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Use of pop-up satellite archival tags to identify oceanic-migratory patterns for adult Atlantic Sturgeon, *Acipenser oxyrinchus oxyrinchus* Mitchell, 1815

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Summary

Oceanic-migratory behavior of adult Atlantic Sturgeon, *Acipenser oxyrinchus oxyrinchus*, was examined using pop-up satellite archival tags (PSAT). Twenty-three Atlantic Sturgeons were caught and tagged with PSATs in the Hudson River, New York during 2006 and 2007. Fifteen of those fish returned to the ocean (with PSATs attached) 6–132 days after tagging. These PSATs remained attached to fish for a period of 108–360 days archiving light, temperature, and depth, before releasing from fish, ascending to the surface, and transmitting data to satellites. The location of PSATs was measured to within ±150 m by satellites using Doppler shift of radio transmissions within hours after tags reached the surface. Positions prior to pop up were initially estimated using only archived-light data and the tag manufacturers' proprietary software. Positional error associated with light-based estimates is high, especially with regard to latitude. This error was reduced by applying depth, distance, and temperature filters. Thirteen of the 15 Atlantic Sturgeons that left the Hudson River with PSATs attached remained within the Mid-Atlantic Bight for up to 1 year after tagging. Their geographic distributions generally extended from Long Island, New York to Chesapeake Bay at depths between 5 and 40 m. Aggregation areas were identified off southwest Long Island, along the New Jersey coast, off Delaware Bay, and off Chesapeake Bay. Depth distribution was seasonal; fish inhabited deepest waters during winter and shallowest waters during summer and early fall. Two Atlantic Sturgeons traveled outside of the Mid-Atlantic Bight. One migrated north to Cobequid Bay (terminal end of the Bay of Fundy, Nova Scotia), whereas the other traveled south to the coast of Georgia.

Introduction

The Atlantic Sturgeon, *Acipenser oxyrinchus oxyrinchus* Mitchell, 1815, is an anadromous fish that currently inhabits 32 river systems and spawns in 14 river systems in North America (Pikitch et al., 2005). A status review (ASSRT, 2007) identified five Distinct Population Segments (DPS) for Atlantic Sturgeon that are genetically and ecologically distinct. On January 6, 2010, the National Marine Fisheries Service (NMFS) announced their intent to prepare a determination on whether to list Atlantic Sturgeon as endangered under the U.S. Endangered Species Act, or as an alternative, to list each DPS separately as either threatened (Gulf of Maine and South Atlantic Bight DPSs) or endangered (New York Bight, Chesapeake Bay, and Carolina DPSs; NOAA, 2010).

Understanding the distribution and habitat utilization patterns of Atlantic Sturgeons in the ocean is an important step in their recovery. Even though Atlantic Sturgeons spawn in fresh water, adults and sub-adults spend a considerable portion of their lives in coastal waters along the U.S. and Canadian east coasts (Collins and Smith, 1997; Stein et al., 2004a; ASSRT, 2007; Laney et al., 2007; Munro et al., 2007; Savoy, 2007) where they are subject to bycatch mortality by commercial fisheries (Collins et al., 1996; Armstrong and Hightower, 2002; Trencia et al., 2002; Stein et al., 2004b; Spear, 2007), directed harvest by commercial fisheries in Canada (Trencia et al., 2002), poor water quality in certain bays (Collins et al., 2000; Dadswell, 2006) and other potential threats (ASSRT, 2007; Munro et al., 2007). Unfortunately, the habitats and migratory patterns utilized by Atlantic Sturgeons during this oceanic phase are largely unknown, especially on a DPS-specific basis. Some aggregation areas and recapture locations for Atlantic Sturgeons have been identified using fishery-dependent data (e.g. Collins et al., 1996; Collins and Smith, 1997; Stein et al., 2004a; Laney et al., 2007; Savoy, 2007). However, use of fishery-dependent data (including research fishing) typically underestimates the extent of the habitats occupied by fishes (Hunter et al., 2004, 2005), which will ultimately underestimate impacts of potential threats (e.g. fishing) to Atlantic Sturgeon stocks. Furthermore, it is uncertain whether different DPSs mix or remain separate while in the ocean.

The objective of this research was to examine the movements of adult Atlantic Sturgeons after leaving the Hudson River, New York. The Hudson River currently represents the most significant spawning system for the New York Bight DPS. To describe the geographic distribution of adult Atlantic Sturgeons, we utilized pop-up satellite archival tags (PSATs; Teo et al., 2004; Domeier et al., 2005; Schaefer et al., 2007), a fishery-independent method.

Methods

Twenty-three adult Atlantic Sturgeons ranging in sizes from 1.5 to 2.4 m TL (Table 1) were caught in the Hudson River, New York (Fig. 1) using bottom gillnets and tagged during

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Table 1
Data associated with Atlantic Sturgeons that were caught and tagged in the Hudson River, New York with PSATs during 2006 and 2007. Data includes: sex (1 = male, 2 = female), total length (TL, m), and fork length (FL, m). The date that fish left the Hudson River was estimated using PSAT data. U = unknown

Fish no.	PSAT no.	Sex	TL	FL	Date tagged	Date left river	Programmed pop-up date	Actual pop-up date
1	65720	1	1.92	1.68	5/23/06	NA	11/30/06	<6/24/06
2	65722	1	2.00	1.77	7/5/06	NA	11/30/06	8/21/06
3	66461	1	2.09	1.91	5/26/06	10/5/06	11/30/06	11/30/06
4	65733	1	1.84	1.63	5/23/06	U	2/15/07	U
5	65723	1	1.92	1.71	7/5/06	8/6/06	2/15/07	11/22/06
6	65724	1	1.98	1.73	6/19/06	7/4/06	2/15/07	1/13/07
7	65734	1	2.01	1.80	6/20/06	7/3/06	2/15/07	2/15/07
8	65725	1	1.93	1.60	5/25/06	NA	3/15/07	<7/8/06
9	65721	2	2.42	2.12	6/28/06	U	6/1/07	U
10	66462	2	2.08	1.82	6/19/06	7/6/06	6/1/07	2/1/07
11	41265	1	1.91	1.73	6/27/07	7/5/07	12/15/07	10/13/07
12	41261	1	1.87	1.65	7/10/07	9/22/07	12/15/07	12/15/07
13	41273	1	1.70	1.45	8/1/07	9/22/07	12/15/07	12/15/07
14	41279	1	1.52	1.31	7/31/07	U	2/15/08	U
15	41291	1	1.75	1.58	7/27/07	U	2/15/08	U
16	41293	1	1.94	1.75	6/21/07	9/20/07	2/15/08	2/15/08
17	41306	1	1.66	1.44	7/26/07	U	3/15/08	U
18	41307	1	1.74	1.49	6/27/07	9/27/07	3/15/08	3/15/08
19	41310	2	2.08	1.92	7/13/07	7/19/07	6/15/08	11/25/07
20	41308	1	1.80	1.60	7/26/07	10/16/07	6/15/08	6/15/08
21	41444	1	2.01	1.74	6/21/07	9/22/07	6/15/08	6/15/08
22	41475	2	2.24	1.97	7/30/07	9/17/07	6/15/08	6/15/08
23	41477	U	2.41	2.16	6/28/07	9/10/07	6/15/08	6/15/08

Fig. 1. Map of the study area. Adult Atlantic Sturgeons were caught and tagged with PSATs in the Hudson River, New York during 2006 and 2007. Nine major coastal rivers (black lines) and the 50-m contour (gray line) are shown

spring and summer months of 2006 and 2007. Nets measured 92 m (length) by 2.4 m (height) and were comprised of meshes ranging from 31 to 36 cm stretched between knots. Sets were made and retrieved within individual slack tides from Stony Point, river kilometer (rkm) 56 to Catskill at rkm 182 (Fig. 1). Most sturgeons were caught and tagged near Norrie Point between rkm 129 and 135.

All individuals were tagged with PSATs manufactured by either Wildlife Computers (Mk10; length = 175 mm, weight = 75 g) or Microwave Telemetry (PTT-100; length = 122 mm, weight = 68 g). These tags were attached to 180-kg (tensile strength) monofilament that was passed through the base of the dorsal fin using a tagging needle (Erickson and Hightower, 2007). These individuals were measured to the nearest cm [total length (TL) and fork length (FL)], and sexed by either gonadal biopsy or by applying pressure to the abdomen, causing the release of milt or eggs (Table 1). The PSATs were programmed to release (pop up) from fish on specific days (Table 1), when they transmitted actual (Microwave Telemetry) or summarized (Wildlife Computer) data to the ARGOS satellite system within hours of reaching the surface. Positions of the PSATs while on the surface were measured to within ±150 m by the ARGOS-satellite system using the Doppler shift of the radio transmissions. These transmissions were managed by CLS America, who relays the information to the researcher.

In 2006, 10 adult Atlantic Sturgeons were tagged with the PSATs manufactured by Wildlife Computer (Table 1). These tags measured temperature (±0.05°C), depth (±0.5 m), and light (irradiance per cm^2 at a wavelength of 550 nm in logarithmic units) every minute. The PSATs were programmed to pop up and transmit data on 30 November 2006 (n = 3), 15 February 2007 (n = 4), 15 March 2007 (n = 1), and 1 June 2007 (n = 2). Temperature and depth data were summarized into thirteen bins prior to satellite transmission. Data were received as the proportion of time spent within each bin during 6-h periods (04.00, 10.00, 16.00, and 22.00 GMT). Upper limits for temperature bins (°C) were 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, and >26. Upper limits for depth bins (m) were 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 150, 200, and >200. In addition, these tags transmitted minimum and maximum water temperatures observed at the most extreme depths (i.e. at minimum and maximum depths) during each 6 h period (=PDT data). In 2007, 13 adult Atlantic Sturgeons were tagged with the PSATs manufactured by Microwave Telemetry (Table 1). These tags recorded depth (±2.7 m), temperature (±0.05°C), and light once every 15 min to once every hour, depending on data-storage requirements. The PSATs were programmed to pop up on 15 December 2007 (n = 3), 15 February 2008 (n = 3), 15 March 2008 (n = 2), and 15 June 2008 (n = 5). Actual data recorded by these PSATs were transmitted to satellites.

The approximate date that Atlantic Sturgeons departed the Hudson River was estimated by comparing water temperatures recorded by PSATs and water temperatures recorded by a USGS gaging station located at approximately rkm 109 near Poughkeepsie, NY (USGS 01372058; Fig. 1). We assumed that an abrupt divergence in water temperatures between the two devices represented the approximate moment that individuals entered marine waters. Daily average temperatures and depths recorded by PSATs were analyzed to identify seasonal patterns for adult Atlantic Sturgeons while in the ocean. To ensure that fish were in the ocean for these analyses, we added 7 days to our estimated date that fish entered marine waters. Analysis of variance (ANOVA) was used to test for differences in temperature and depth among seasons and among PSATs using SAS (SAS Institute Inc., Cary, NC). The General Linear Model (GLM) procedure was applied. Independent variables were season, PSAT, and their interaction.

Pop-up locations were estimated with high accuracy by the ARGOS satellite system (±150 m). Light-based relocations prior to pop up, however, can be extremely variable (error may exceed hundreds of miles). Errors for these relocations are substantially higher for latitude (estimated using day length) than for longitude (estimated using the time at midday or midnight). Hence, we implemented methods introduced by other researchers (e.g. Teo et al., 2004; Domeier et al., 2005; Schaefer et al., 2007) to reduce error associated with light-based relocations. Horizontal movement patterns of Atlantic Sturgeons were analyzed using ArcGIS (ESRI®ArcGIS™). Light-based longitude estimates provided by the PSATs (±0.5°) were used to establish initial constraints for all possible fish locations on a daily basis. Latitudinal bounds for these daily relocations were user defined at 20–55°N latitude. A series of filters were subsequently applied to the relocations to reduce error. The initial filter applied to the 1°W × 35°N longitude-latitude clips was to eliminate all light-based longitude estimates that were separated by unreasonable distances. We applied a modified forward and backward iterative process described by McConnell et al. (1992) to eliminate all relocations that exceeded a daily movement rate of 2°W longitude to conservatively account for maximum sustained swimming speeds of sturgeons and our defined error associated with light-based longitudinal estimates (±0.5°). Others have applied distance filters of 2° longitude to eliminate unreasonable relocations for other aquatic species (e.g. Teo et al., 2004). The extent of the remaining 1°W × 35°N clips was further reduced by selecting bathymetric pixels (NGDC 3 Arc-Second Coastal Relief Model, http://www.ngdc.noaa.gov/mgg/coastal/) that were within minimum and maximum daily depths recorded by PSATs. This step required the assumption that sturgeons migrate near the ocean substrate, which is supported by catches in bottom trawls (Stein et al., 2004a; Erickson and Hightower, 2007; Laney et al., 2007) and sink gill nets (Stein et al., 2004a). All other bathymetry pixels within the original 1°W × 35°N clip were dropped. The third filter applied to the remaining range of the relocations required that sea surface temperatures (SST) and PSAT-recorded temperatures were similar. The purpose of this filter was to verify results and reduce variation. Pixels identified from the previous steps were retained only if corresponding SST data was within minimum (−0.5°C) and maximum (+0.5°C) temperatures recorded by PSATs at the shallowest daily depths (i.e. nearest the surface). Sea surface temperatures were 8-day mean composites recorded at night from the moderate resolution imaging spectroradiometer (MODIS; http://poet.jpl.nasa.gov/). Resolution for SST was 4 km and 0.1°C. The remaining pixels identified by the filter processes were converted to points and considered potential relocations. To condense these many relocations into a single daily location, their mean latitude and longitude were calculated and used in subsequent analyses. The fourth and final filter was to exclude all relocations that were unrealistically separated in the north-south direction. This was accomplished by eliminating latitudinal differences that exceeded 1°N per day using a modified version of the forward and backward iterative process described by McConnell et al. (1992). Teo et al. (2004) applied a 1°N constraint to filter unrealistic movements for other fish species.

Relocations were mapped in GIS to visualize the movement patterns of individuals. A kernel density analysis was performed on pooled data using the Kernel Density tool in the Spatial Analyst extension of ArcGIS. This function calculates the magnitude per unit area from points. Darkest patterns represent the highest densities per unit area.

Results

Sixty Atlantic Sturgeons were caught and measured (1.52–2.41 m TL) in the Hudson River, New York during May, June, July, and August of 2006 and 2007 (Fig. 1). Fifty-three were male, five were female, and one was not sexed. The PSATs were attached to a subset of these fish (18 male, four female, and one unknown sex; Table 1), all of which were caught in fresh water (Fig. 1). The size distribution of fish tagged with PSATs (Table 1) was similar to the length-frequency distribution of all Atlantic Sturgeons caught during the 2 years of field work (Fig. 2).

In all cases where PSAT data were available, PSAT-temperatures emulated river temperatures recorded by the USGS gaging station for an extended period of time until PSAT temperatures dropped below river temperatures (Fig. 3). This divergence in temperatures between the two recording devices was observed during summer and fall months for 15 of 23 tagged individuals. The remaining PSATs either detached prematurely before fish left the river or were never heard from (Table 1). The dates that tagged individuals entered the ocean, estimated using these temperature data, ranged from 3 July to 16 October (Table 1), when river temperatures recorded by the USGS gaging station were between 22 and 20.7°C. The maximum river-water temperatures recorded by the USGS gaging station during 2006 and 2007 were 28.5 and 27.5°C respectively. Time spent in the river by Atlantic Sturgeons after tagging ranged from 6 to 132 days (mean = 55 days). The PSATs remained attached to these fish for a total of 108–360 days after tagging.

Oceanic-depths inhabited by tagged individuals (Figs 4 and 5) were analyzed beginning 7 days after the estimated departure date from the Hudson River. The monthly patterns of mean-daily depths occupied by Atlantic Sturgeons were similar for 13 of 15 tagged individuals during 2006–2008 (Fig. 4).

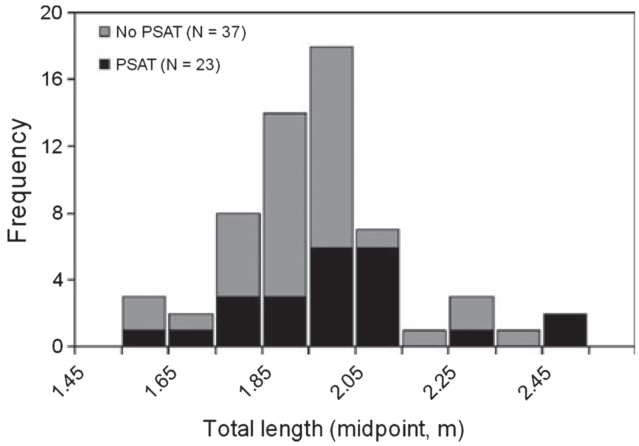

Fig. 2. Total length (m) of Atlantic Sturgeons caught using gill net in the Hudson River, New York during 2006 and 2007. Fish tagged with PSATs are shown in black, whereas all other Atlantic Sturgeons caught during this study are shown in gray. Total lengths are shown in 10 cm bins. A midpoint of 1.45 represents values ranging from 1.40 to 1.49

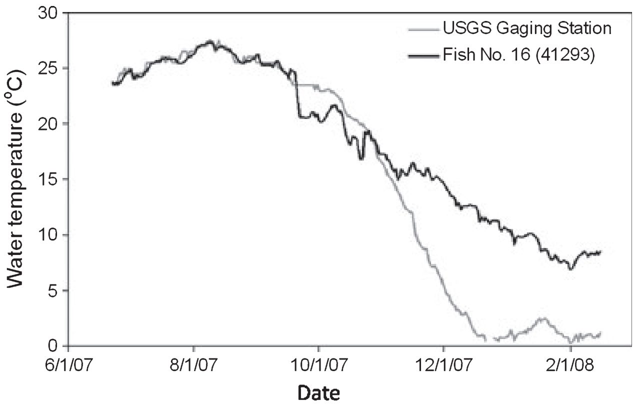

Fig. 3. Daily maximum water temperatures in the Hudson River recorded by a USGS gaging station (No. 01372058) at Poughkeepsie, NY (gray line) and daily maximum water temperatures recorded by a PSAT for fish no. 16. The PSAT was attached to the adult Atlantic Sturgeon while in the Hudson River. This fish left the Hudson River and entered the ocean on approximately 20 September 2007, when the two temperatures initially diverge

Mean-daily depths typically ranged from 5 to 35 m, and never exceeded 40 m. Mean depths occupied by these sturgeons were significantly different among quarters (ANOVA; $F = 161$. d.f. = 3, $P \leq 0.001$). Atlantic Sturgeons occupied the deepest waters during winter and early spring (December–March) and shallowest waters during late spring to early fall (May–September). Quarterly-mean depths (Table 2) ranged from 9.9 m during the third-calendar quarter to 24.4 m during the first-calendar quarter. Two fish (Fig. 5) utilized depths during winter months that differed from sturgeons shown in Fig. 4. Although depth patterns were similar during summer and fall months between these two fish (Fig. 5) and the thirteen other fish carrying PSATs (Fig. 4), mean-daily depths during December and January were shallower for fish no. 10 (5–15 m) and deeper for fish no. 22 (35–70 m) relative to depths shown in Fig. 4. The deepest water occupied by fish no. 22 was 92 m during December (Fig. 5).

Water temperatures occupied by adult Atlantic Sturgeons while in the ocean (Table 3) were examined beginning 7 days after the estimated-departure date from the Hudson River. Mean-monthly water temperatures ranged from 8.3°C in February to 21.6°C in August for the 13 fish that exhibited similar depth distributions. Minimum and maximum water temperatures inhabited by these fish were 6.8°C during January and February and 23.9°C in August. The two sturgeons that exhibited different winter-depth distributions (Fig. 5) relative to the remaining 13 sturgeons carrying PSATs (Fig. 4) also inhabited different water temperatures during the winter. Water temperatures inhabited by fish no. 10 were significantly higher than water temperatures inhabited by the remaining 13 sturgeons during December and January (ANOVA; $F = 675$, d.f. = 1, $P \leq 0.001$). Mean-water temperature inhabited by this fish during December and January was 14.7°C, whereas mean temperatures associated with the other 13 sturgeons were 11.3 and 9.0°C during the same months. In contrast, the winter-water temperatures inhabited by fish no. 22 were significantly lower than mean water temperatures recorded for the other 13 sturgeons during December and January (ANOVA; $F = 476$, d.f. = 1, $P \leq 0.001$). Mean water temperatures inhabited by fish no. 22 were 7.9 and 5.3°C during December and January. Mean water temperatures recorded for this fish were even lower during February (2.7°C), March (1.8°C), and April (2.5°C) when this fish occupied

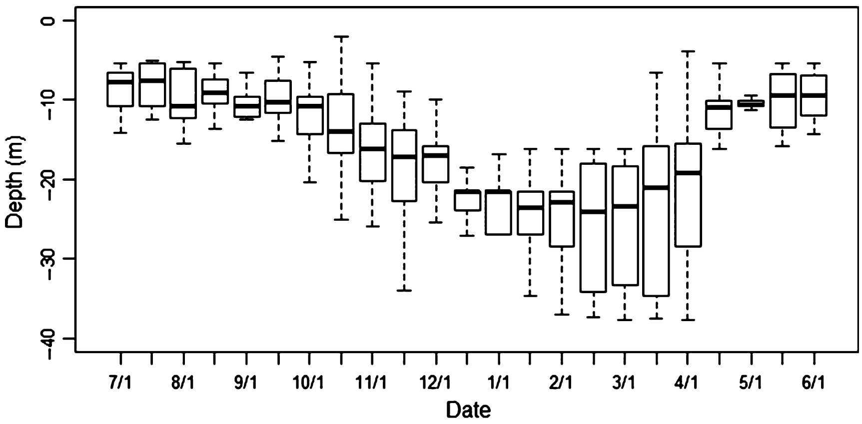

Fig. 4. Bi-monthly box plots of average-daily depths (m) for 13 of 15 Atlantic Sturgeons with PSATs beginning 7 days after leaving the Hudson River and entering the Atlantic ocean. The median is shown by the dark horizontal line. Boxes represent the 75th and 25th percentiles. Whiskers are maximum and minimum values

Table 2
Descriptive statistics for average daily depths occupied by adult Atlantic Sturgeons in coastal waters by quarter (e.g. first quarter = Jan, Feb, and Mar). This analysis was conducted for 13 of the 15 Atlantic Sturgeons that showed similar depth distributions (see Fig. 4) and included data beginning 7 days after the estimated river-departure date (see Table 1)

Calendar quarter	N	Depth (m) Mean	Min	Max	SD
1	335	24.4	6.5	37.6	5.9
2	146	12.9	3.8	37.7	6.9
3	287	9.9	4.5	25.0	3.8
4	701	16.1	2.0	33.9	5.7

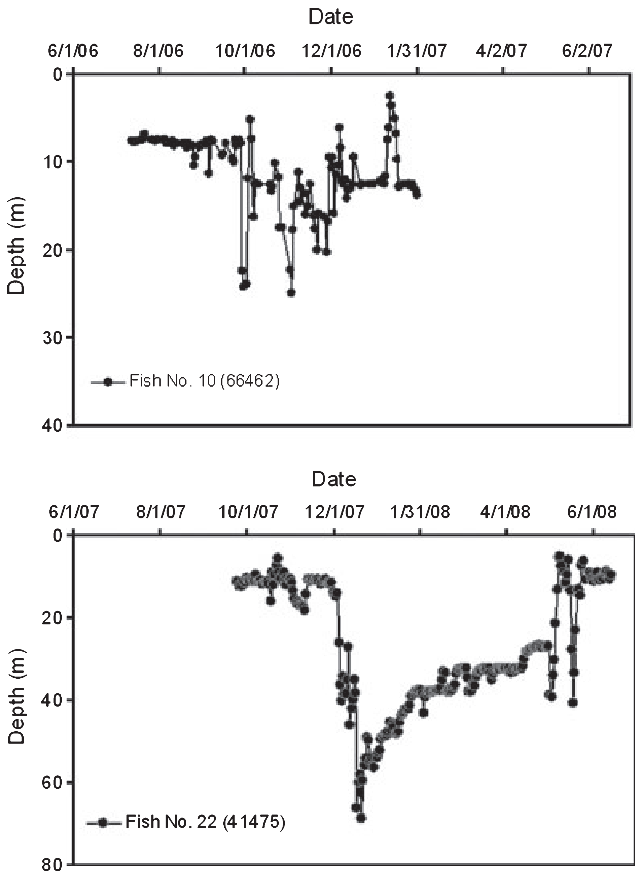

Fig. 5. Average-daily depths (m) for two Atlantic Sturgeons with PSATs beginning 7 days after leaving the Hudson River and entering the Atlantic ocean

depths (Fig. 5) that were similar to maximum depths occupied by the other 13 individuals (Fig. 4).

Ten PSATs released from Atlantic Sturgeons and transmitted data to satellites on the programmed pop-up date (Table 1). Five of these PSATs began transmitting data outside of Chesapeake Bay (Fig. 6) during December, February, and March. Two PSATs popped up near Delaware Bay (Fig. 6) during November and June. The remaining tags popped up during June inside of New York Harbor, in the Hudson River at approximately rkm 57, and at the terminal end of the Bay of Fundy (Cobequid Bay), Nova Scotia. All tags popped up over shallow water (< 40 m) and were near the most recent relocation position when estimates were made within a reasonable amount of time. Examples of pop-up positions relative to relocations for three PSATs are shown in Fig. 7.

Fifteen of 23 PSATs provided relocation data for Atlantic Sturgeons while in the ocean. Ten PSATs provided 458 relocations for the 2007–2008 data set whereas five PSATs provided only 74 relocations for the 2006–2007 data set. Examples of relocations for four of these individual fish are shown in Fig. 7 by calendar quarter. Relocations displayed quarterly trends. Most relocations ranged from Long Island to Delaware Bay during the third and fourth calendar quarters and from Delaware Bay to Chesapeake Bay during the fourth and first calendar quarters. Second-quarter relocations ranged from Chesapeake Bay to Long Island.

Even though one PSAT popped up inside of Cobequid Bay, Nova Scotia on June 15, 2008 (Fig. 6), light-based relocations were available only through December 26, 2007, presumably because either the light sensor became inoperable or because light levels were too low to estimate positions after December 26. The final light-based relocations placed the fish inside of the Mid-Atlantic Bight along the south shore of Massachusetts.

Our data suggest that one sturgeon (fish no. 10), shown to travel no farther south than Cape Hatteras when applying all data filters, may have swam as far south as Georgia (Fig. 8a). The temperature filter resulted in the elimination of a series of relocations south of Cape Hatteras for this fish. Relocations using only depth and distance filters showed that this fish migrated through the South Atlantic Bight to Georgia near the mouth of the Altamaha River (Fig. 8a). Sea surface temperature data in the South Atlantic Bight was sparse during winter months relative to SST data in the Mid-Atlantic Bight, especially for the near shore where waters become

Table 3
Descriptive statistics for average daily water temperatures (°C) occupied by adult Atlantic Sturgeons in coastal waters by month. Calculations included data beginning 7 days after the estimated river-departure date (see Table 1)

	Water temperature (°C)										
	Fish no. 3, 5–7, 11–13, 16, 18–21, 23					Fish no. 22			Fish no. 10		
Month	N	Mean	Min	Max	SD	Mean	Min	Max	Mean	Min	Max
Jan	144	9.0	6.8	11.6	0.9	5.3	4.1	6.3	14.7	12.7	15.8
Feb	111	8.3	6.8	10.5	0.8	2.7	1.9	4.0			
Mar	76	9.4	7.6	12.3	1.1	1.8	1.1	2.2			
Apr	60	10.7	9.0	13.0	1.1	2.5	1.1	2.2			
May	67	13.8	11.2	15.6	0.9	7.9	4.0	12.1			
Jun	30	15.5	10.1	18.4	1.9	13.7	12.0	14.8			
Jul	49	20.6	18.0	22.9	1.4				20.3	18.4	22.1
Aug	104	21.6	17.9	23.9	1.5				21.4	19.0	22.8
Sep	137	20.5	15.0	22.2	1.1	21.9	21.8	22.3	19.9	17.6	21.6
Oct	277	18.5	13.3	22.1	1.6	19.2	14.8	21.5	17.5	14.7	19.0
Nov	263	14.7	10.4	18.6	1.5	13.1	9.9	16.8	15.1	14.1	16.5
Dec	169	11.3	8.5	14.3	1.2	7.9	5.7	11.1	14.7	13.8	17.0

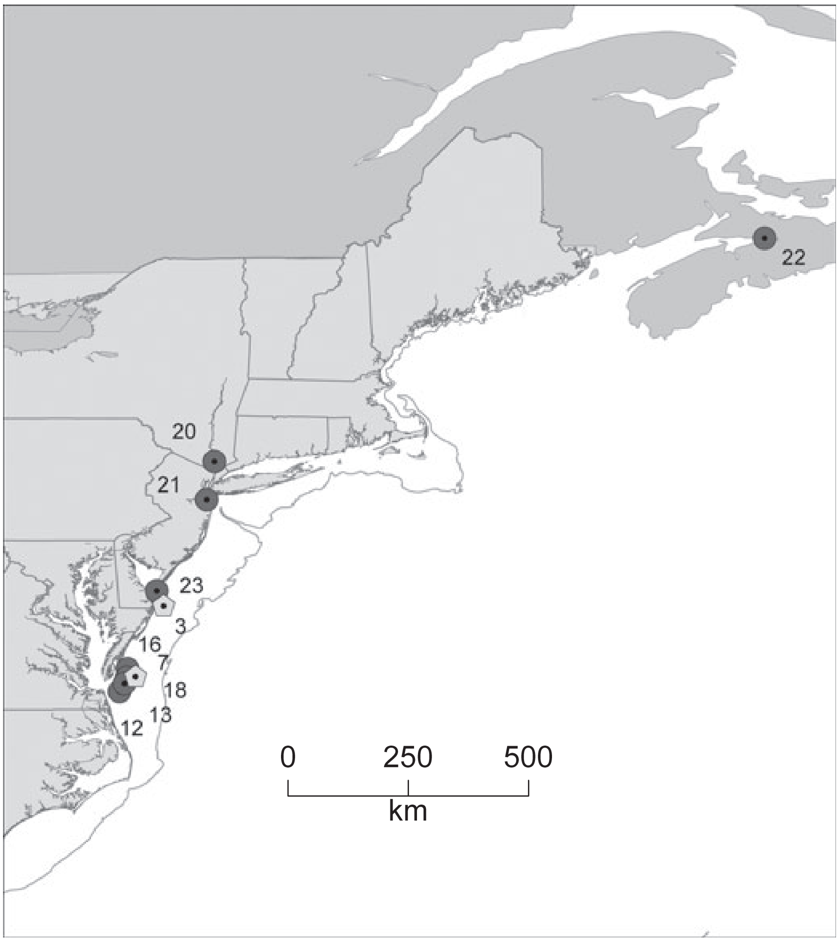

Fig. 6. Pop-up locations of PSATs that were attached to adult Atlantic Sturgeons while in the Hudson River, New York. Pentagons = tags deployed during 2006. Circles = tags deployed during 2007. Fish identification numbers are shown next to pop-up locations (see Table 1). PSATs popped up during November (fish no. 3), December (fish no. 12, 13), February (fish no. 7, 16), March (fish no. 18), and June (fish no. 20, 21, 22, 23). Note that fish number 20 left the Hudson River during 2006 and re-entered the river during 2007, when the PSAT popped up. The 50-m contour (gray line) is shown

progressively cooler relative to deeper waters (Fig. 8b). Some 8-day composites of SST showed gaps that spanned throughout most of the South Atlantic Bight during winter months. Hence, the likelihood of non-matching temperatures between PSAT and SST data is high within the South Atlantic Bight during winter months due to a lack of SST data in the region.

Kernel density analysis was used to identify oceanic-aggregation areas and migratory corridors for adult Atlantic Sturgeons that were tagged in the Hudson River (Fig. 9). Areas of concentration sites within the Mid-Atlantic Bight were similar between 2006–2007 and 2007–2008 data sets, therefore, all relocation data from this region were combined for this analysis (n = 525). The migratory corridor for most Atlantic Sturgeons tagged with PSATs ranged from Long Island to Chesapeake Bay at depths < 40 m. Atlantic Sturgeons tagged with PSATs aggregated off the southwest shores of Long Island, along the New Jersey shoreline, off Delaware Bay, and off Cheseapeake Bay. This data also shows small concentrations of Atlantic Sturgeons within Long Island Sound (Fig. 9).

Discussion

Numerous researchers have successfully used PSATs to track pelagic- and shallow-aquatic species in relatively clear waters using light levels (i.e. day length and time at mid-day; Teo

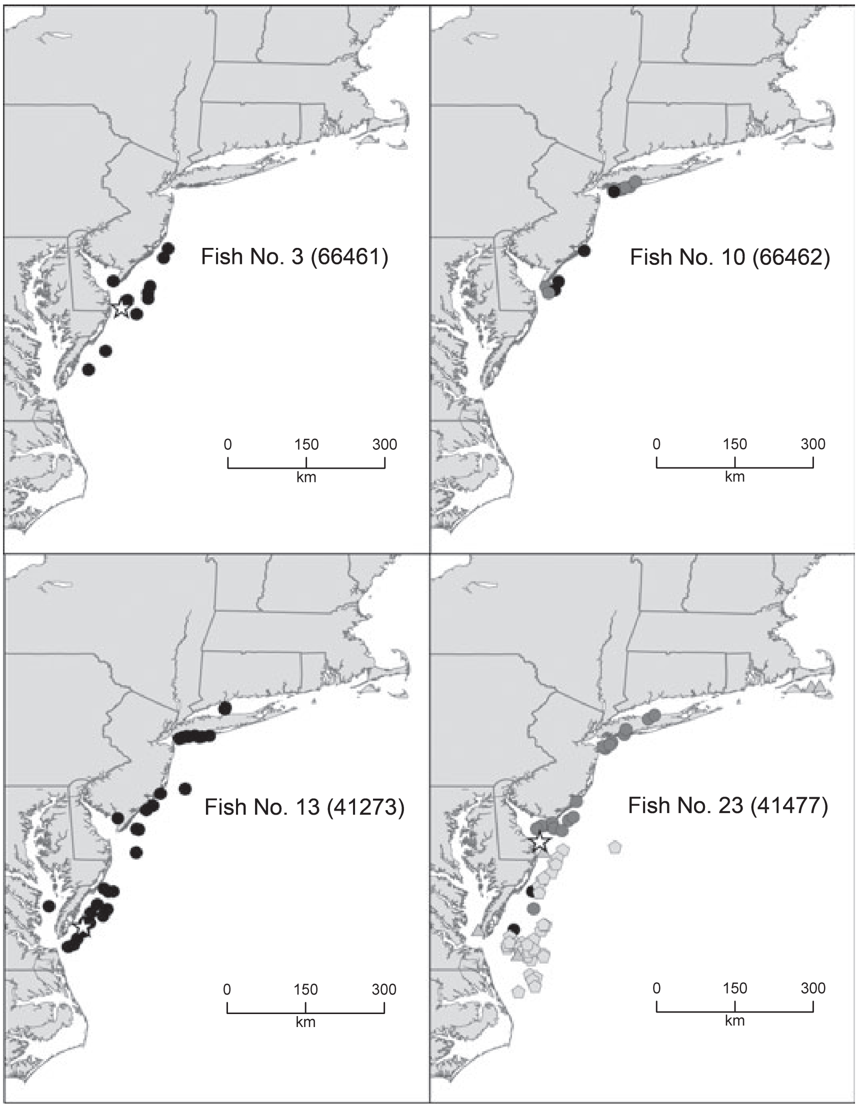

Fig. 7. Relocations and PSAT pop-up locations for Atlantic Sturgeons after leaving the Hudson River, New York. These fish, tagged with PSATs in the Hudson River, entered the ocean during July–October 2006. Relocations were estimated using day length and filtered using depth, distance, and water temperature. Star = pop-up locations. Relocations are shown by calendar quarter: gray circles (= third quarter), black circles (= forth quarter), pentagons (= first quarter), and pyrimids (= second quarter)

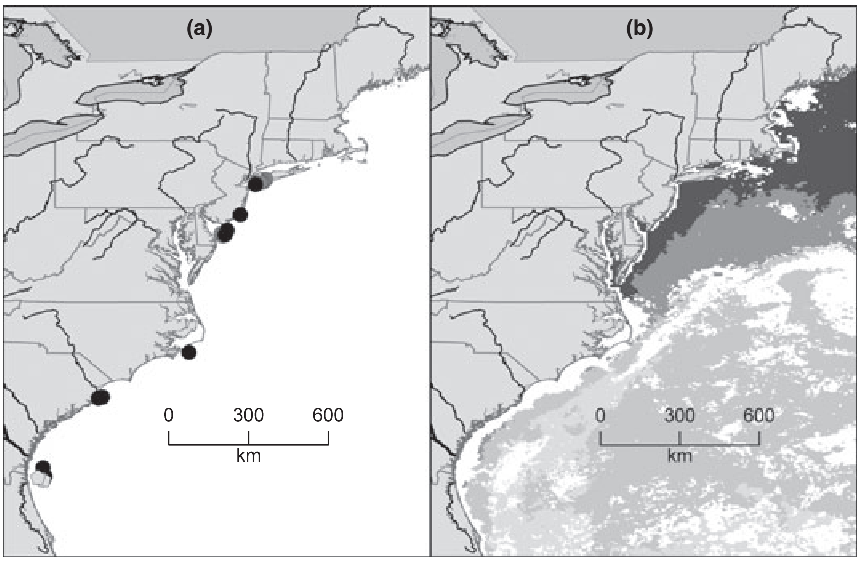

Fig. 8. (a) Relocations for an Atlantic Sturgeon (fish no. 10) carrying a PSAT during 2006 and 2007. Dates associated with the relocation estimates are shown for the fish in both the Mid-Atlantic and South Atlantic Bights. Depth, distance and temperature filters were applied to the PSAT data prior to 11 ⁄ 28 ⁄ 06, whereas only depth and distance filters were applied thereafter. Relocations are shown by calendar quarter: gray circles (= third quarter), black circles (= forth quarter), and pentagons (= first quarter). (b) An example of sea surface temperatures (8-day composite beginning 11 December 2006) used to filter PSAT data. The temperature categories are 5–12 (darkest), 12–19, 19–24, and 24–28°C (lightest). White areas represent no data

et al., 2004; Domeier et al., 2005; Schaefer et al., 2007) or species that consistently remain near the sea bed at somewhat constant depths (i.e. using tidal cycles; Hunter et al., 2004, 2005; Gröger et al., 2007). Examining movements of sturgeons in coastal environments using PSAT technology has been problematic, because this group of fishes may inhabit relatively

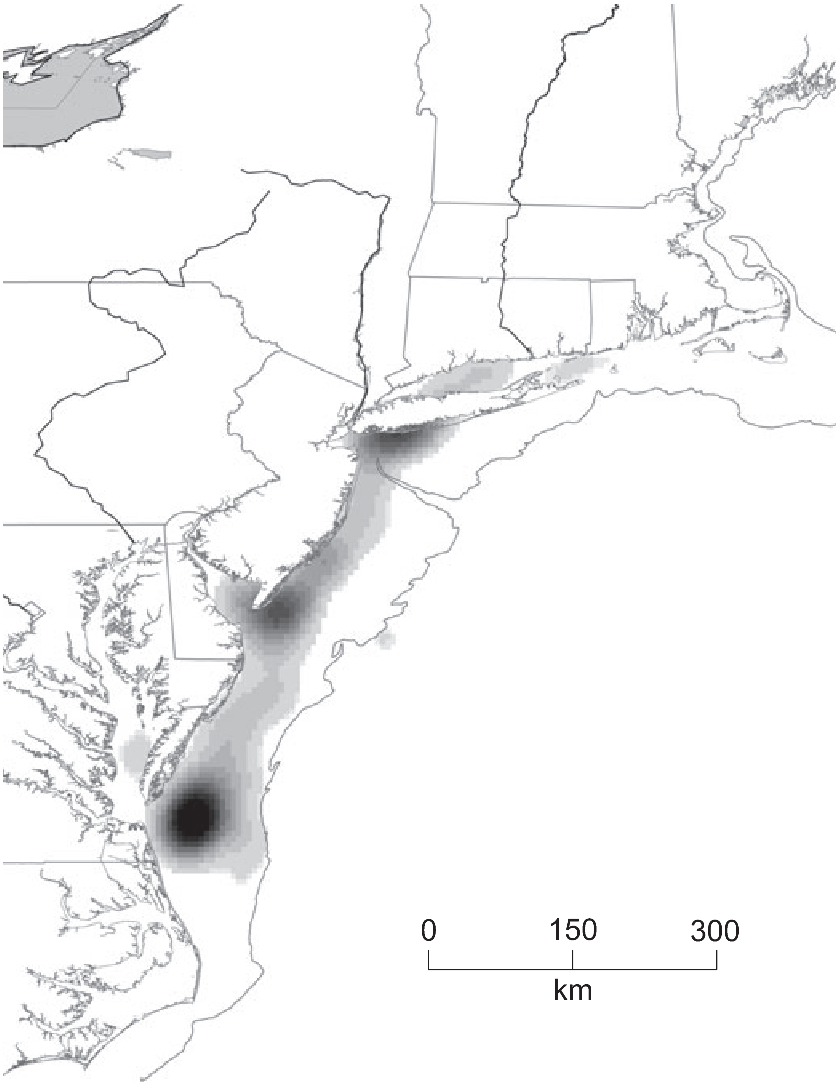

Fig. 9. Kernal analysis demonstrating concentrations and the migratory corridor of adult Atlantic Sturgeons after leaving the Hudson River, New York with PSATs attached. Relocations were estimated using day length and modified using depth, distance, and temperature filters. Darker contours represent higher concentrations. The 50-m contour (black line) is shown

deep and murky waters (Erickson and Hightower, 2007), exhibit frequent depth changes (Erickson and Hightower, 2007; Sulak et al., 2007), and shed external tags at high rates (Edwards et al., 2007). Other researchers who have attempted to use PSATs to describe horizontal movements of sturgeons are Erickson and Hightower (2007) with Green Sturgeons (*Acipenser medirostris*), Edwards et al. (2007) with Gulf Sturgeons (*Acispenser oxyrinchus desotoi*), and Doukakis et al. (2008) with Beluga (*Huso huso*) and Ship Sturgeons (*Acipenser nudiventris*). The PSATs attached to Green Sturgeons were retained by fish for up to 8 months and transmitted large data sets, however, Erickson and Hightower (2007) were unable to provide precise relocations because light levels were too low and inconsistent due to the low-water clarity of the eastern Pacific at the depths occupied by Green Sturgeons. Gulf Sturgeons shed PSATs soon after tagging and therefore did not provide meaningful tracking information (Edwards et al., 2007). Radio-frequency interference in the Caspian Sea region was so severe that Doukakis et al. (2008) recovered almost no useable data from PSATs.

Even though some PSATs used in this study released prematurely or were never heard from, we received oceanic data (relocations, depths, and temperatures) from five of 10 tags for the 2006–2007 field season and from 10 of 13 tags during the 2007–2008 season. More than 500 fishery-independent relocations and 10 pop-up positions were recovered from these PSATs over a 2-year period. We suggest that the use of PSATs and archival tags may identify broader distributions of fishes than fishery- or recapture-dependent methods (e.g. mark-recapture; Hunter et al., 2004, 2005) because active sampling or recaptures of tagged fish depend on the location of sampling and recapture gear. Methods such as sonic telemetry are an improvement, but are still hampered by gear limitations. Lindley et al. (2008) utilized sonic telemetry and arrays of stationary receivers to describe movements of Green Sturgeons in coastal waters of the eastern Pacific from California to the Gulf of Alaska. Although use of sonic transmitters and stationary receivers provided information for movements of these fishes among rivers and bays and in the ocean, results remained dependent on the pre-selected locations for anchoring receivers. Edwards et al. (2007) demonstrated that sonic-tagged sturgeons can be relocated in the Gulf of Mexico by manual tracking, but the extent of these results was limited by pre-selected search locations. Our results suggest that PSAT-technology is an effective means for quickly describing movements and habitat use of Atlantic Sturgeons, and possibly other sturgeon species, in coastal waters. Some combination of sonic telemetry (Edwards et al., 2007; Lindley et al., 2008) and PSAT-technology would provide the most comprehensive and detailed fishery-independent data set for examining movements of sturgeons in coastal waters.

All Atlantic Sturgeons tagged with PSATs during this study were likely adults and part of the Hudson River population (Grunwald et al., 2008) and the New York Bight DPS (ASSRT, 2007). All fish were tagged with PSATs in the freshwater portion of the Hudson River (above the salt wedge) during the spawning season. In most cases, the release of milt and eggs by sturgeons tagged with PSATs provided definitive evidence of maturity. The remaining fish tagged with PSATs were likely mature based on their size (see Dovel and Berggren, 1983; Van Eenennaam and Doroshov, 1998).

Although 13 of 15 Atlantic Sturgeons tagged with PSATs in the Hudson River remained in the Mid-Atlantic Bight, one migrated as far south as Georgia and another as far north as Cobequid Bay, Nova Scotia. This extends the known migratory range for this population of Atlantic Sturgeon. Dovel and Berggren (1983) reported that subadult Atlantic Sturgeons tagged in the Hudson River were recaptured as far north as north of Cape Cod and as far south as south of Cape Hatteras. One Atlantic Sturgeon tagged in coastal waters off North Carolina in an earlier study (Laney et al., 2007) was recaptured in the Hudson River at approximately rkm 127.

We demonstrated that adult Atlantic Sturgeons from the Hudson River spend most time in the Mid-Atlantic Bight, consistent with the results of past studies. Dovel and Berggren (1983) showed that 58 of 60 juvenile sturgeons tagged in the Hudson River were recaptured within the Mid-Atlantic Bight primarily in Delaware Bay and Chesapeake Bay. Four Atlantic Sturgeons that were tagged in Long Island Sound were recaptured between New Jersey to Massachusetts (Savoy and Pacileo, 2003). Finally, mitochondrial DNA analysis demonstrated that more than 97% of subadult Atlantic Sturgeons caught in the Mid-Atlantic Bight were of Hudson River origin (Waldman et al., 1996).

Relocations of PSAT-tagged adult Atlantic Sturgeons tended to concentrate within specific areas in the Mid-Atlantic Bight at depths < 40 m. The densest concentrations of relocations were off Chesapeake Bay, the southwest of Long Island, off Delaware Bay, and off New Jersey. This corresponds with earlier reports. Dovel and Berggren (1983) found that most subadults tagged in the Hudson River were recaptured in Delaware and Chesapeake Bay. Stein et al. (2004a) showed aggregation areas for commercial bycatch of Atlantic Sturgeons off Long Island, the New Jersey Coast, and between Delaware Bay and Chesapeake Bay at depths of 10–50 m. Our PSAT data were also suggestive of smaller aggregations within Long Island Sound, corresponding to areas of highest catches described by Savoy and Pacileo (2003) and Savoy (2007). Even though most PSAT-tagged Atlantic Sturgeons relocated in the Mid-Atlantic Bight were in depths < 40 m, Timoshkin (1968) reported one adult Atlantic Sturgeon caught by trawl at a depth of 110 m in the area of the Hudson Canyon. Indeed, one of our PSAT-tagged individuals reached a depth of 92 m during December while migrating toward the Bay of Fundy. Light-based relocation estimates suggest that this fish was off the south shore of Massachussetts when at its deepest recorded depth. Hence, the most extreme depths reached by adult Atlantic Sturgeons in the Mid-Atlantic Bight may reach 100 m or more. Atlantic Sturgeons enter deeper waters more frequently in the Gulf of Maine where the continental shelf is narrow. Stein et al. (2004a) showed consistent commercial fisheries bycatch to depths of 80 m in the Gulf of Maine.

Horizontal and vertical distributions for adult Atlantic Sturgeons tagged with PSATs exhibited a seasonal pattern within the Mid-Atlantic Bight. During winter and early spring, relocations were concentrated in the southern part of the Mid-Atlantic Bight deeper than 20 m. During summer and early fall, relocations were concentrated in the northern portion of the Mid-Atlantic Bight at depths < 20 m. Smith (1985) discussed a similar seasonal-movement pattern for Atlantic Sturgeons.

We found that one Atlantic Sturgeon, while in the South Atlantic Bight, exhibited a shallower winter-depth distribution than sturgeons in the Mid-Atlantic Bight and the Gulf of Maine. Although Collins and Smith (1997) showed that Atlantic Sturgeons were caught in the ocean off South Carolina from near shore to 40 m during winter and early spring months, they did not provide a depth-distribution of catches. Laney et al. (2007) showed depth distributions for Atlantic Sturgeon catches off the coast of North Carolina that were similar to those described by us in the South Atlantic Bight (< 20 m).

This research demonstrates that the New York Bight DPS (ASSRT, 2007) moves widely through the near shore Atlantic ocean and thus likely mixes with other Atlantic Sturgeon DPSs along the East Coast of the USA. Whether other Atlantic Sturgeon DPSs exhibit the long-range migratory behavior described herein is currently unknown. Satellite tagging described by this manuscript and/or sonic tagging studies (e.g. Lindley et al., 2008) are needed to understand the movements, habitat needs, and threats of the other Atlantic Sturgeon DPSs. These tools should be applied to both subadults and adults because it is possible that habitat preference differs between life stages.

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