Abundance and distribution of Atlantic sturgeon (*Acipenser oxyrinchus*) within the Northwest Atlantic Ocean, determined from five fishery-independent surveys

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Abstract—A lack of knowledge of how oceanic habitat is used by juvenile marine migrant Atlantic sturgeon (*Acipenser oxyrinchus*) is hindering conservation measures directed at restoring severely depleted populations. Identifying the spatial distribution of Atlantic sturgeon is necessary to identify critical habitat and appropriate management actions. We used five fishery-independent surveys to assess habitat use and movement of Atlantic sturgeon during their marine life stage. The size distribution ranged from 56 to 269 cm total length (mean=108 cm). Ninety-eight percent of all Atlantic sturgeon were smaller than 197 cm—a size that indicated the majority were immature. The pattern of habitat use revealed concentration areas and potential migration pathways used for northerly summer and southerly winter migrations. Atlantic sturgeon were largely confined to water depths less than 20 m and aggregations tended to occur at the mouths of large bays (Chesapeake and Delaware bays) or estuaries (Hudson and Kennebec rivers) during the fall and spring and to disperse throughout the Mid-Atlantic Bight during the winter. In most surveys depth, temperature, and salinity were significantly related to the distribution of Atlantic sturgeon. Knowledge of their habitat and movements can be used to devise spatially based conservation plans to minimize bycatch and to enhance population recovery.

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The Atlantic sturgeon (*Acipenser oxyrinchus*) is a long-lived anadromous fish with a historic range from Hamilton Inlet on the coast of Labrador to the Saint Johns River in Florida (Smith and Clugston, 1997). A major commercial fishery once existed throughout the historic range and estimated U.S. landings peaked at 3.3 million kg in 1890 (Smith and Clugston, 1997). Unable to support such intensive fishing, Atlantic sturgeon populations collapsed throughout the eastern seaboard by 1901 (Secor et al., 2002). During the late 1900s, there was a brief re-emergence of the Atlantic sturgeon fishery in New York and New Jersey (Kahnle et al., 2007) and landings peaked at 125,000 kg in the late 1980s (Waldman et al., 1996; Bain et al., 2000). In 1990 the Atlantic States Marine Fisheries Commission (ASMFC) developed a fishery management plan for the conservation and restoration of Atlantic sturgeon in order to restore population levels that would support harvests at 10% of the historical peak landings (ASMFC[1]). With a continued decline in the population, a 1998 ASMFC amendment began a 40-year moratorium in order to protect 20 year classes of spawning females (ASMFC[2]). Currently, Atlantic sturgeon are a candidate species to be listed under the United States Endangered Species Act.

Atlantic sturgeon use river, estuarine, coastal, and oceanic environments at different life stages but spend the majority of their lives in saltwater (Smith and Clugston, 1997). However, information on oceanic habitat use is lacking beyond evidence of broad-scale marine migrations and an exchange of populations among river systems based on tag recaptures (Dovel and Berggren, 1983) and commercial fisheries bycatch data (Stein et al., 2004a, 2004b). Fisheries-dependent data indicate that most At-

[1] Atlantic States Marine Fisheries Commission (ASMFC). 1990. Fishery management plan for Atlantic sturgeon. Fishery management report number 17, 85 p. ASMFC, Washington, D.C.

[2] Atlantic States Marine Fisheries Commission (ASMFC). 1998. Amendment 1 to the interstate fishery management plan for Atlantic sturgeon, Fishery Management report 31, 59 p. ASMFC, Washington, D.C.

lantic sturgeon inhabit shallow inshore areas of the continental shelf (Stein et al., 2004a, 2004b). More recently, some long-term fishery-independent data have revealed that juvenile Atlantic sturgeon use the inshore waters of North Carolina during the winter months (Laney et al., 2007). Additionally, there are a handful of reported cases of Atlantic sturgeon captured in deeper offshore areas (Timoshkin, 1968; Collins and Smith, 1997; Stein et al., 2004a, 2004b). Still, more information is needed to guide management towards the best mechanisms to protect the remaining Atlantic sturgeon.

One contributing factor to the continued decline of Atlantic sturgeon populations is incidental capture of juveniles in non-target marine fisheries (Collins et al., 1996; Stein et al., 2004a). Most of the current bycatch mortality occurs in gill and drift net fisheries (Stein et al., 2004a; ASSRT[3]). Discard mortality from trawl fisheries is hard to estimate because few direct mortalities are observed. Mortality however may be very high due to delayed effects on captured individuals (Davis, 2002; Broadhurst et al., 2006). Because Atlantic sturgeon do not reach maturity until 12–14 years of age and reproductive output increases later in life (Van Eenennaam and Doroshov, 1998), reducing mortality on juveniles is key to restoring depleted populations (Boreman, 1997).

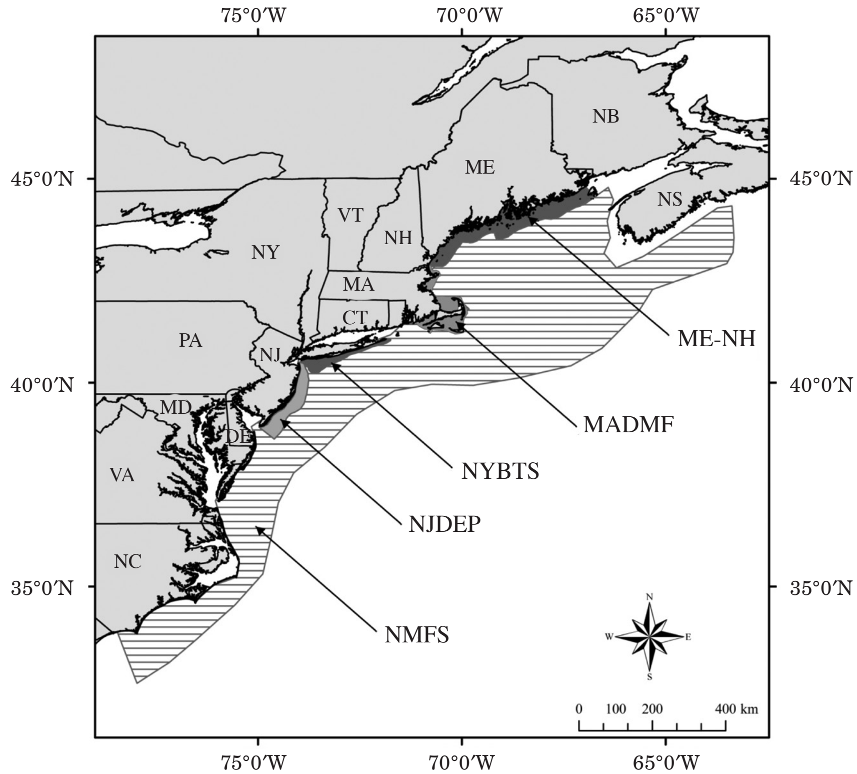

Figure 1

Coverage area of the Maine-New Hampshire inshore bottom trawl survey (ME-NH), Massachusetts Division of Marine Fisheries bottom trawl survey (MADMF), New York bottom trawl survey (NYBTS), New Jersey Department of Environmental Protection finfish survey (NJDEP), and the National Marine Fisheries Service bottom trawl surveys (NMFS). The area covered by the NMFS survey is represented by horizontal stripes. All other surveys are represented by shades of gray.

In order to adequately protect both juvenile and adult Atlantic sturgeon, marine distributional patterns must be identified such that essential habitat may be protected. In this article we use data from five different oceanic fishery-independent surveys to reveal the seasonal distribution, abundance, and habitat use of Atlantic sturgeon along the Northwest Atlantic continental shelf from Cape Hatteras, NC, to the Gulf of Maine (GOM) (Fig. 1).

Materials and methods

We analyzed data from five fishery-independent surveys conducted by the following agencies: 1) National Marine Fisheries Service (NMFS); 2) New Jersey Department of Environmental Protection (NJDEP); 3) Maine Department of Marine Resources and the New Hampshire Fish and Game Department (ME-NH); 4), Massachusetts Division of Marine Fisheries (MADMF); and 5) New York Bottom Trawl Survey (NYBTS) (Fig. 1). Catch per unit of effort (CPUE) was calculated (number of fish per tow) for each survey and depth (m). Depth (m), temperature (°C), and salinity (ppt) data were obtained from the NMFS, NJDEP, and NYBTS databases to estimate environmental preferences. For all surveys, except the MADMF, depth was calculated as the average between the maximum and minimum values. Depth values used in the MADMF analysis are the depth at which the tow started. For all surveys, tows were analyzed for each season, which are defined as winter (21 Dec–20 Mar), spring (21 Mar–20 Jun), summer (21 Jun–20 Sept), and fall (21 Sep–20 Dec). Specifics of each survey are discussed in detail below.

Because male and female Atlantic sturgeon mature at different size ranges (van Eenennaam and Doroshov,

[3] Atlantic Sturgeon Status Review Team (ASSRT). 2007. Status review of Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*), 174 p. Report to National Marine Fisheries Service, Northeast Regional Office, Gloucester, MA, 23 Feb 2007. National Oceanic and Atmospheric Science Administration, Washington D.C.

1998) and because we could not distinguish between gender, we applied female size at maturation to all individuals. Female maturation is reached at a total length of 197 cm (van Eenennaam and Doroshov, 1998).

NMFS bottom trawl survey

These surveys were conducted primarily by the research vessels *Albatross IV* and *Delaware II* where a Yankee 36 bottom trawl with a 1.27-cm mesh liner was towed for 30 minutes at 3.79 knots. Sampling was conducted during the day and night (Sosebee and Cadrin[4]). A total of 300–400 trawls were executed each season from the Gulf of Maine to just south of Cape Hatteras, NC (Fig. 1). Sampling for the NMFS fall survey began in 1963 and the waters of southern New England and the Gulf of Maine were sampled before tows were expanded to include inshore stations in 1973. The NMFS survey was further expanded to include spring samples in 1973. We also used some additional NMFS surveys that were conducted during the winters of 1964–66, 1972, 1978, 1981, and 1992–2007, and summers of 1977–81 and 1993–95.

NJDEP finfish survey

The NJDEP finfish survey began in 1988 and is conducted five times per year in April, June, August, October, and January. A total of 186 tows are conducted each year (39 stations per trip for spring–fall months and 30 stations per trip for winter months). Sampling occurred from NY Harbor to the entrance of Delaware Bay, DE, from 8 to 30 m depth (Fig. 1). A depth-stratified random sampling design was used and a minimum of 10 tows were completed per depth interval (0–10 m, 10–20 m, and 20–30 m). The survey was conducted with a three-to-one two-seam trawl (25-m headrope, 30.5-m footrope) with 12-cm stretched mesh forward netting that tapered down to 8-cm stretched mesh rear netting that was lined with a 6.4-mm mesh codend liner. Tows were conducted at a speed of 3–3.5 knots for a duration of 20 minutes during daylight hours.

ME-NH inshore bottom trawl survey

This survey began in fall of 2000 and primarily covered the inshore waters of Maine and New Hampshire and a depth range of 9–150 m and distance up to 19.3 km offshore (in accordance with the 12-mile territorial limit) (Fig. 1). A total of 115 trawls were attempted each fall and spring. 100 stations were selected on the basis of a depth-stratified, random sampling design and of the 100 stations, 15 were fixed location stations. For this survey a 57–70 modified shrimp trawl (17.37-m head rope, 21.34-m footrope) was used with 5.08-cm stretched mesh and a 2.54-cm stretched mesh liner in the codend. Tows were conducted for 20 minutes at 2.2–2.3 knots during daylight hours.

MADMF bottom trawl survey

Conducted during the spring and fall from 1978–2007, this bottom trawl survey encompassed the Massachusetts inshore waters up to 5.6 km from the boundaries of New Hampshire and Rhode Island (Fig. 1). A ¾ size North Atlantic two-seam otter trawl (head rope 11.9 m, footrope 15.5 m) with a 6.4-mm lined codend was towed at 2.5 knots for 20 min during daylight hours. The survey sampled 100 stations per year selected using a depth-stratified, random sampling design.

New York bottom trawl surveys (NYBTS)

The NY surveys consisted of two surveys—the New York young-of-the-year bluefish survey and the NY trawl survey for subadult Atlantic sturgeon. The sampling area encompassed the waters inshore of a depth of 30 m; the practical inshore limit was 8–10 m from Montauk Point to the entrance of NY Harbor (Fig. 1). For this survey a depth-stratified sampling design was used with strata based on the depth intervals 0–10 m, 10–20 m, and 20–30 m. Tows were randomly selected by using a random number generator and were conducted for a duration of 20 minutes at a tow speed of 3–3.5 knots during daylight hours. The net was a three-to-one two-seam trawl (25-m headrope, 30.6-m footrope) with forward netting of 12-cm stretched mesh tapering down to the rear netting of 8-cm stretched mesh and lined with a 6.0-mm mesh liner within the codend. Because exactly the same gear was used for the surveys, they were combined for the purpose of this analysis. Further differences between the two surveys are described below.

The NY young-of-the-year bluefish survey was initially restricted to the 10- and 20-m depth strata where 10 tows per depth stratum were completed for a total of 20 tows per cruise. Sampling took place June–October in 2005 and August–September in 2006. The survey was confined to the 10-m depth strata in September, October, and November of 2007 when 25, 24, and 27 tows were completed, respectively.

For the NY trawl survey for subadult Atlantic sturgeon, a total of 10 cruises were conducted from October 2005 through June 2007 with 30 tows per cruise distributed within the 10-, 20-, and 30-m depth strata. Sampling months were October, November, January, April, May, and June. A total of 10 tows were completed for each depth. In June 2007, 36 tows were confined to the 10-m depth stratum.

Spatial analysis

Atlantic sturgeon captures were mapped by season with ESRI® ArcGIS™, vers. 9.2 software (ESRI; Redlands,

[4] Sosebee, K. A., and S. X. Cadrin.
2006. A historical perspective on the abundance and biomass of northeast demersal complex stocks from NMFS and Massachusetts inshore bottom trawl surveys, 1963–2002. NEFSC Ref. Doc. 06-05, 200 p. Northeast Fisheries Science Center, National Marine Fisheries Service, Woods Hole Laboratory, 166 Water St., Woods Hole, MA 02543.

CA). Map base layers were obtained from the United States Geological Survey Coastal and Marine Geology Program GIS catalogue. Atlantic sturgeon captures were plotted by using graduated symbols in the following categories: 1, 2, 3–4, 5–10, 11–14, and >15 Atlantic sturgeon per tow.

Habitat preferences

We estimated the habitat preference of Atlantic sturgeon by using the catch-weighted methods of Perry and Smith (1994) for correcting bias that arises in stratified surveys where sampling effort differs between strata. With this method, a comparison of a catch-weighted cumulative distribution of available (all habitat sampled) and occupied (habitat where Atlantic sturgeon were captured) habitat was made and a randomization routine was used to estimate whether the occupied habitat was significantly different from available habitat. Habitat variables analyzed included temperature, dissolved oxygen, and salinity.

The cumulative distribution function (cdf) of the environmental variable was calculated with the following function:

$$f(t)=\sum_h \sum_i \frac{W_h}{n_h} I(x_{hi}), \qquad (1)$$

where W_h = the proportion of the survey in stratum h;
n_h = the number of tows in stratum h;
x_{hi} = the habitat variable in tow i and stratum h; and
I = an indicator function where

$$I(x_{hi}) = \begin{cases} 1, & if\ x_{hi} \le t \\ 0, & otherwise \end{cases} . \qquad (2)$$

The following function relates the catch weighted cdf to the habitat variable:

$$g(t)=\sum\sum \frac{W_h}{n_h}\frac{y_{hi}}{\bar{y}_{st}} I(x_{hi}), \qquad (3)$$

where y_{hi} = the number of fish captured in tow i in stratum h; and
y_{st} = the stratified mean abundance.

The strength of the association is measured by the difference between the available and occupied cdf:

$$\max\left|g(t)-f(t)\right| = \max\left|\sum_h \sum_i \frac{W_h}{n_h}\left(\frac{y_{hi}-\bar{y}_{st}}{\bar{y}_{st}}\right)(x_{hi})\right|. \qquad (4)$$

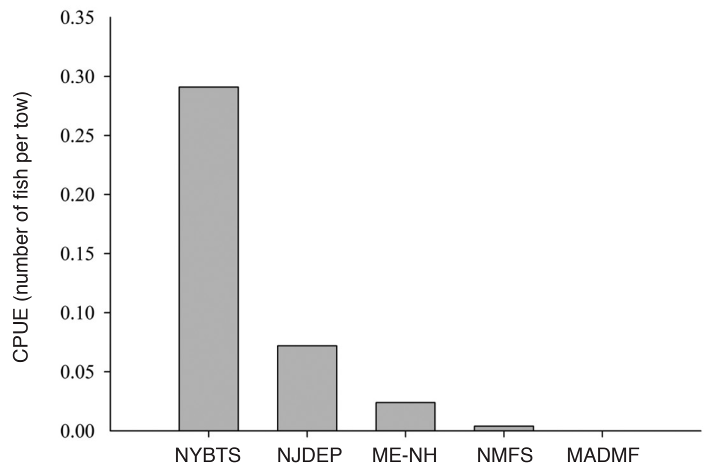

Figure 2

Catch per unit of effort (CPUE) for Atlantic sturgeon (*Acipenser oxyrinchus*) during the New York bottom trawl survey (NYBTS), New Jersey Department of Environmental Protection finfish survey (NJDEP), Maine-New Hampshire inshore bottom trawl survey (ME-NH), National Marine Fisheries Service bottom trawl surveys (NMFS), and Massachusetts Division of Marine Fisheries bottom trawl survey (MADMF).

Significance is determined by randomizing for 1000 trials the pairings of x_{hi} and $(W_h/n_h)\ (y_{hi}-\bar{y}_{st})/\bar{y}_{st})$ and by dividing the number of trials that are greater than the test statistic by the total number of trials.

Results

The NYBTS had the highest CPUE (0.291 fish/tow), followed by the NJDEP finfish survey (0.072 fish/tow), ME-NH inshore bottom trawl survey (0.024 fish/tow), NMFS bottom trawl survey (0.004 fish/tow), and the MADMF bottom trawl survey (<0.001fish/tow), in the latter of which only one Atlantic sturgeon has ever been captured (Table 1; Fig. 2). The details of the CPUE by depth (Fig. 3) and seasonal distribution and abundance (Fig. 4–7) for each survey are reported in detail below. Total length of Atlantic sturgeon captured within the surveys ranged from 56 to 269 cm (mean=108 cm) (Table 2; Fig. 8).

NMFS bottom trawl survey

A total of 107 Atlantic sturgeon were captured in 27,420 bottom trawls (Table 1). The depth distribution of completed tows ranged from 5 to 542 m deep, and 5214 peak tows occurred between 20 and 40 m (Fig. 3A). CPUE of Atlantic sturgeon was highest for the 10-m depth stratum (0.0273/tow) and decreased with each depth interval (Fig. 3A). A total of 71.30% of the Atlantic sturgeon were captured in 20 m or less and no individuals were captured in water deeper than 30 m (Fig. 3A). Atlantic

Table 1

Summary of the surveys effort and Atlantic sturgeon (*Acipenser oxyrinchus*) captures for the New York bottom trawl survey (NYBTS), New Jersey Department of Environmental Protection (NJDEP) finfish survey, National Marine Fisheries Service (NMFS) bottom trawl survey, Maine Department of Marine Resources and New Hampshire Fish and Game (ME-NH) inshore trawl survey, and Massachusetts Division of Marine Fisheries (MADMF) bottom trawl survey. Seasons are defined as winter (21 Dec–20 Mar), spring (21 Mar–20 Jun), summer (21 Jun–20 Sep), and fall (21 Sep–20 Dec).

Survey	Time period	Total number of trawls completed	Total number of Atlantic sturgeon captured	Catch per unit of effort
NYBTS	2005–07	512	149	0.291
	fall	132	46	0.348
	winter	59	4	0.068
	spring	219	73	0.333
	summer	102	26	0.255
NJDEP	1988–2007	3617	261	0.072
	fall	769	74	0.096
	winter	599	74	0.124
	spring	1439	113	0.079
	summer	810	0	0.000
NMFS	1973–2007	27,420	107	0.004
	fall	11,919	26	0.002
	winter	2563	12	0.005
	spring	11,395	68	0.006
	summer	1543	1	0.001
ME-NH	2000–06	1601	38	0.024
	fall	773	31	0.040
	spring	828	7	0.008
MADMF	1978–2007	5563	1	>0.001
	spring	2874	1	>0.001
	fall	2689	0	>0.001

Table 2

Mean, standard deviation, and range of total length (cm) of Atlantic sturgeon (*Acipenser oxyrinchus*) captured in the New York bottom trawl survey (NYBTS), New Jersey Department of Environmental Protection (NJDEP) finfish survey, National Marine Fisheries Service (NMFS) bottom trawl survey, Maine Department of Marine Resources and New Hampshire Fish and Game (ME-NH) inshore trawl survey, and Massachusetts Division of Marine Fisheries (MADMF) bottom trawl survey. Length information includes all recorded lengths over the duration of the entire period of the above surveys.

Survey	Mean total length ±standard deviation (cm)	Range (cm)
NYBTS	112.01 ±27.75	72–215
NJDEP	103.89 ±32.13	52–248
NMFS	113.87 ±40.18	51–269
ME-NH	115.4 ±19.39	76–152
MADMF	78 ±0	—

sturgeon were captured during all seasons but were most abundant during the spring, with an average CPUE of 0.006 fish/tow, followed by winter (0.005 fish/tow), fall (0.002 fish/tow), and summer (0.001 fish/tow) (Table 1).

In the spring, 70.59% of Atlantic sturgeon were captured in Virginia (VA) and NC waters and 23.53% were captured in NY and NJ. One Atlantic sturgeon was captured south of Cape Hatteras and one was captured offshore of northern MA. During winter months captures were evenly distributed from NJ to NC. A total of 42.30% (11 fish) of fall captures occurred off Long Island, NY, whereas 30.76% (8 fish) occurred in the mouth of Delaware Bay, Delaware (DE). In addition three fish were captured in NJ, one fish south of Cape Hatteras, and one fish near Cape Cod, MA. Only one Atlantic sturgeon was captured during this survey in the summer months in NY waters off of Long Island.

NJDEP finfish survey

A total of 261 Atlantic sturgeon were captured within 3617 bottom trawls from 1988 through 2007 (Table 1) at all depths sampled (Fig. 3B). Tow distribution ranged

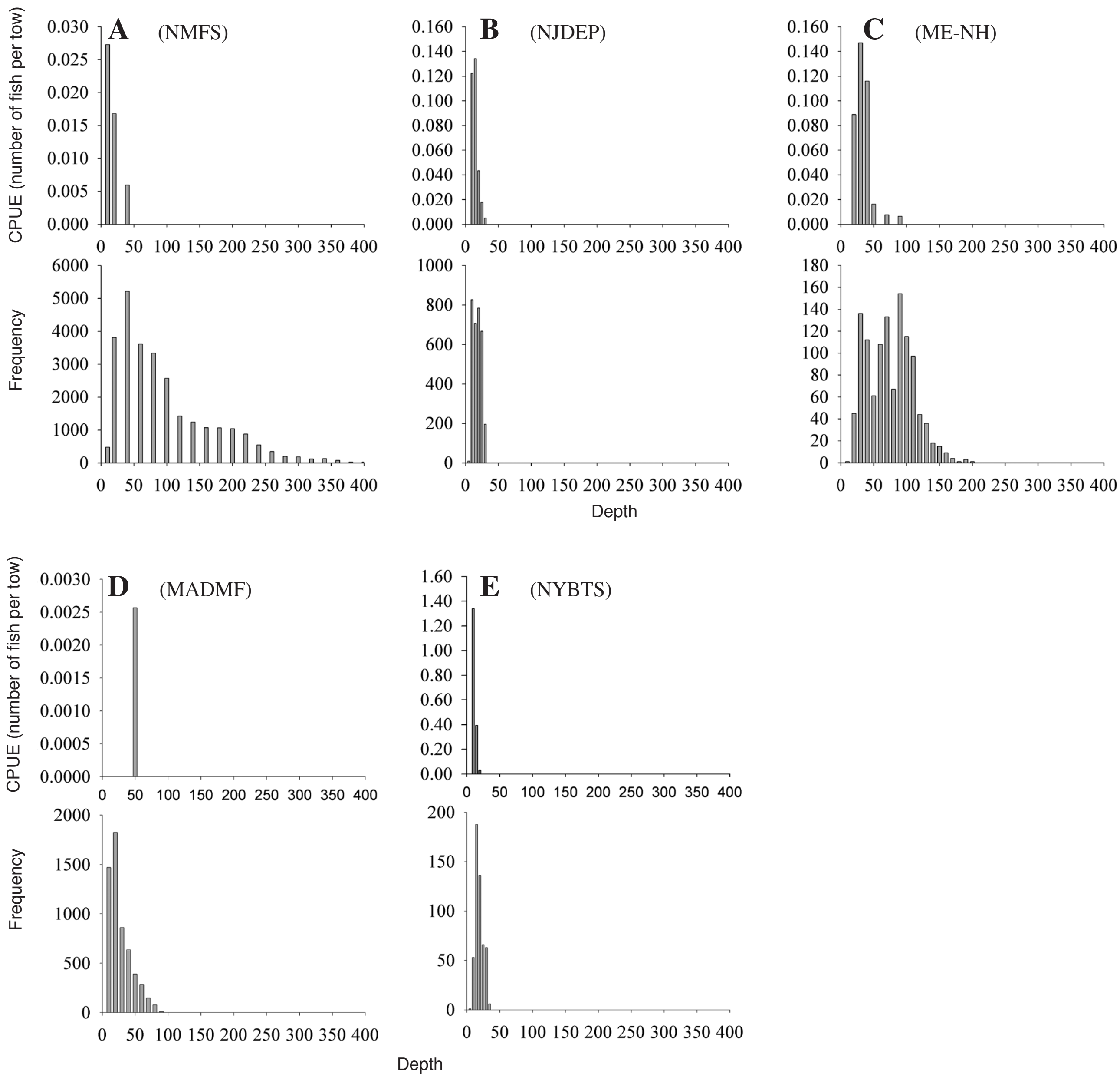

Figure 3

Catch per unit of effort (CPUE) for Atlantic sturgeon (*Acipenser oxyrinchus*) and frequency of tows conducted by depth for the (**A**) National Marine Fisheries Service bottom trawl surveys (NMFS), (**B**) Maine-New Hampshire inshore bottom trawl survey (ME-NH), (**C**) New Jersey Department of Environmental Protection finfish survey (NJDEP), (**D**) New York bottom trawl survey (NYBTS), and (**E**) Massachusetts Division of Marine Fisheries bottom trawl survey (MADMF).

from 5 to 30 m and the majority of the tows occurred within the 10–25 m range (Fig 3B). CPUE was highest for the 10–15 m depth range (0.134 fish/tow) and lowest for 20–30 m range (0.005 fish/tow) (Fig. 3B). A total of 94.78% of all captures occurred in depths less than 20 m (Fig. 3B). CPUE was highest for the winter months (0.124 fish/tow) followed by fall (0.096 fish/tow) and spring (0.079 fish/tow) (Table 1). No Atlantic sturgeon were captured during the summer months (Table 1). During the winter, 74 Atlantic sturgeon were captured of which 67 were captured off northern NJ and of that number, 59 were taken within a small area outside Sandy Hook, NJ. Three fish were captured at 0–20 m depth outside of Delaware Bay, DE. During the fall season, 74 Atlantic sturgeon were captured of which 92% (68 fish) were taken north of Little Egg Inlet, NJ. Of

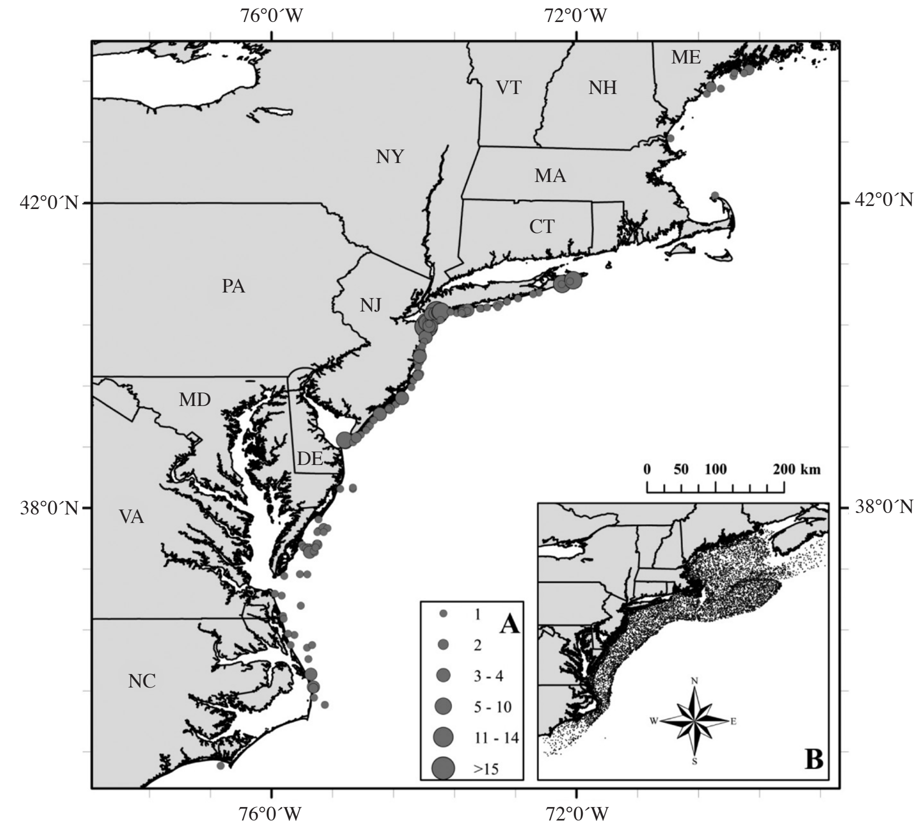

Figure 4

Number of captures of Atlantic sturgeon (*Acipenser oxyrinchus*) from all surveys during spring months. Circle size corresponds to total number of Atlantic sturgeon captured at a given location (insert **A**). Locations of all tows can be seen in insert **B**.

the total Atlantic sturgeon captured, 64% (48 fish) were captured off northern NJ. Captures within the spring occurred along the entire coast of NJ and 44.2% of the captures occurred in Sandy Hook, NJ.

ME-NH inshore bottom trawl survey

A total of 38 Atlantic sturgeon were captured in a total of 1601 bottom trawls from 2001 through 2006 (Table 1). Sampling depths ranged from 10 to 200 m, and three defined peaks in sampling effort occurred at 30 m, 65 m, and 90 m (Fig. 3C). All Atlantic sturgeon were captured between 15 and 90 m depth (Fig. 3C) and 36 of the 38 Atlantic sturgeon were captured near the Kennebec estuarine complex (Fig. 9A). Two additional Atlantic sturgeon were captured south of the Kennebec River, closer to the Saco River.

MADMF bottom trawl survey

Only one Atlantic sturgeon was captured in a total of 5563 bottom trawls (Table 1). Sampling depths ranged from 4 to 86 m, and a peak in sampling effort occurred at a depth of 20 m (Fig. 3D). The only Atlantic sturgeon captured was collected during the spring at a depth of 41 m.

NYBTS

A total of 149 Atlantic sturgeon were captured in 512 random stratified tows (Table 1). Sampling depths ranged from 5 to 35 m and a peak in sampling effort occurred at a depth of 15 m (Fig. 3E). Atlantic sturgeon were captured within all months sampled; however, no Atlantic sturgeon were captured deeper than 20 m. A total of 85% of all Atlantic sturgeon were captured between 5 and 10 m with a mean CPUE of 1.34 (Fig. 3E). CPUE was highest during the fall (0.35 fish/tow) followed by spring (0.33 fish/tow) and summer (0.26 fish/tow) and was lowest during the winter (0.07 fish/tow) (Table 1). Of the 149 Atlantic sturgeon captured, 51% were collected off the western coast of Long Island, 30% were captured off central Long Island, and only one was captured off the east end of Long Island. During the spring, Atlantic sturgeon were captured along the entire coast of Long Island, NY, but 57% were captured off western Long Island, specifically Rockaway, NY. The Rockaway region was also an important area during the fall, accounting for

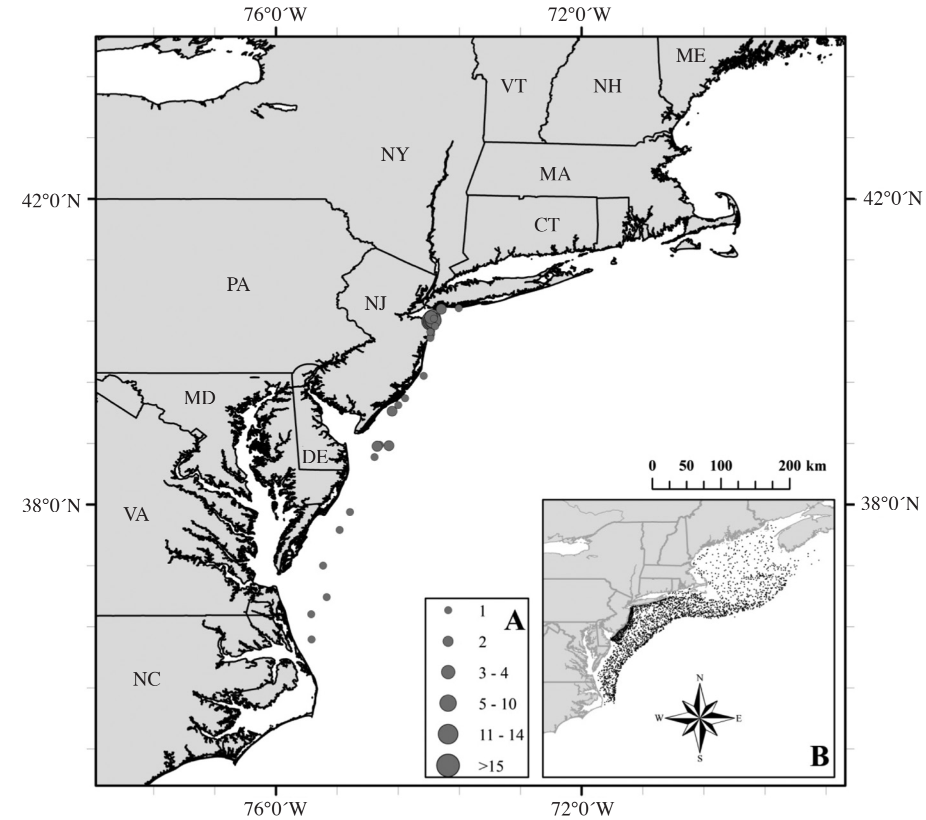

Figure 5

Number of captures of Atlantic sturgeon (*Acipenser oxyrinchus*) from all surveys during winter months. Circle size corresponds to total number of Atlantic sturgeon captured at a given location (insert **A**). Locations of all tows can be seen in insert **B**.

70% of the catches occurring within this region. Twenty-six Atlantic sturgeon were captured in the summer months; 99% were captured in western-central Long Island, NY, and only one was captured along the east end of Long Island. During the winter, all Atlantic sturgeon were captured off the western end of Long Island.

Habitat preferences

Hydrographic variables and distributions of Atlantic sturgeon were compared only for the NMFS bottom trawl survey, NJDEP finfish survey, and for NYBTS for the spring and fall seasons because these contained sufficient Atlantic sturgeon capture data to perform the analyses. The depths (habitat) occupied by Atlantic sturgeon was significantly different from the available depths in the NMFS survey and NYBTS for both the spring and fall surveys and the NJDEP spring survey (Tables 3 and 4). Atlantic sturgeon occupied areas with significantly different temperatures compared to available habitat in the NYBTS spring and NMFS fall survey, as well as areas of significantly different salinities in the NMFS fall and spring surveys and NJDEP spring survey (Table 3). Survey-specific cumulative distribution functions for available and occupied habits with depth, salinity, and temperature profiles are shown in Figure 10 and median values and 95% confidence intervals are listed in Table 4. Where significant differ-

Table 3

P-values from the analysis of habitat preference of Atlantic sturgeon (*Acipenser oxyrinchus*) by season in the northwestern Atlantic Ocean. The fish were captured in the National Marine Fisheries Service (NMFS) bottom trawl survey, New Jersey Department of Environmental Protection (NJDEP) finfish survey, and New York bottom trawl survey (NYBTS). Bold font indicates a significant difference ($P<0.01$) between Atlantic sturgeon habitat preference and the available habitat.

Season	Survey	Depth	Temperature	Salinity
fall	NMFS	<0.005	<0.005	<0.005
fall	NJDEP	0.129	0.173	0.273
fall	NYBTS	<0.005	0.518	0.530
spring	NMFS	<0.005	0.355	0.001
spring	NJDEP	<0.005	0.173	<0.005
spring	NYBTS	<0.005	0.001	0.084

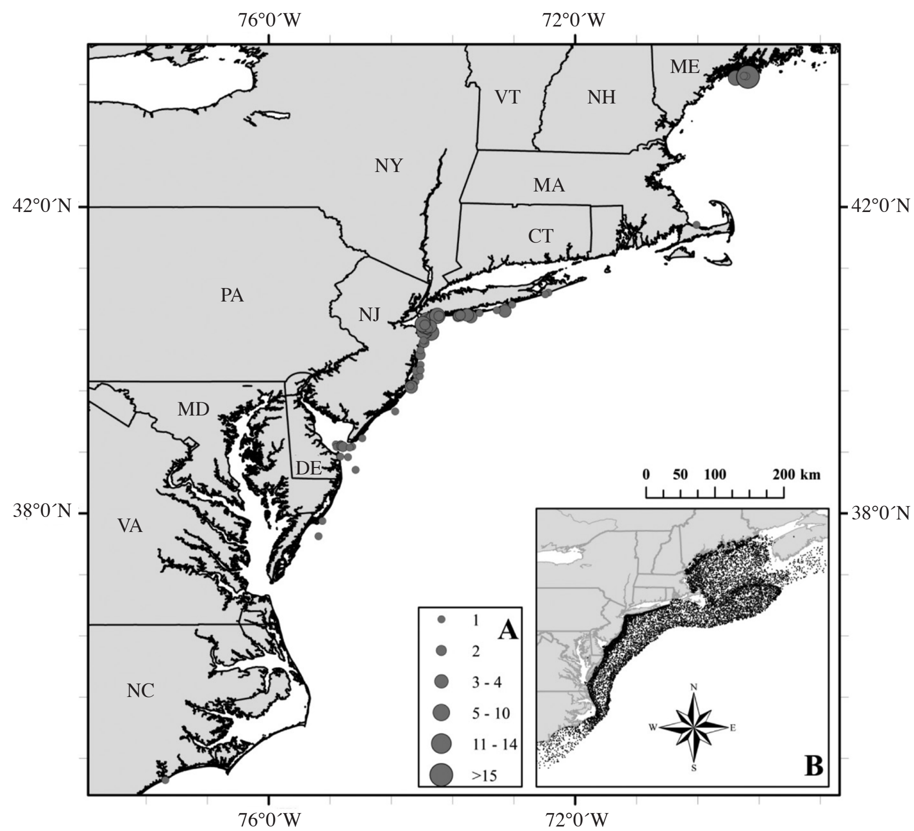

Figure 6

Number of captures of Atlantic sturgeon (*Acipenser oxyrinchus*) from all surveys during fall months. Circle size corresponds to total number of Atlantic sturgeon captured at a given location (insert **A**). Locations of all tows can be seen in insert **B**.

ences in depth occurred, Atlantic sturgeon were always found in shallower water than in potentially available habitat (Table 4, Fig. 10). Salinities of occupied areas were less than those of available habitat in all surveys, although only the NMFS fall and spring survey and NJDEP spring survey had significant differences (Table 4, Fig. 10). In two circumstances the temperature of occupied habitat was significantly warmer than that of available habitat, whereas temperature for the other seasons and surveys showed no trend (Table 4, Fig. 10).

Discussion

A majority of the Atlantic sturgeon captured along the continental shelf from ME to NC were juveniles aggregating in specific locations around the mouths of estuarine complexes and along narrow dispersal corridors in shallow water (<20 m) from Cape Hatteras (NC) to the southern tip of Long Island (NY). The highest catches occurred within the NY Bight in water 10–15 m deep, particularly during the spring and fall. Few sturgeon were captured north of MA. Little work has been done to describe the marine habitat distribution and habitat preference of Atlantic sturgeon, but similar coast-wide, shallow (with respect to regional bathymetry) marine distributions have been shown for green sturgeon (*Acipenser medirostris*) (Erickson and Hightower, 2007) and Gulf sturgeon (*Acipenser oxyrinchus desotoi*) (Edwards et al., 2007; Ross et al., 2009). The shallow, coast-wide habitat identified within this study is also consistent with Atlantic sturgeon bycatch data (Stein et al., 2004a, 2004b). Our comprehensive analysis of a coast-wide collection of surveys revealed the area between the NY Bight to VA as a region of overwintering habitat for juvenile Atlantic sturgeon. This finding agrees with that of Laney et al. (2007), who found the coastal waters off NC and VA to be important overwintering habitat for Atlantic sturgeon. Atlantic sturgeon that originated from the Hudson River represented 43.5% of those in the NC overwintering habitat (Laney et al., 2007) a percentage that agrees with Dovel and Berggren's (1983) tagging data that revealed a southerly movement of Atlantic sturgeon from the Hudson River. In addition to Laney et al. (2007), there have been further reports of Atlantic sturgeon in marine waters off the coast of South Carolina during winter months (Collins and Smith, 1997). The identification of the NY Bight as an important overwintering area has not been widely reported; therefore determining the

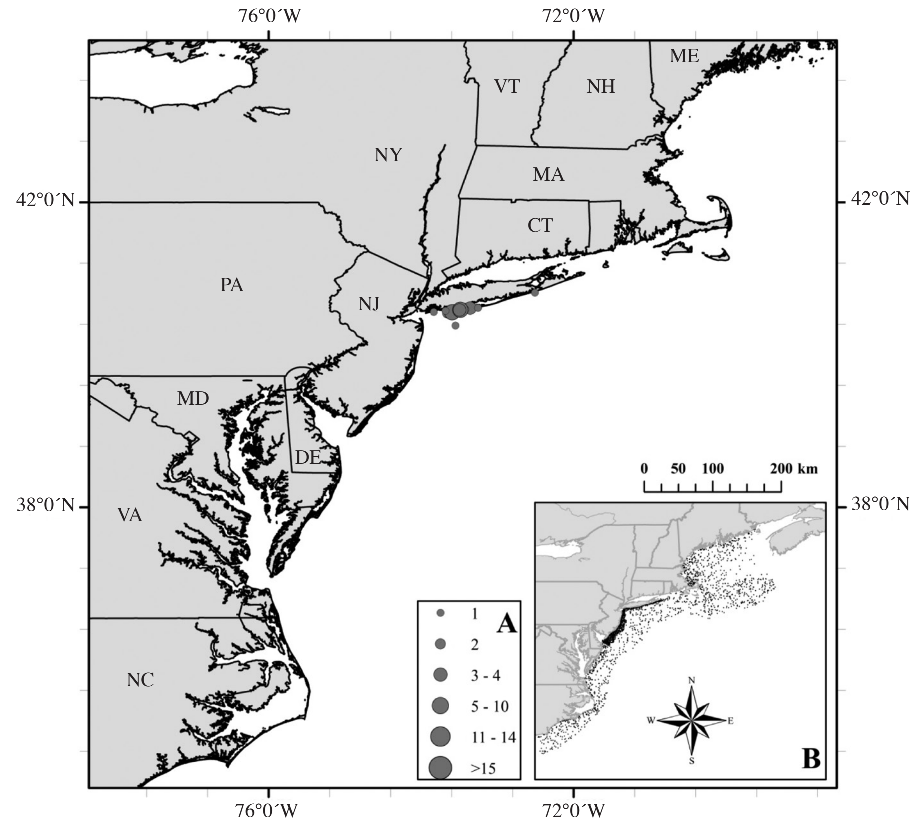

Figure 7

Number of captures of Atlantic sturgeon (*Acipenser oxyrinchus*) from all surveys during summer months. Circle size corresponds to total number of Atlantic sturgeon captured at a given location (insert **A**). Locations of all tows can be seen in insert **B**.

genetic makeup of the sturgeon in this area would add important information on Atlantic sturgeon demographics and movements.

Atlantic sturgeon had a coast-wide distribution during the spring and fall, and southerly and centrally located distributions during the winter and summer, respectively. These results corroborate tagging data that indicate that Atlantic sturgeon undergo large-scale southerly fall migrations and northerly spring migrations (Dovel and Berggren, 1983). Catches varied by season, but were greatest during the fall and spring months. Because of the strong seasonal movements of Atlantic sturgeon, the timing of surveys is critical for observing movement patterns.

Interaction of Atlantic sturgeon abundance with temporal and spatial variability in sampling effort

Some of the variation in distribution and abundance of Atlantic sturgeon can be explained by temporal and spatial differ-

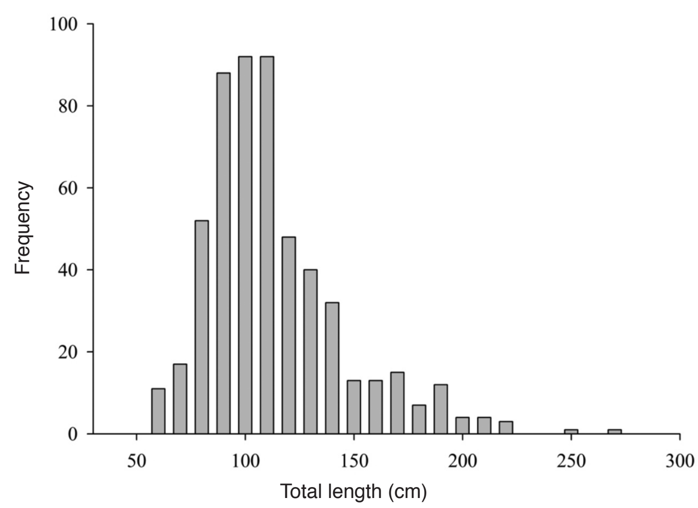

Figure 8

Total length distribution for Atlantic sturgeon (*Acipenser oxyrinchus*) captured in all surveys combined.

ences in sampling effort. Stein et al. (2004a) reported that MA ports have one of the highest cumulative catches of Atlantic sturgeon. This high rate contrasts with that for the MADMF bottom trawl survey, during which virtually no Atlantic sturgeon were captured. The discrepancy between reports of Atlantic sturgeon in MA waters likely comes from the timing of sampling. Stein et al. (2004a) showed the highest bycatch rates in June and November for bottom trawl fisheries, whereas the MADMF survey took place during May and September. Any aggregations and dispersal of Atlantic sturgeon within MA marine waters may occur at spatial and temporal scales that are missed by the survey. The absence of Atlantic sturgeon during the MADMF survey does, however, indicate lower abundance within the area surveyed during comparable time frames because Atlantic sturgeon are captured at relatively high rates by other surveys during this period. More work should be done to monitor Atlantic sturgeon habitat during other months not typically sampled by the MADMF survey because it is possible that Atlantic sturgeon are present in higher concentrations during months that are not routinely sampled.

The NMFS survey missed critical areas for Atlantic sturgeon because inshore areas in certain regions could not be sampled. Such areas include important overwintering habitat identified within this study in NY waters and by Laney et al. (2007) in VA and NC waters, in addition to critical habitat within the GOM. The ME-NH inshore bottom trawl survey was used to identify the Kennebec estuarine complex as an important concentration area for Atlantic sturgeon within the GOM region because shallower areas are sampled with this survey. During additional inshore surveys, such as the Northeast Fisheries Sciences Center (NEFSC) industry-based surveys for cod (*Gadus morhua*) and yellowtail (*Limanda ferruginea)*, Atlantic sturgeon have been captured between the Saco and Kennebec rivers in fall, winter, and spring (Fig. 9A; W. Kramer, personal commun.[5]). Stein et al. (2004a, 2004b) also showed that Atlantic sturgeon are captured as bycatch within this region in sink gillnets. The depth distribution of Atlantic sturgeon within the GOM was deeper than that for the other coast-wide captures, but similar to those reported for green sturgeon (Erickson and Hightower, 2007) in that both species occupied areas of shallow depth in relation to the bathymetric characteristics of the region. There has not been sufficient inshore trawling conducted during the winter and summer to validate whether the GOM is important year-round habitat.

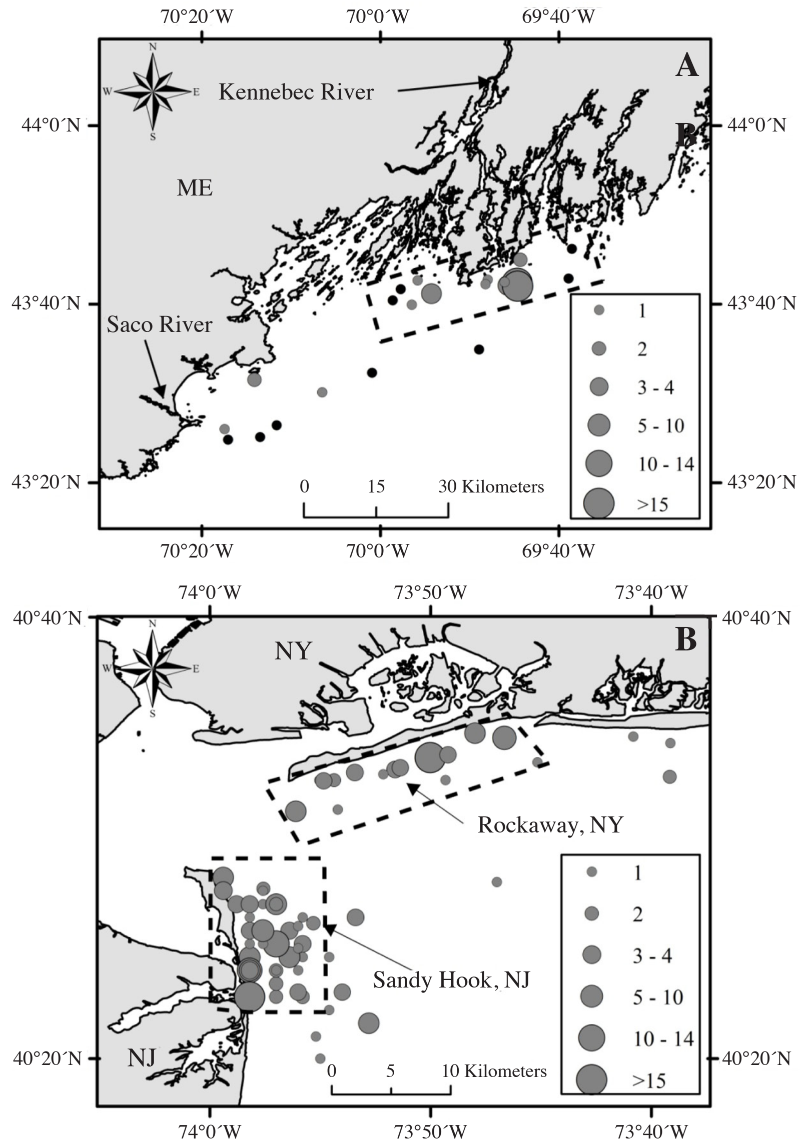

Figure 9

Number of captures of Atlantic sturgeon (*Acipenser oxyrinchus*) determined from (**A**) the Gulf of Maine from the Maine-New Hampshire bottom trawl surveys (gray circles) and from the Northeast Fisheries Science Center industry-based surveys for cod (*Gadus morhua*) and yellowtail (*Limanda ferruginea)* (black circles) and (**B**) Sandy Hook, NJ and Rockaway NY, including all captures from the National Marine Fisheries Service bottom trawl survey, New Jersey Department of Environmental Protection finfish survey, and New York bottom trawl survey. Dotted lines in both panels represent suggested closed areas for habitat protection. Note different scales in figure.

5 Kramer, William. 2009. NOAA Fisheries Service, Ecosystems Survey Branch, 166 Water St., Woodshole, MA 02543.

Table 4

Median and 95% confidence intervals for available and occupied habitat of Atlantic sturgeon (*Acipenser oxyrinchus*) for depth, temperature, and salinity for the fall and spring National Marine Fisheries Service bottom trawl survey (NMFS), New Jersey Department of Environmental Protection finfish survey (NJDEP), and New York bottom trawl survey (NYBTS) where "available habitat" represents all habitat sampled and "occupied habitat" represents habitat where Atlantic sturgeon were captured.

Season	Parameter	Survey	Median	95% confidence interval
Fall	Depth (m)	NMFS available habitat	76.0	15.5–260.5
		NMFS occupied habitat	18.0	10.0–25.0
		NJDEP available habitat	19.0	8.0–27.0
		NJDEP occupied habitat	16.0	7.0–22.0
		NYBTS available habitat	23.8	9.5–30.3
		NYBTS occupied habitat	10.7	9.0–17.0
	Temperature (°C)	NMFS available habitat	10.6	5.9–22.5
		NMFS occupied habitat	18.9	13.3–23.3
		NJDEP available habitat	15.8	12.3–18.6
		NJDEP occupied habitat	14.8	13.3–17.6
		NYBTS available habitat	15.3	13.5–19.3
		NYBTS occupied habitat	16.8	13.6–19.9
	Salinity (ppt)	NMFS available habitat	33.1	31.0–35.4
		NMFS occupied habitat	31.6	29.3–32.0
		NJDEP available habitat	32.0	29.6–33.5
		NJDEP occupied habitat	31.5	29.5–33.1
		NYBTS available habitat	31.4	30.1–32.9
		NYBTS occupied habitat	31.3	29.4–31.8
Spring	Depth (m)	NMFS available habitat	76.0	16.0–259.0
		NMFS occupied habitat	18.0	8.0–27.0
		NJDEP available habitat	19.0	7.5–27.0
		NJDEP occupied habitat	12.0	7.0–18.0
		NYBTS available habitat	22.4	9.9–29.7
		NYBTS occupied habitat	9.9	9.9–13.9
	Temperature (°C)	NMFS available habitat	6.0	3.4–12.5
		NMFS occupied habitat	6.4	3.2–15.0
		NJDEP available habitat	9.1	4.9–18.8
		NJDEP occupied habitat	11.0	5.7–19.0
		NYBTS available habitat	9.4	5.1–14.6
		NYBTS occupied habitat	11.1	5.7–13.9
	Salinity (ppt)	NMFS available habitat	33.2	31.4–35.4
		NMFS occupied habitat	32.0	27.0–32.8
		NJDEP available habitat	32.0	30.0–34.0
		NJDEP occupied habitat	30.0	28.8–35.0
		NYBTS available habitat	31.6	30.2–33.1
		NYBTS occupied habitat	30.9	29.9–32.3

Although the NMFS survey covered the entire continental shelf, no fish were captured deeper than 30 m. However, Atlantic sturgeon of unknown size have been captured in deeper waters (>100 m) on the continental shelf as bycatch in gillnet fisheries (Stein et al. 2004b; ASMFC[6]). Additionally, there have only been two recorded trawl captures of an Atlantic sturgeon in deep waters; one mature Atlantic sturgeon (225 cm) was captured in the Hudson canyon in water 110 m deep off NY and NJ and another was captured in Wilmington Canyon, 113 km southeast of Atlantic City, NJ (Timoshkin, 1968). The lack of trawl-caught fish on the continental shelf may be a result of either a gap in timing of the sampling and Atlantic sturgeon migrations on or off the shelf, a function of gear selectivity towards smaller

[6] ASMFC (Atlantic States Marine Fisheries Commission). 2007. Estimation of Atlantic sturgeon bycatch in coastal Atlantic commercial fisheries of New England and the Mid-Atlantic, 95 p. ASMFC,Washington D.C.

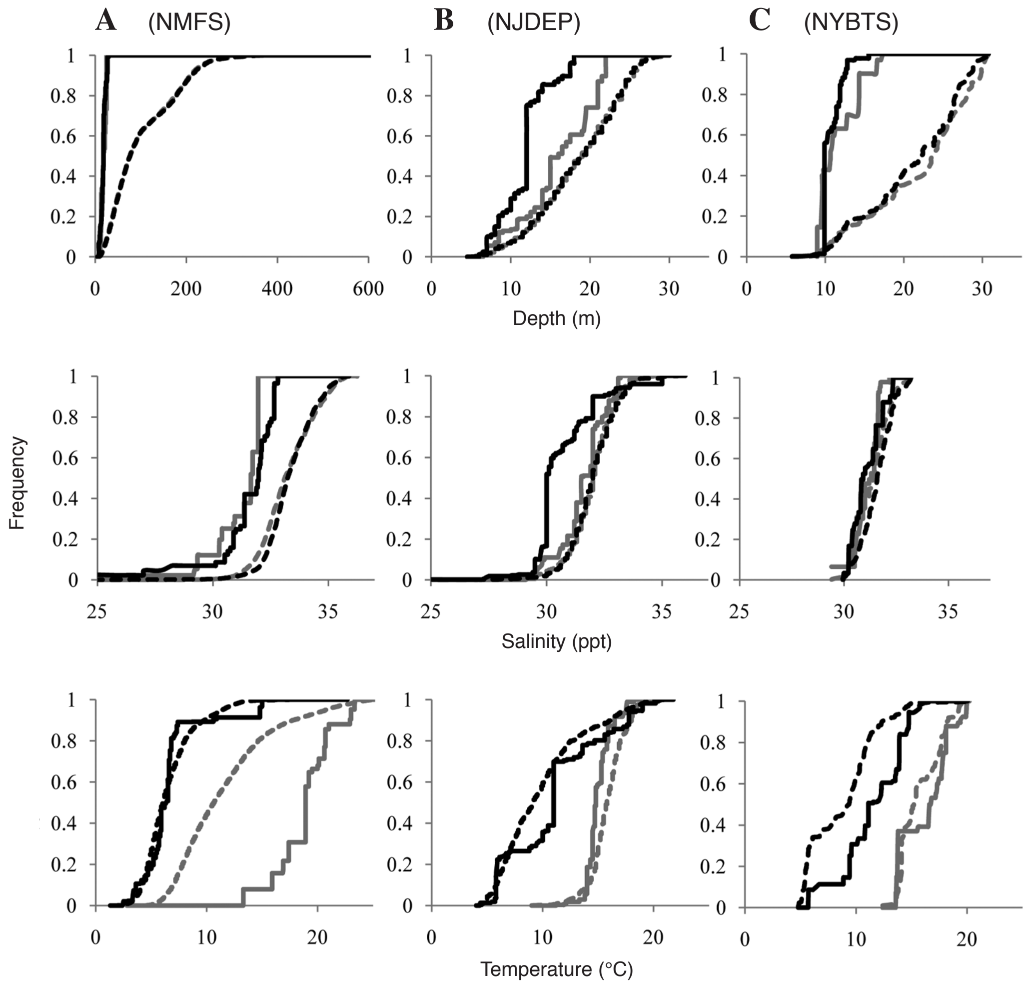

Figure 10

Cumulative distribution functions for available habitat and habitat occupied by Atlantic sturgeon (*Acipenser oxyrinchus*) in the fall and spring surveys for (**A**) National Marine Fisheries Service bottom trawl surveys (NMFS), (**B**) New Jersey Department of Environmental Protection finfish survey (NJDEP), and (**C**) New York bottom trawl survey (NYBTS) for depth (m), salinity (ppt), and temperature (°C). Solid lines indicate habitat occupied by *A. oxyrinchus* (gray=fall; black=spring) and dashed lines indicate available habitat (dashed gray=fall; dashed black=spring).

fish, or simply a scarcity of Atlantic sturgeon. Either a substantial increase in trawl survey effort or the use of different gears, such as gillnets, may be required in order to capture Atlantic sturgeon along the shelf.

Essential fish habitat

The Magnuson-Stevens Fishery Conservation and Management Act requires identification of Essential Fish Habitat (EFH), defined as waters or substrate used for spawning, breeding, feeding or growth to maturity, in order to minimize adverse effects of fishing and to promote conservation and enhancement of such habitat for particular species. Unfortunately, EFH can only be defined for federally managed species and does not include species such as Atlantic sturgeon which are managed by regional fishery management councils. Atlantic sturgeon is a current candidate species for listing under the US Endangered Species Act, and if listed, the identification of critical habitat necessary to recover the species will be required. The identification of critical habitat for listed species is mandatory and is defined as all areas essential to the conservation of the species. Without EFH or critical habitat designation, habitat degradation and incidental mortality within critical areas will continue to hinder population recovery.

Our analysis of habitat preferences indicated that depth was the primary environmental characteristic defining the Atlantic sturgeon distribution. Thus, essential habitat for juvenile marine migrant Atlantic sturgeon can broadly be defined as coastal waters <20 m depth, and it is concentrated in areas adjacent to estuaries such as the Hudson River–NY Bight, Delaware Bay, Chesapeake Bay, Cape Hatteras, and Kennebec River. This narrow band of shallow water appears to represent an important habitat corridor and potential migration path. There are likely additional hotspots along the migration corridor, but greater temporal and spatial sampling effort is required to identify them. Other authors have reported concentrations of Atlantic sturgeon in Long Island Sound (Bain et al., 2000; Savoy and Pacileo, 2003) and NC (Laney et al., 2007), and Stein et al. (2004a) reported several concentrations of Atlantic sturgeon in Massachusetts Bay, RI, NJ, and DE. However, Stein et al. (2004a) used bycatch data in areas where captures were lowest during the summer months while the fishing rates were highest. However, this change in fishing effort may influence the observed distributions.

The reason(s) for aggregations of Atlantic sturgeon migrants are not understood, nor are their movements to and from aggregation areas. Concentrations identified by Stein et al. (2004b) led the authors to suggest that temperature, bathymetry, geomorphic formations, food habits, and the sampling gear type used may contribute to observed movements and aggregation of Atlantic sturgeon. Complex water circulation patterns are also a potential reason for observed concentrations of Atlantic sturgeon (Wilk and Silverman, 1976; Savoy and Pacileo, 2003). Hatin et al. (2002) found that Atlantic sturgeon concentrated within the St. Lawrence estuary had large numbers of nematodes and oligochaetes within their stomachs, which would indicate that these habitats are feeding areas. Known seasonal migrations often involve energetic demands related to food availability, environmental factors, and reproductive activity (Roff, 2002). Because the majority of captures are juveniles, reproductive activity is not a likely cause for movement, although causal mechanisms influencing traits under selection are difficult to identify because life-history stages are often linked through long-term fitness (Taborsky, 2006). We hypothesize that migrations are depth restricted and aggregations are related to food availability, and that seasonal cues, temperature in particular, drive movement.

Current and future management of Atlantic sturgeon

Current knowledge indicates that the majority of Atlantic sturgeon populations have been extirpated and that the Hudson River stock is one of the largest remaining populations (Waldman et al., 1996; van Eenennaam et al., 1998; Savoy and Pacileo, 2002; Secor et al., 2002). Three fishery management tools commonly used to help restore depleted populations are 1) minimum size limits, 2) temporary closures of the fishery, and 3) marine reserves (Nowlis, 2000). Management of Atlantic sturgeon has been accomplished by minimum size limits since the early 1990s, followed directly by a 40-year complete closure of the fishery beginning in 1998. Currently, after 10 years of the fishery closure, recruitment within the Hudson River still remains at historic lows (Kahnle et al., 2007).

Because previous Atlantic sturgeon management has not resulted in significant improvements to populations, recovery efforts should now focus on establishing marine reserves or implementing area closures to protect essential habitat and to reduce fishing mortality on juveniles (Collins et al., 2000). Specifically, Sandy Hook (NJ), Rockaway (NY), and Kennebec (ME), which are hotspots of Atlantic sturgeon captures, as identified by this study, should be protected. Although sturgeon are not as abundant in the Kennebec region in ME as in NY and NJ waters, this region represents a unique hotspot. It is of particular importance because Atlantic sturgeon captured in ME river systems have been shown to represent a separate discrete population segment (Grunwald et al., 2008). The genetic origins of the Atlantic sturgeon captured within marine waters of ME are unknown, but they are likely to originate from multiple stocks. Because of the proximity of ME river systems, it is probable that the majority of these Atlantic sturgeon are part of this discrete population segment. If our recommended habitat protection were to occur, the total amount of closed area within these locations would be relatively small—totaling 85.47 km^2 within NJ (Fig. 9A), 106.19 km^2 within NY (Fig. 9A), and 209.79 km^2 within ME (Fig. 9B). In addition, although Atlantic sturgeon are highly migratory, primary juvenile habitat and migrations are limited to narrow corridors in waters less than 20 m deep. The presence of Atlantic sturgeon in such narrow bands of water indicates a seasonal or permanent closure to gillnet and trawl fisheries could be successful. By focusing immediate efforts on the protection of these hotspots and corridor pathways, bycatch mortality will be reduced effectively through protection of habitat. Further efforts should also be made to protect important areas within other systems and to conserve the several discrete population segments defined by ASSRT[3] and Grunwald et al. (2008) and to promote genetic diversity among Atlantic sturgeon populations.

By understanding the time periods of localized aggregations and movements of Atlantic sturgeon, plans could be developed that minimize the extent and length of closures that are concentrated within narrow corridors. Some states already restrict inshore trawling which limits fishery interactions with Atlantic sturgeon, such as NJ (3.22 km limit), MD (1.61 km limit), DE (no trawling), and NY (various no trawl zones in marine waters). Any spatial closures require proper enforcement and substantial community-level support for successful implementation (Sumaila et al., 2000). Although broad-scale movement patterns are becoming clearer, work is required to understand the finer scale movements of Atlantic sturgeon such that any spatial management plans could be minimized while still achieving adequate protection. Current plans toward understanding finer-scale movements are aided by cooperative efforts such as those of the Atlantic Cooperative Telemetry (ACT) network, which is a large scale collaborative telemetry network of ~30 groups from Maine to South Carolina (D. Fox and T. Savoy, personal commun.[7,8]). Such coordinated efforts are steps in the right direction for species conservation. Once fine-scale movements are understood, in particular for aggregation areas, fishery managers will be better informed as to how to limit interactions between fisheries and the near-endangered Atlantic sturgeon while minimizing economic impacts. Improving estimates of fishery bycatch mortality would be of enormous value, in particular if these estimates included a spatial perspective. Regardless of the outcome of the current consideration of Atlantic sturgeon for listing under the endangered species act, a coordinated effort among academic, federal, state, and local institutions will be required to conserve this ancient species.

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