased in the hypercapnic fish. However, after two days, arterial pH started to compensate, increasing in pH towards the level found in normocapnic sturgeon, due to significant accumulation of bicarbonate ion. This response was more

limited (ca. 35% of pH restoration) and slower than the response observed in most teleosts studied so far (Crocker and Cech 1998).

3.2.5 SALINITY

All bony fishes with jaws must maintain quite a tight control of total salt and water concentrations (osmoregulation) and specific ion concentrations (ionic regulation) for efficient physiological functioning (LeBreton and Beamish 1998). Regulatory mechanisms are similar in sturgeon and teleost fishes (reviewed by Cech 2000). Depending on their life history characteristics, sturgeon have been characterized as freshwater, semi-anadromous, or anadromous (Doroshov 1985). The lake sturgeon, although generally considered to be a freshwater species of the Great Lakes, Mississippi River, and Hudson Bay regions of North America, has been observed in elevated salinity regions of the St. Lawrence River and Hudson Bay (Harkness and Dymond 1961, Vladykov and Greeley 1963). Because salinities in these systems may approach 28ppt (Martini 1986), it was hypothesized that lake sturgeon possessed hyperosmoregulatory capabilities (LeBreton and Beamish 1998). Juvenile lake sturgeon showed no signs of osmoregulatory distress at salinities below 23ppt. However, after 24h exposure to 2ppt, swimming and feeding activity decreased, and smaller individuals (640-690g live weight) died with exposure to 25ppt (LeBreton and Beamish 1998). Mean plasma osmolality and electrolyte concentrations showed sharp increases in 25-ppt-acclimated sturgeon, compared with those acclimated to lower salinities, indicating poor regulation (Table 3-2). In contrast, anadromous white sturgeon adults acclimated to freshwater or to 22-26ppt salinity showed few osmolality or plasma electrolyte concentration differences (McEnroe and Cech 1985, Table 2). McEnroe and Cech (1985) also demonstrated that juvenile white sturgeon show increased percent survival with increased size when abruptly transferred to hypertonic water of 15ppt salinity. Whereas none of the 0.4 - 0.9g (live weight) white sturgeon survived the transfer, half of the 0.9 - 1.8g fish and all of the 4.9-9.5g fish survived the transfer (McEnroe and Cech 1985).

Juveniles of anadromous Gulf of Mexico sturgeon, of Gulf of Mexico coastal water rivers such as the Suwannee River in Florida, also showed body size-related abilities to tolerate more saline waters. At age 13 months, only sturgeon of greater than approximately 200g live weight could survive direct transfer into 25ppt salinity water, with half of the larger juveniles (>450g) surviving at 30ppt (Altinok et al. 1998). After acclimation to brackish (20ppt) and to sea water (34ppt), gulf sturgeon increased the number and size of mitochondria-rich, chloride cells in their gills (Altinok et al. 1998). After two weeks acclimation to brackish water, all of the size classes showed significantly increased plasma osmolality, and plasma Na^+ and Cl^- concentrations after subsequent acclimation to seawater conditions, compared with those acclimated to freshwater (0ppt) conditions (Altinok et al. 1998, Table 3-2).

The semi-anadromous shortnose sturgeon inhabits coastal rivers and estuaries of North America's Atlantic coast. Acoustically tagged juveniles (<56cm TL) mostly inhabited Savannah River (Georgia - South Carolina, USA) salinities between 0.1ppt and 5.4ppt except for brief high tide events when they were exposed to salinity increases to 17.6ppt (Collins et al. 2002). Comparative growth rates of age-16-month, shortnose sturgeon juveniles (mean live weight: 274g), acclimated to four salinities, showed that mean weight gain was significantly lower at 20ppt, compared with those measured at lower (0, 5, 10ppt) salinities (Jarvis et al. 2001).

Table 3- 2. Lake sturgeon (LS), Gulf sturgeon (GS), and white sturgeon (WS) sample sizes, mean (SD) weights, serum osmolarities (or osmolalities in mOsm kg⁻¹ for GS) and electrolyte concentrations, in various salinities. Data are from LeBreton and Beamish (1998, LS), Altinock et al. (1998, GS) and McEnroe and Cech (1985, WS).

Species	Salinity	Sample size	Mass (g)	Osm (mOsm l ⁻¹)	Na ⁺ (mmol l ⁻¹)	Cl ⁻ (mmol l ⁻¹)
LS	0	5	1195 (284)	247 (9)	126 (5)	117 (6)
LS	10	5	2275 (511)	273 (10)	141 (5)	133 (4)
LS	15	5	1225 (185)	301 (26)	155 (14)	152 (16)
LS	25	5	1228 (316)	451 (56)	224 (26)	223 (19)
GS	0	6	110-170	261	152	90
GS	34	8	110-170	306	160	158
GS	0	6	230-290	266	131	118
GS	34	8	230-290	286	149	145
GS	0	6	460-700	255	125	112
GS	34	8	460-700	291	147	145
WS	0	7	> 10,000	236 (7)	132 (4)	111 (4)
WS	22-26	7	> 10,000	249 (14)	125 (8)	122 (3)

3.2.6 SUBSTRATE/DEPTH/VELOCITY

North American sturgeon substrate, depth and velocity preferences vary with species. Peake (1999) found that juvenile lake sturgeon significantly preferred a sand substrate, compared with rock, gravel, or smooth plastic substrates in a laboratory flume. Shortnose sturgeon preferred sand and cobble substrates in lower velocity, curved reaches and deeper channels (avoiding the higher velocity, straight runs of the Connecticut and Merrimack Rivers (Massachusetts, USA), presumably to save energy by not requiring strenuous swimming (Kynard et al. 2000). Using radio and ultrasonic telemetry, Bramblett and White (2001) determined that pallid sturgeon preferred sandy

substrates while shovelnose sturgeon preferred gravel and cobble substrates in the Yellowstone-Missouri River system. Although pallid sturgeon used greater depths significantly more often than the shovelnose sturgeon, their depth ranges (0.6 - 14.5m for pallids, 0.9-10.1m for shovelnose) overlapped. Water velocity preferences also overlapped for these two species, but the mean bottom velocity at pallid sturgeon locations (0.65m s^{-1}) was significantly less than that for shovelnose sturgeon (0.78m s^{-1} , Bramblett and White 2001). During low-water conditions of the Mississippi River in 1988, radio-tagged shovelnose sturgeon were found in the highest-available-velocity areas: with 0.23m s^{-1} water velocity at 5.8m depth and a sand bottom (Curtis et al. 1997). During winter in the Kansas River (Kansas, USA), radio-tagged shovelnose sturgeon preferred 1.0 - 2.0-m depths with $0.02 - 0.79\text{m s}^{-1}$ currents over sand substrates (Quist et al. 1999). Potential spawning areas are suggested by spring and early summer aggregations of pallid sturgeon in the lowermost 14km of the Yellowstone River. In contrast, the infrequent use of the Missouri River reach between the Fort Peck Dam and the confluence with the Yellowstone River suggest that the dam's influences (alterations of hydrograph, temperature, sediment and organic matter transport) have shifted the habitat characteristics to be similar to the less turbid conditions upstream of the pallid sturgeon's native range (Bramblett and White 2001). Missouri River fishes evolved under high-turbidity conditions (Pflieger and Grace 1987). Both pallid and shovelnose sturgeon avoid the clear water, impounded areas of the system, where visually oriented, non-native species are favoured (Bramblett and White 2001).

Substantial river flows, following natural hydrographs, typically constitute optimal sturgeon spawning habitat. Changes in hydroelectric operations below the Prickett Dam on the Sturgeon River (Michigan, USA) to near run-of-the-river flows attracted 74% more lake sturgeon (68% more females) with increased reproductive readiness to spawning sites (Auer 1996). Spawning Sacramento River white sturgeon upstream movements (up to 25km d^{-1}) were stimulated by small increases in river flow (Schaffter 1997). Similarly, Parsley and Beckman (1994) showed that decreased spring and summer river discharges from Columbia River (Washington and Oregon, USA) hydropower system operations decreased the quantity and quality of white sturgeon spawning habitat. Gulf of Mexico sturgeon eggs were found on bedrock limestone thinly overlain with fine sand and densely distributed elliptical gravel in the southern half of the Suwanee River at 2-4m depth (Sulak and Clugston 1998). Laboratory flume studies on age-0, Gulf of Mexico sturgeon revealed a preference shift from sand substrates at low velocities to cobble substrates at moderate velocities and no preferences at high velocities (Chan et al. 1997). Preferred spawning velocities and substrates vary for different species and locations, with a typical velocity range of $1-2.5\text{m s}^{-1}$ and a hard substrate, such as cobble, gravel, boulders and sand (McCabe and Tracy 1994, Bruch and Binkowski 2002, Perrin et al. 2003). Variations in thickness and the adhesive properties of the outer-egg chorion layer in different species may be associated with spawning habitat preferences (Deng et al. 2002).

3.2.7 NUTRITION

All fishes require sufficient quantities of high-quality food in their diets to develop, grow, and reproduce. First-feeding larval fish are the most susceptible to food deprivation. Resting-routine, O_2 consumption rates of green sturgeon from hatching to 31 days post hatch increased 5-fold under normoxic conditions, before yolk sac

reserves became limiting and metabolic rates declined (Gisbert et al. 2003). These increased O₂ consumption rates were associated with organogenesis, acquisition of organ functions, and the conversion of yolk sac into new metabolizing larval biomass. If food-deprived, larvae showed body mass decreases, presumably from tissue resorption, and a 3-fold decrease in O₂ consumption rates within 15-31 days post hatch, during which most larvae died (Gisbert et al. 2001).

Sturgeon rely heavily on chemosensory mechanisms, olfaction and gustation, for finding food (Kasumyan 2002). Shortnose sturgeon fed on crustacea, insects, and small molluscs in the Hudson River estuary (Carlson and Simpson 1987). Subadult Gulf of Mexico sturgeon fed on lancelets, brachiopods, amphipods, grass shrimp, polychaetes, and gastropods (Mason and Clugston 1993). Two-year-old lake sturgeon, which were starved for 60 days, showed decreased plasma glucose, but only to day 10, followed by increased plasma concentrations of 11 free amino acids. The maintenance or increased plasma levels of glucogenic amino acids in combination with the maintenance of blood glucose concentrations indicated active gluconeogenic processes in the liver supported by muscle proteolysis (Gillis and Ballantyne 1996). Consequently, amino acids are available for the sturgeon's oxidative metabolic needs under those conditions (Gillis and Ballantyne 1996).

Juvenile white sturgeon specific growth rate increased linearly with increasing ration size, when fed tubificid worms (Cui et al. 1996). When first-feeding, these fish preferred chopped tubificid worms to a prepared diet, showing increased survival and growth rates when either consistently fed on the Tubifex diet or switched to it from the prepared diet (Lindberg and Doroshov 1986). Juvenile white sturgeon generally digest carbohydrates quite well (Herold et al. 1995) without adverse effects on growth and liver functions (Fynn-Aikens et al. 1993). To determine the specific dietary requirements of juvenile white sturgeon, Hung et al. (1987) found that purified diets containing 42.9 - 43.8% crude protein, 15.5% lipids (including the phospholipid, lecithin), 7.4 - 8.1% moisture, and 4.1 - 4.2% minerals produced the best growth rates. Sturgeon dietary requirements are reviewed by Hung and Deng (2002).

3.2.8 OUTLOOK

This review summarizes the environmental requirements, preferences, and tolerance limits of North American sturgeons. The recent declines of sturgeon populations, world-wide, due to habitat alterations and overharvesting (i.e., for their roe or flesh), has made the acquisition of such knowledge about these ancient fishes even more urgent. For example, more information is needed about these species' passage around barriers such as dams in rivers. Data from radio and ultrasonic-tagged lake sturgeon in the upper Mississippi River showed that navigation dams can be barriers to their upstream movements (Knights et al. 2002). With appropriate data for management and modelling efforts (e.g., concerning river fragmentation by dams, Jager et al. 2001), the best, science-based decisions can be made to make sure that these magnificent, North American fishes do not slip into extinction.

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