

Anadromous Sturgeons: Habitats, Threats, and Management

Synthesis and Summary

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Introduction

Anadromous sturgeons spend most of their lives at sea and migrate into rivers to spawn (Bemis and Kynard 1997). This migratory pattern includes not only species from coastal oceanic waters, but also species from the mesohaline Ponto-Caspian seas (Rochard et al. 1991). Oceanic anadromous species include European sturgeon *Acipenser sturio*, Atlantic sturgeon *A. oxyrinchus oxyrinchus*, Gulf sturgeon *A. o. desotoi*, green sturgeon *A. medirostris*, Sakhalin sturgeon *A. mikadoi*, and Chinese sturgeon *A. sinensis*. Species migrating back and forth from freshwaters to estuaries, but dependent on estuarine feeding for their growth, are called amphidromous, an example of which is the shortnose sturgeon *A. brevirostrum* (Kynard 1997). Semianadromous sturgeons like the white sturgeon *A. transmontanus* comprise populations that grow in estuaries and migrate upriver to spawn, but generally include also potamodromous populations, which migrate in rivers or lakes (Doroshov 1985). Both amphidromous and semianadromous sturgeons

can travel long distances in oceanic waters. This symposium focused on oceanic anadromous sturgeons, hereafter termed anadromous sturgeons, but also included papers regarding shortnose sturgeon and white sturgeon. Sakhalin sturgeon and Chinese sturgeon were not discussed during the symposium.

The sturgeon family Acipenseridae is one of the most threatened fish families (Birstein et al. 1997; IUCN 2006), and there are highly (European sturgeon) and moderately (Atlantic sturgeon) threatened species among the anadromous sturgeons. In recent decades, two major types of management measures that increase the hope for recovery of anadromous sturgeons have been implemented. First, fishing has been banned for nearly all populations. Second, renewed consideration of the importance of habitat in restoration efforts has resulted in increased habitat research and new habitat protection measures. In protection or restoration plans, designations such as essential or critical habitat (Endangered Species Act 1973; Magnuson-Stevens Fishery Conservation and Management Act 1996; Species at Risk Act 2003; IUCN red list (IUCN 2006)) can be powerful management

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tools if supported by adequate scientific definitions and content. Many papers summarized below in the habitat section contribute to our understanding of the ecological function of essential habitats. Threats to habitats and to populations are covered in a second section. Finally, a review of the papers on management and population trends examines whether progress has been made by the U.S. Atlantic sturgeon populations since fishing was banned. In this synthesis, we summarize the contents of the symposium papers, making occasional reference to presentations not reported as papers. We emphasize the main findings, using common agreements reached by the researchers in the symposium discussion panels. We also provide selected references for background information. This compendium of papers, bearing on sturgeon species with similar life histories, will contribute to development of sound conclusions and recommendations regarding the ecology and management of anadromous sturgeons.

Habitats

Habitats of anadromous sturgeons range geographically from freshwater spawning sites that are far up major rivers to marine feeding habitats that are very distant from the natal rivers. Therefore, papers presented in a single symposium cannot provide complete coverage, but only touch on a small subset of these habitats.

Freshwater Habitats

Sulak et al. (2007, this volume) provided new information about the freshwater habitats of Gulf sturgeon in which adults reside in a nonfeeding mode for several months during the summer. Previously, authors had suggested that freshwater residency provided a thermal refuge, especially near springs that inject cooler groundwater (Chapman and Carr 1995). Cessation of feeding was thought to be caused by prey depletion within the limited area of these spring-associated thermal refuges (Chapman and Carr 1995). Sulak et al. (2007) showed that holding habitats during the summer freshwater residency in the

Suwannee River, Florida were not substantially cooler than the river in general or cooler than marine habitats in the Gulf of Mexico. Furthermore, Sulak et al. (2007) showed that prey abundance within the holding areas was not significantly different from those of other areas of the river, indicating that nonfeeding was not due to prey depletion. These same authors pointed out that Gulf sturgeon regularly move out of and between holding areas, demonstrating that they are not trapped in thermal refuges as has been previously suggested and that they would have ample opportunity to move to other foraging sites (Sulak et al. 2007). This shows that the nonfeeding mode is not a response to localized prey depletion, but instead probably evolved as a bioenergetic response to the generally insufficient abundance and biomass of suitable prey for adult sturgeon in most riverine environments.

Parkyn et al. (2007, this volume) studied movement rates and temperatures experienced by Gulf sturgeon in the Suwannee River and estuary. Using ultrasonic transmitters and archival temperature tags attached to adult sturgeons, they found a lower rate of movement in the river in the summer months and a higher rate during spring and fall migrations. The annual temperature range experienced by three marked individuals was 8.1–28.7°C, with the mean monthly maximum (26°C) occurring in the river during summer. The authors suggested that the summer temperature should have important effects on the metabolic rate of Gulf sturgeon. This statement is consistent with the hypothesis proposed by Sulak et al. (2007). To test the bioenergetics hypothesis, it might be useful to study the metabolic rate of Gulf sturgeon under different temperature and food availability regimes to determine the feeding/nonfeeding trade-off limit.

Randall and Sulak (2007, this volume) used a 19-year mark–recapture database to estimate yearly recruitment of Gulf sturgeon in the Suwannee River, using a length–age equation derived from fish of known age. Recruitment was positively correlated with the high monthly mean flow in September and December. They postulated that the correlation was

the result of (1) increased survival of late-winter, estuarine-feeding, age-0 juveniles during high-flow years in less saline estuarine waters, or (2) an enhanced feeding potential due to increased delivery of suspended organic matter to the estuary.

Estuarine Habitats

The symposium yielded consistent information on the distribution and feeding of anadromous sturgeons in estuaries. Results from several studies show that age-1 and age-2 juveniles, hereafter called early juveniles, occur in the uppermost part of estuaries, while older juveniles and subadults have a wider distribution, extending into more saline waters. In the St. Lawrence estuarine transition zone (ETZ), the core areas of sonic-tagged early juvenile (age-2) Atlantic sturgeon occurred within the freshwater front and upper oligohaline zones, only 3 km wide across the river axis (Hatin et al. 2007b; this volume). Nellis et al. (2007a, this volume) showed that the ETZ is characterized by a sequence of benthic assemblages, with the early juvenile concentrations co-occurring with the oligochaete benthic assemblage associated with fine sediments accumulated near the upper limit of the salt wedge (Simons 2004). Guilbard et al. (2007, this volume) showed that oligochaete tubificids were the dominant taxon in stomachs of early juvenile Atlantic sturgeon. Age-0 Atlantic sturgeon were mostly captured in the freshwater front, upstream from the salt wedge limit occupied by early juveniles (Hatin et al. 2007b). The freshwater frontal zone was occupied by the *Gammarus tigrinus* amphipod assemblage (Nellis et al. 2007a), the main food item of age-0 Atlantic sturgeon (Guilbard et al. 2007). Considering that the St. Lawrence Atlantic sturgeon population is distributed over more than 5,000 km of coastline, including the Gulf of St. Lawrence and portions of the Labrador and Atlantic coasts (F. Caron, Ministère des Ressources naturelles et de la Faune, Québec, personal communication), the small relative size of early juvenile and age-0 concentration areas should qualify these areas as essential habitats

for that population (DFO 2004; Hatin et al. 2007b).

In the Hudson River estuary, Haley (1999) previously found a similar concentration of juvenile Atlantic sturgeon in the upper oligohaline zone (salinity of 0.5–3.0). At a finer scale, she also found that the juveniles were associated with silty substrate. Using drifting nets in the Edisto River estuary, South Carolina, McCord et al. (2007, this volume) captured high numbers of age-1 Atlantic sturgeon in the oligohaline zone. In the Suwannee River estuary, Brooks and Sulak (2005) reported that the main food items of small juvenile Gulf sturgeon (free-living amphipods, isopods, and insect larvae) were concentrated in the mesohaline–oligohaline zone, located around river kilometer 0–8 (with 0 being the river mouth) under medium flow conditions. Like the St. Lawrence estuary, the Gironde estuary in France is characterized by a salt wedge within which early juvenile European sturgeon (<45 cm fork length) concentrate in the oligohaline zone, whereas larger juveniles and subadults are found further downstream, in the polyhaline zone (M. Lepage, CEMAGREF Bordeaux, personal communication).

Nelson et al. (2007, this volume) reported that young juveniles of the semianadromous white sturgeon were concentrated in side channels (sloughs) of the Fraser River tidal estuary located above the saltwater–freshwater limit. A sensitivity analysis of their population model revealed that juvenile survival had the largest influence on population growth. They inferred that improving juvenile survival in the slough habitats was essential for the conservation of this white sturgeon population. Similarly, juveniles of the amphidromous shortnose sturgeon appear to concentrate above the saltwater–freshwater limit in the Hudson River estuary (Bain 1997).

Guilbard et al. (2007) studied the feeding regime of Atlantic sturgeon and lake sturgeon co-occurring in the St. Lawrence ETZ. Diets of the two species had a low overlap index for both juveniles and subadults: tubificids were the dominant taxon in Atlantic sturgeon stomachs whereas gammarids dominated the lake sturgeon diet. Haley (1999) found similar results for shortnose

sturgeon and juvenile Atlantic sturgeon co-occurring in the Hudson River estuary, with the two species using different microhabitats and different foods. Results from those two studies suggest a noncompetitive situation for juvenile and older life stages of sturgeon species pairs co-occurring in estuaries (Bemis and Kynard 1997), which is contrary to the hypothesis that had been put forward by Bain (1997). The situation could be different for age-0 sturgeons, as Guilbard et al. (2007) found a high diet overlap for age-0 Atlantic sturgeon and lake sturgeon in the St. Lawrence estuary, where both species feed mainly on gammarids.

Marine Habitats

Winter marine habitats, for which little information was previously available, were addressed in some depth in this symposium. The articles pertaining to winter marine habitats (Edwards et al. 2007; Erickson and Hightower 2007; Laney et al. 2007; Parkyn et al. 2007; all this volume) have numerous parallel and convergent results that provide new understanding of this aspect of anadromous sturgeon ecology.

Edwards et al. (2007) used a combination of satellite pop-up archival tags (PATs) and acoustic tags to determine that Gulf sturgeon migrated long distances along the Florida Gulf of Mexico coast to winter habitats, where they were concentrated with fish from other river systems. Laney et al. (2007) summarized catches of the closely related Atlantic sturgeon using a 16-year data set of otter trawl surveys that were primarily conducted for the tagging of striped bass *Morone saxatilis* in winter habitats off Virginia and North Carolina. Their trawl catches of Atlantic sturgeon suggested that the sturgeon were concentrated, and limited tag returns suggested that individuals from different river systems utilized the same winter habitat area. Stein et al. (2004) reported that Atlantic sturgeon caught as bycatch in Atlantic coast fisheries were frequently caught in nearshore areas distant from any rivers supporting large populations, furthering the idea that they migrate to distant marine habitats.

Edwards et al. (2007) determined that the winter habitat of Gulf sturgeon was relatively close to shore (as determined by acoustic relocations and PAT pop-up locations) and shallow (typically < 10 m and always < 24 m). Laney et al. (2007) found that most Atlantic sturgeon were caught at stations less than 10 m deep and all in stations less than 20 m deep. These are remarkably similar results. Stein et al. (2004) likewise found that most Atlantic sturgeon taken as bycatch were concentrated in inshore areas. Erickson and Hightower (2007) found that the migration patterns and marine habitats of green sturgeon paralleled those of Atlantic and Gulf sturgeon in that green sturgeon migrated long distances (221–968 km) along the coast, remained in relatively shallow (typically 40–100 m) depths, and appeared to concentrate in specific sites. Erickson and Hightower (2007) also discuss their results relative to past conventional tagging studies and concluded that green sturgeon from different rivers probably concentrate and mix at such sites, such as northwest of Vancouver Island.

Winter habitat areas have been characterized only in very general ecological terms so far. In previous studies, sturgeon were most abundant in areas of sand substrate (Fox et al. 2002; Stein et al. 2004). Atlantic sturgeon collected by Laney et al. (2007) were also concentrated in sandy areas, but the authors indicate that concentration areas were near areas with substantial gravel content. Sediments in Gulf sturgeon concentration areas found by Edwards et al. (2007) were primarily sand (F. M. Parauka, U.S. Fish and Wildlife Service, unpublished data) and at another location were well-sorted sands inhabited by large numbers of lancelets *Branchiostoma floridae* (R. E. Edwards, unpublished data). The presence of gravel near the areas reported by Laney et al. (2007) may reflect high-energy environments where waves or currents produce similarly well-sorted sediments.

Perhaps the most general important new finding of these studies is that these three anadromous sturgeon species all migrate long distances to winter habitats where they mingle with individuals originating from other rivers. For these

three species, genetic analyses have shown that distinct subpopulations exist within rivers or groups of rivers (e.g., Bowen and Avise 1990; Waldman et al. 1996; Waldman and Wirgin 1998; Israel et al. 2004). Such genetic structuring can be maintained only if these sturgeon species, which migrate long distances to marine winter feeding habitats, return to natal rivers or systems with high degrees of fidelity, much as anadromous salmonids do.

Threats and Restoration

Threats

Researchers at the symposium agreed that bycatch in marine or estuarine fisheries was a very serious threat to the recovery of sturgeon populations. Bycatch was reported to be an important mortality factor by Kahnle et al. (2007, this volume) for Atlantic sturgeon of the Hudson River, by Berg et al. (2007, this volume) for Gulf sturgeon of the Yellow River, and by Erickson and Hightower (2007) for green sturgeon. In a risk analysis of factors that could impair the restoration of Atlantic sturgeon in the Baltic, Gessner et al. (2007, this volume) similarly identified bycatch in river fisheries as a serious threat. Based on a survey of commercial fishermen, M. Lepage (CEMAGREF Bordeaux, symposium presentation) considered bycatch of subadults at sea to be the main factor preventing the recovery of the critically endangered European sturgeon. Collins et al. (2000) estimated a high rate of mortality of Atlantic sturgeon from incidental captures along the northern and southern U.S. Atlantic coasts. This symposium produced additional information on important habitats where bycatch may have more detrimental effects, including early juvenile habitats in the estuarine transition zone and the subadult/adult habitat in the nearshore oceanic zone. Both of these habitats are limited in area yet have been shown to contain sturgeon concentrations or preferred sites, indicating that these habitats warrant careful consideration from fishery managers.

Eutrophication (and resultant hypoxia) was

identified in the symposium as a widespread threat to sturgeon habitat. In an effort to determine the population status of shortnose sturgeon in the Neuse River (North Carolina), Oakley and Hightower (2007, this volume) did an intensive gill-netting survey in which no shortnose sturgeon were captured. Their apparent absence in the Neuse River was at odds with predictions from a logistic model developed to predict the presence or absence of shortnose sturgeon based on watershed and river characteristics. Oakley and Hightower (2007) observed that one sonic-tagged Atlantic sturgeon avoided the estuary in the summer months, when severe hypoxic conditions were measured. They hypothesized that the absence of shortnose sturgeon populations from many mid-Atlantic estuaries is due to eutrophication resulting from poor flushing conditions characteristic of large and partly enclosed estuaries. In the Suwannee River, eutrophication was proposed by Randall and Sulak (2007) as a possible explanation for low juvenile Gulf sturgeon recruitment rates associated with September and December low water levels. They suggested that the development of algal mats on the bottom and nightly hypoxia would reduce habitat feeding potential for the 6-month juveniles in the river or 9-month juveniles reaching the estuary in December. In the Kennebec River, T. Squiers (Maine Department of Marine Resources, symposium presentation) attributed the recent Atlantic sturgeon population increases to 20 years of good ecological practices leading to habitat recovery from hypoxia. Niklitschek and Secor (2005) showed that hypoxia can substantially reduce the amount of suitable summer habitat for early juveniles in Chesapeake Bay. High salinities and low dissolved oxygen levels in the lower bay limit early juveniles to the upper estuary and tributaries, where the habitat may become unsuitable because of high summer temperatures. Along the Pacific coast, high water temperatures and oxygen depletion resulting from low flow rates in dam-controlled rivers are important issues for green sturgeon habitat (NOAA Fisheries 2005).

In the St. Lawrence River estuary, the impacts of dredged sediment disposal on Atlantic

sturgeon habitat were examined through an integrated study conducted by Hatin et al. (2007a, 2007b, both this volume), McQuinn and Nellis (2007, this volume), and Nellis et al. (2007a, 2007b, both this volume). These authors characterized a 13-km-long sand dune complex that was created in 1971–1974 during dredging operations to deepen the navigation channel. They also examined the effects of annual sediment disposal using a bottom-load transport model to locate the sediment drift path and potential accumulation areas. By comparison with extensive control areas, they showed that the sand dune complex as well as the sediment disposal site and drift path had lower rates of Atlantic sturgeon occupation and lower benthic feeding potential for juvenile Atlantic sturgeon. Moreover, Hatin et al. (2007b) showed that these modified biotopes cut across the main core area of early juvenile Atlantic sturgeon. These findings stress the need to reassess the dumping management plan in the St. Lawrence ETZ. Collins et al. (2000) previously noted that dredging and dumping in the freshwater–saltwater interface was one important threat to Atlantic sturgeon and shortnose sturgeon habitats in rivers of the southeastern United States.

Restoration and Habitat Connectivity

Restoration of Atlantic sturgeon in the Oder River (Germany–Poland border) (Gessner et al. 2007) was undertaken based on indications that this river offered good nursery habitats in the estuary as well as suitable spawning habitats in the upper reaches of the river. The restoration of Atlantic sturgeon was preferred over European sturgeon because the former was the last indigenous species and probably is better adapted to Baltic conditions (Ludwig and Gessner 2007, this volume). Small-scale habitat diversity and sufficient connectivity within the river system were recognized as essential, but ensuring that spawners have access to good spawning sites, often located above dams, was deemed to be most important. Multiple managerial, political, and social interventions were needed to sustain the project. Gessner et al. (2007) proposed that the presence

and good condition of an anadromous sturgeon population should be considered as a formal indicator of total river–estuary ecosystem quality.

Connectivity is also an issue for white sturgeon populations in the Columbia River basin where numerous dams severely restrict sturgeon movements (Rieman and Beamesderfer 1990). Jager et al. (2007, this volume) used a population model to study options for reconnecting two white sturgeon subpopulations separated by a dam on the Snake River, a tributary of the Columbia River. Simulations suggested that the upstream population, which inhabits a long river segment with adequate spawning habitat, acts as a demographic source. The downstream population, which inhabits a short river segment lacking spawning habitat, acts as a demographic sink. The study simulated the demographic and genetic consequences of providing upstream passage, downstream passage, or smaller screen spacing at the dam. The combination of enhanced screening to prevent entrainment of sturgeon with both upstream and downstream passage yielded the best demographic results. For this river configuration, screening was most important because it kept more spawners in the upstream segment where spawning habitat was located.

Management and Population Trends

Historical Perspective

Stocks of anadromous sturgeons are at historic low levels worldwide. Presentations at this symposium added sobering detail to the extent of decline for these fishes. Spear (2007, this volume) reported that the harvest, and presumably stock levels, of Atlantic sturgeon along the U.S. Atlantic coast declined precipitously in the late 19th century due to large-scale commercial fishing. The harvest remained at less than 5% of the 19th century levels through 1998, when the fishery was closed coastwide. Atlantic sturgeon were known to occur in 34 rivers in the United States and are still present in 32 of those rivers (NMFS and USFWS 1998). However, spawning is now known to occur in only 14 rivers. Kahnle et al.

(2007) estimated that fewer than 300 mature female Atlantic sturgeon remain in the Hudson River estuary in the 1990s compared to the estimated 6,000 at the end of the 19th century (Secor 2002). Symposium presentations on the status of the European sturgeon and Atlantic sturgeon in European waters portrayed reductions that are even more drastic. Gessner et al. (2007) indicated that the former range of European sturgeon included the Black Sea, the Mediterranean Sea, the eastern Atlantic Ocean, and the North Sea. Today, only the population in the Gironde River, France, remains. Gessner et al. (2007) reported that Atlantic sturgeon from the Baltic Sea and tributaries were an important food source and trade item for local residents as early as the 10th century. Signs of overfishing were evident by the 17th century, at which time stocks began a decline that persisted through the 20th century. Atlantic sturgeon are now extinct in all Baltic Sea tributaries (Ludwig and Gessner 2007).

Populations of amphidromous and semi-anadromous sturgeons have also declined. Stocks of shortnose sturgeon in the United States are at extremely low levels, and many stocks have apparently been extirpated (Oakley and Hightower 2007). Gulf sturgeon currently occur along the U.S. Gulf of Mexico coast from the Pearl River, Louisiana to the Suwannee River, Florida. Abundances of most populations are reduced relative to historical levels (USFWS and GSMFC 1995). Berg et al. (2007) report recent estimates of abundance for several populations ranging from a low of 62–218 adults in the Apalachicola River to a high of 7,600 in the Suwannee River.

Management Response

The effects of fishing on sturgeon stocks have long been recognized, and some of the earliest management responses to stock declines involved fishery regulations. Limitations on fishery rights for sturgeon have been known for the Baltic Sea coast since 1273 (Gessner et al. 2007). Restrictions since that time in Europe and North America have included season and area closures, size limits, total allowable catch

limits, and gear restrictions. Currently, the harvest of Atlantic sturgeon in U.S. waters and Atlantic and European sturgeon in European waters is prohibited. The Atlantic sturgeon harvest in Canada is controlled by size limits, season, gear restrictions, and a total allowable catch (Caron et al. 2002; Trencia et al. 2002). Possession of shortnose and Gulf sturgeon in the United States is prohibited, and both species are protected under the U.S. Endangered Species Act. White sturgeon in the Fraser River, British Columbia are protected under a catch and release statute (Nelson et al. 2007). Restricted harvest of white sturgeon continues in the U.S. Pacific coastal states.

Another early response to declines of sturgeon stocks was artificial propagation and stock augmentation. Propagation efforts on the U.S. Atlantic coast started in the late 19th century (Smith 1985). The first successful artificial spawning of Atlantic sturgeon from the Hudson River occurred in 1875, and propagation efforts for Atlantic sturgeon of the Delaware River started in 1888. Recent efforts to refine spawning techniques for Atlantic sturgeon in the U.S. have been undertaken in South Carolina (Smith 1985) and at the U.S. Fish and Wildlife Service Laboratory in Lamar, Pennsylvania, with the latter culminating in the publication of a culture manual for Atlantic sturgeon (Mohler 2004). Experimental releases of Atlantic sturgeon have occurred in a Chesapeake Bay tributary (Secor et al. 2000) and the Hudson River (Kahnle et al. 2007). Recent U.S. propagation efforts have focused on reintroducing species to waters whose natural stocks have been extirpated or are at extremely low levels (ASMFC 1996). Early propagation activities began in Europe in the late 19th century with stocking of European sturgeon to the Elbe, Stor, and Eider rivers (Gessner et al. 2007). Recent activities in Europe include plans to reintroduce European sturgeon to German tributaries of the North Sea and Atlantic sturgeon to the Oder River, a tributary of the Baltic Sea (Gessner et al. 2007). The introductions of Atlantic sturgeon will utilize broodstock from northern U.S. and Canadian populations.

Management responses to the bycatch of sturgeons have been limited. On the U.S. Atlantic coast, resource agencies are required to collect and annually report data on sturgeon bycatch (ASMFC 1998). Researchers on the U.S. Pacific coast (Erickson and Hightower 2007) and the Atlantic coast (Laney et al. 2007) have started to document ocean areas of sturgeon concentration. Data on fisheries with high bycatch and on locations of sturgeon concentrations can be used to regulate fisheries that appear to or potentially could cause the greatest damage. In France, politicians, scientists, and nature associations are attempting to reduce bycatch of European sturgeon in the Gironde River by explaining the problem to the public and to commercial fishermen (Lepage, symposium presentation). Gessner et al. (2007) reported that experimentation has started in Germany on gill-net modifications that could reduce the bycatch of sturgeon in coastal waters of the Oder River with the intent of reducing losses of planned introductions of Atlantic sturgeon.

Attempts to improve water quality and access to spawning sites have increased in popularity and are likely to benefit stocks of many anadromous fishes. Plans to restore Atlantic sturgeon to the Oder River on the Baltic Sea include a consideration of water quality problems and obstructions (Gessner et al. 2007). In North America, momentum has grown for the removal of dams that interfere with fish migrations in Atlantic coastal tributaries. Spear (2007) reported that dams have recently been removed on the Kennebec, Connecticut, and Rappahannock rivers. The removal of the Edwards Dam on the Kennebec River restored 27 km of riverine habitat available to the recovering stock of Atlantic sturgeon in that river (Squiers, symposium presentation).

Sampling for Abundance Trends

Measuring the abundance or relative abundance of sturgeons is made difficult by their complex life histories, use of disparate habitats at different life stages, and long migrations between

habitats. The issue of how to sample for estimates of Atlantic sturgeon was discussed in several symposium presentations. A consensus emerged that abundance should be measured at the juvenile life stage prior to emigration from natal estuaries at age two (Bain et al. 1999 and symposium presentation; Kahnle et al. 2007; McCord et al. 2007). Presenters further agreed that sampling age-1 fish yielded the best data because age-1 fish are predictably concentrated, can be captured with relative consistency, and are not affected by emigration. The general distribution of age-0 sturgeon is known in some estuaries, but this age was rejected for abundance sampling because age-0 fish are very difficult to sample and are rarely collected. Participants did not recommend abundance sampling from aggregations of spawning adults because such sampling carries risks to low populations from unintended mortalities and generally does not yield adequate sample sizes for detection of population change. Moreover, the spawning areas for many remnant Atlantic sturgeon populations remain unknown.

Agreement was reached during the symposium with regard to the best locations to sample juvenile Atlantic sturgeon. McCord et al. (2007) and Sweeka et al. (2006) recommended that juveniles be sampled in essential habitats located above or in the salt wedge in South Carolina rivers and in the Hudson River. The authors differed in their recommended season of sampling. McCord et al. (2007) reported that summer sampling was the most productive, while Sweeka et al. (2006) recommended sampling overwintering concentrations in very early spring. Researchers in the St. Lawrence River estuary, Quebec sampled early juvenile Atlantic sturgeon during summer in concentration areas at the upper limit of the salt wedge and older juveniles and subadults within a wider reach of the ETZ (Hatin et al. 2007a, 2007b; McQuinn and Nellis 2007).

Gill nets and bottom trawls were reported as the gears of choice for sampling juvenile Atlantic sturgeon. Bain et al. (1999) evaluated anchored gill nets and bottom trawls for sampling the relative abundance of juvenile stur-

geon in the Hudson River estuary. McCord et al. (2007) evaluated the use of anchored gill nets, drifting gill nets, and bottom trawls to collect juvenile Atlantic sturgeon in South Carolina rivers. Both studies concluded that gill nets were superior to bottom trawls for developing an index of relative abundance because the effectiveness of bottom trawls was often hampered by bottom obstructions and because gill nets and associated gear were less expensive and required less expertise. McCord et al. (2007) showed that drifting gill nets worked best in South Carolina rivers, while Bain et al. (1999) only evaluated anchored gill nets in the Hudson River. Researchers in the St. Lawrence River estuary based their gear recommendations on the targeted life stage. Bottom trawls produced the most consistent catches of early juveniles because this life stage had a restricted home range and were better sampled by an active gear (Hatin et al. 2007b) while set gill nets were the gear of choice for older juveniles (Hatin et al. 2007a); drifted nets were not evaluated. Regardless of the gear selected, the authors reiterated that sample location needed to match the concentration location of the targeted life stage. Kahnle et al. (2007) developed indices of relative abundance for juvenile Atlantic sturgeon in the Hudson River estuary from data collected by bottom trawl throughout the estuary and from bycatch data from a commercial gill-net fishery for American shad. They noted that neither sampling effort was designed to capture Atlantic sturgeon, and the high frequency of zero catches reduced the effectiveness of resulting abundance indices.

Two papers in this symposium evaluated the use of hydroacoustic technology to sample sturgeon abundance. McQuinn and Nellis (2007) used bottom trawl and classical hydroacoustic methods to evaluate the summer juvenile distribution and relative abundance in the St. Lawrence River estuary. Bottom trawl collections were used to verify the species composition of targets detected by the hydroacoustic sampling. The authors concluded that hydroacoustic methods could be used to estimate the density of Atlantic sturgeon and other demer-

sal fish species. Nealsen and Brundage (2007, this volume) evaluated the use of split-beam hydroacoustic gear for detecting shortnose sturgeon in winter concentration areas of the Delaware River. They concluded that the technique could detect shortnose sturgeon and that the species could be differentiated from other demersal fish species present in the river.

Symposium participants also touched on the use of modeling to evaluate or predict population status. Oakley and Hightower (2007) developed logistic regression models for predicting the presence or absence of shortnose sturgeon based on watershed and river conditions in Atlantic coastal rivers. Nelson et al. (2007) evaluated population dynamics of white sturgeon of the Fraser River of British Columbia using an age-based demographic model. Jager et al. (2007) used a genetics and age-based model to predict the correct balance of spawners and juveniles between segments upstream and downstream from dams in the Snake River.

Recent Trends

An initial objective of this symposium was to determine if populations of Atlantic sturgeon along the U.S. Atlantic coast have increased since the harvest moratorium was imposed in 1998. Results to date have been mixed. The relative abundance of juveniles has been monitored for several Atlantic coastal stocks (Spear 2007) and has been found to have increased in the Kennebec River, the Hudson River, and Albemarle Sound. However, relative abundance decreased in the nearshore New Jersey coastal ocean and the Delaware, Rappahannock, York, James, and Altamaha rivers. Abundances of all Atlantic coastal populations remain at relatively low levels.

Recent abundance changes in other sturgeon species have been negative. In Europe, the condition of the single remaining stock of European sturgeon has worsened. Estimated numbers of spawning individuals in the Gironde River, France, declined from 150 in the 1970s to 10 in the 1990s (Lepage, symposium pre-

sentation). Nelson et al. (2007) estimated that white sturgeon of the Fraser River declined from 4% to 10% per year from the mid-1980s to the mid-1990s.

Conclusions and Recommendations

This symposium on anadromous sturgeons provided additional evidence that necessary habitats for each life stage are surprisingly limited with regard to location and areal extent, even though the total area occupied by anadromous sturgeon populations may be immense.

The fresh-brackish water zone had been previously recognized as the prime nursery habitat for Atlantic sturgeon in mid-Atlantic rivers (Dovel and Berggren 1983; Bain 1997; Collins et al. 2000). Symposium papers on the distribution and feeding of Atlantic sturgeon in the St. Lawrence estuary provided a more detailed ecological understanding of this relationship, in which age-0, early juvenile, and older juvenile Atlantic sturgeon were found in the estuarine transition zone associated with a sequence of benthic assemblages corresponding to their primary food. Similar life stage and habitat relationships exist in estuarine transition zones in the Hudson River and South Carolina rivers for Atlantic sturgeon, the Suwannee River for Gulf sturgeon, and the Gironde River for European sturgeon. Considering that the early juvenile life stage is often found to be the most sensitive stage in population models, its spatially limited habitat within estuaries should be designated essential with respect to population survival and given the highest level of protection.

The habitat sequence in the St. Lawrence was shown to be governed by the hydrodynamic properties of a tidally recurrent salt wedge that maintains epi- and suprabenthic amphipods at the freshwater front and oligochaetes within the silt-clay sediment accumulated in its upper portion. Although salinity and hydrodynamic patterns vary among estuaries, they are always the primary determining factors for the benthic community sequence. It is therefore proposed that hydrodynamic models be increasingly used for estuarine transition zones harboring major anadromous sturgeon populations. Such mod-

els would have several important advantages: (1) defining the limits of essential habitats, (2) following annual hydrodynamic changes that modify early juvenile survival and habitat size, (3) predicting sediment impacts for proposed dredging and dumping operations, (4) predicting the extent of hypoxic conditions following upstream changes in flow or water quality, (5) anticipating the effects of global climate change; and (6) providing a powerful tool for integrated management of the river-estuary ecosystem.

Papers from this symposium have demonstrated through detailed bycatch and tracking studies that the nearshore zone is the main oceanic area occupied by subadult and adult anadromous sturgeons. In addition, suitable habitat in the nearshore zone appears limited, as suggested by sturgeon concentrations found repeatedly at the same locations. Finally, the intermixing of distinct sturgeon populations in nearshore wintering areas was generalized within anadromous sturgeons discussed in this symposium. Therefore, we propose that the nearshore oceanic zone should be considered sensitive habitat with regard to bycatch of anadromous sturgeons. Furthermore, sturgeon concentration areas in the nearshore oceanic zone should be designated as essential habitats and protected against habitat disturbance and fishing impacts.

Hypoxia, caused in some estuaries by limited water exchange between river and ocean, was identified as a major threat to estuarine sturgeon habitats. Hypoxia is often enhanced by excess nitrogen inputs and in many cases also depends on dam-controlled flows. This chain of effects points to the value of integrated management of whole river-estuarine basins, including restoring water quality and habitat connectivity. Because of their life history characteristics, reliance on many different habitats, and high iconic value as ancient fish, anadromous sturgeons should be formally adopted as quality indicators of large river-estuary-nearshore systems.

Some of the most important advances in habitat knowledge provided by this symposium were obtained through ultrasonic and satellite tagging and tracking studies. More such stud-

ies are urgently needed as they are the most efficient means to delineate important habitats and migration patterns. Moreover, integrated programs that combine sturgeon tracking with hydrodynamic models as well as benthos and feeding regime studies should be favored to develop a more complete ecological knowledge of important habitats.

The population models presented in this book showed great utility in identifying key life stages, predicting population size, and evaluating alternate management options. Given the improving knowledge of habitat requirements by life stage, models incorporating habitat and population dynamics by life stage are worth consideration. Such models, which can be built up iteratively with increasing amounts of data, have proven useful in identifying sensitive life stages and limiting habitats.

The symposium participants gave much attention to monitoring population levels and trends, and arrived at a consensus that the early juvenile stage is the best life stage to sample and that the oligohaline zone is the best location for such sampling. Much experience in the capture of early juveniles came out of the symposium studies. Drifting gill nets and bottom trawling produced the highest capture levels, with the choice of gear depending mostly on the size of the estuary, bottom configuration, current, and frequency of obstacles on the bottom.

Our conclusions regarding the current trends of anadromous sturgeon populations are generally pessimistic. While some populations have been found to or show indications to have increased, most appear to remain in precarious condition. This assessment, agreed upon by an ensemble of researchers on anadromous sturgeons, should encourage management authorities to consider additional protection measures for essential habitats and adopt integrated management plans for water flow and water quality of whole river systems.

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