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Atlantic Sturgeon Marine Bycatch and Mortality on the Continental Shelf of the Northeast United States

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Abstract.—Protected sturgeon *Acipenser* spp. are caught in a number of different commercial fishing gears along the east coast of the USA. During their life cycle, Atlantic sturgeon *Acipenser oxyrinchus* migrate into marine waters, where they are caught by otter trawls, sink gill nets, and drift gill nets targeting other species. We investigated fishing records collected by onboard observers to calculate Atlantic sturgeon bycatch and mortality rates for each fishing gear. Bycatch rates were based on fishing trips monitored between 1989 and 2000 and were indexed by landed species and state. Rates were then raised to fisherywide estimates of bycatch based on total landings for the relevant gears at each location. Where data were available, we estimated sturgeon mortality for each gear. The results showed that Atlantic sturgeon bycatch was highest for sink gill nets in specific areas of the coast. The observed immediate mortality rates of Atlantic sturgeon captured in sink gill nets and drift gill nets were 22% and 10%, respectively, suggesting that annual mortality in these fisheries may be on the order of 1,500 fish per year. The resulting mortality estimates are a source of concern for the continued recovery of Atlantic sturgeon resources.

The recovery of protected resources is a multifaceted problem involving the regulation of both targeted and nontargeted species (Pascoe 2000). Bycatch mortality is a particularly acute problem in long-lived species, such as marine mammals and primitive groups of fishes like the sturgeons *Acipenser* spp. and paddlefish *Polyodon spathula* of the order Acipenseriformes (Boreman 1997; Kynard 1997; Caswell et al. 1998; Clark and Hare 1998). In these groups, late maturation and inconsistent spawning intervals combined with even modest levels of fishing mortality can have a substantial effect on reproductive potential (Boreman 1997; Caswell et al. 1998; Morrow et al. 1998). Sturgeon populations are particularly vulnerable to juvenile mortality, as Gross et al. (2002) illustrated in elasticity analyses of sturgeon species, including Atlantic sturgeon *Acipenser oxyrinchus*. In a review of bycatch literature, Hall et al. (2000) supported the argument that a substantial proportion of commercial catch is comprised of nontarget or restricted species. For some gears, much of the bycatch will result in immediate mortality and unquantified delayed mortality (Chopin and Arimoto 1995; Hall et al. 2000). Although measurement of the effect of different fishing gears is difficult, bycatch and mortality estimates are necessary to properly manage marine populations (Caswell et al. 1998; Crowder and Murawski 1998).

Though the available data are fragmented, sturgeon populations along the east coast of the USA have been seriously impacted by incidental catch and associated mortality. In the southeastern USA, capture of Atlantic sturgeon chiefly occurs in gill nets within river and estuarine systems, but marine trawls are also a source of substantial bycatch and mortality (Collins et al. 2000). In South Carolina, 16% of the Atlantic sturgeon bycatch was reported as mortality, while 20% sustained noticeable injury (Collins et al. 1996). Smith and Clugston (1997) noted that sturgeon captures were increasing in Canadian waters, while U.S. landings were declining under more stringent regulation. Bycatch plays prominently in the assessment and recovery of Atlantic sturgeon and shortnose sturgeon *Aci-*

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TABLE 1.—Gear code number, gear name, and target species for the main gears catching Atlantic sturgeon on the U.S. east coast.

Gear number	Gear name	Target species
50	Otter trawl, fish	Northern shortfin squid *Illex illecebrosus*, silver hake *Merluccius bilinearis*, longfin inshore squid *Loligo pealeii*
58	Otter trawl, shrimp	Northern shrimp *Pandalus borealis*
59	Otter trawl, other	Atlantic croaker *Micropogonias undulatus*, horseshoe crab *Limulus polyphemus*, summer flounder *Paralichthys dentatus*
100	Sink gill net, fish	Spiny dogfish *Squalus acanthias*, Atlantic cod *Gadus morhua*, pollock *Pollachius virens*, goosefish *Lophius americanus*
110	Drift gill net, fish	Bluefish *Pomatomus saltatrix*, American shad *Alosa sapidissima*

penser brevirostrum populations, the two sturgeon species that occur along the east coast of the USA.

Both sturgeon species inhabit river systems from the St. Lawrence River, Nova Scotia, to the St. Johns River in Florida (Buckley and Kynard 1985; Kynard 1997). Although shortnose sturgeon occur in many of the same river systems as Atlantic sturgeon, they infrequently venture into marine waters and may be amphidromous over part of their range, unlike the Atlantic sturgeon, which is recognized as anadromous (Buckley and Kynard 1985; Bain 1997). Typical of anadromous species, sturgeon life history is relatively well known in freshwater but the marine habits are poorly understood, especially in regard to bycatch dynamics (Collins et al. 1996; Bain 1997). Sturgeons, valued for their meat and caviar, have been fished for centuries. During the 1900s, the fishery focused on Atlantic sturgeon because of their larger size, but shortnose sturgeon were kept as well (Collins et al. 1996). Sturgeon captures in most rivers peaked in the early 1890s and collapsed soon after, with much of the harvest occurring as bycatch in fisheries for herring and shad (Clupeidae; Secor 2002). Dam construction on many river main stems and tributaries prevented sturgeon from reaching their spawning sites, even where fishways were installed, thus extirpating populations from their historic range (Kynard 1997). The effect of overfishing in combination with dam construction on natal spawning rivers accelerated the decline of sturgeon populations, while degraded habitat impeded recovery (ASMFC 1998; Secor and Gunderson 1998). Numbers have declined to the extent that Atlantic sturgeon must be protected to conserve the remaining populations (Birstein 1993; ASMFC 1998). Shortnose sturgeon were placed on the inaugural endangered species list in 1973, and their population remains sufficiently low to continue its protected status (Collins et al. 1996; Kynard 1997; Smith and Clugston 1997).

In this study, we examined the bycatch and resulting mortality of sturgeons for selected fisheries along the east coast of the USA. We used the sea sampling/observer database of the National Marine Fisheries Service (NMFS) as the primary source of data to detect sturgeon marine bycatch. Estimates of bycatch and associated mortality are presented to aid in the management of sturgeon populations.

Methods

Data sets.—The NMFS sea sampling/observer database contains data on monitored commercial fishing trips from 1989 to the present. We retrieved data to characterize the spatial and temporal distribution of both Atlantic sturgeon and shortnose sturgeon. Though some capture records were coded as shortnose sturgeon, upon further scrutiny and in consultation with the database administrators for the regional fishery databases maintained by the NMFS, it was determined that these identifications could not be confirmed and were more likely Atlantic sturgeon. Therefore, all sturgeon records were uniformly treated as Atlantic sturgeon. The monitored cruises are only a small percentage of the commercial fishing trips made during the period covered by the database. The recorded catch includes target and nontarget species, with biological information about individual captures available from 1994 to the present.

The NMFS weigh-out database is a record of port landings from the commercial fisheries from 1964 to the present. The landings are recorded as the undressed weights of fish brought back to port, and do not include estimates of fish that were discarded due to various size and species restrictions. At the database's inception, the data were collected from the northeastern states only, but the database was later expanded to include the states of the mid-Atlantic Bight in the 1970s and several southern states in the mid-1980s. The database has limited

TABLE 2.—Atlantic sturgeon bycatch (lb) from monitored commercial fishing trips for all gears, listed by year and month.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1989						15			150	130	90	17	402
1990				48	140	20				7			215
1991					120	305	387	204	68	70	93	47	1,294
1992	28	12	99	81	314	204	217	17	78	22	266	51	1,389
1993	35		137	319	319	79			8	13	131	7	1,048
1994	203	102	1,020	293	95	135		17		163	274	639	2,941
1995	442	397	981	508	402	176	225	69		235	255	757	4,447
1996	285	460	115	363	615	1,100	20	11		291	792	8	4,059
1997	87	93	69	98	191	32					234	747	1,550
1998	345	140	234	424	618	221	75			305	381	157	2,900
1999	810	250	187	187	267	116		12	20	3	817	235	2,904
2000	183	442	242	167	730	35	50	35					1,884
Total	2,418	1,896	3,084	2,487	3,811	2,438	974	365	324	1,239	3,332	2,665	25,033

information on other aspects of the biology of the catch. The sea sampling and weigh-out data sets are in English units. We chose to use those units in the analysis since they are the original units of the data sets, and to facilitate use by the management bodies responsible for sturgeon management in the area, which still use predominantly English units.

Characterization of the bycatch.—Atlantic sturgeon bycatch records were coded by onboard fishery observers; this provided characterization of the spatial and temporal distribution of the bycatch and the association of bycatch with various fisheries targeting a range of species. Bycatch rates were recorded for each trip as the ratio of sturgeon catch weight to the catch weight of all species landed. Bycatch records from the eastern states were matched with monitored landings in the NMFS database to examine latitudinal trends. The rates were calculated for each commercial fishery producing sturgeon bycatch within monitored commercial landings for target species (i.e., excluding nontarget landings). Gear bycatch rates were calculated for each individual year to create a yearly depiction of bycatch. An analysis of variance (ANOVA) was used to test sturgeon capture weight differences by individual gear.

Estimated sturgeon bycatch.—The Atlantic sturgeon marine bycatch was estimated by post-stratifying the landings and bycatch rates by state and month for the years 1986–2000. After evaluating all gears within the database, we examined a specific subset of gear types that had an impact on sturgeon (Table 1). The bycatch analysis was limited to three principal gears: otter trawls, sink gill nets, and drift gill nets. Each gear is coded to differentiate fishery and mesh size. Otter trawl gear code 58, which is primarily used to capture northern shrimp, caught a minimal amount of sturgeon, and was omitted from the bycatch analysis. Otter trawl gear codes 50 and 59 were combined for analysis because they target similar species and are used in the same areas.

Sturgeon bycatch rates were stratified by state, month, and gear type, and were applied to state landings from the weigh-out database to create estimates of bycatch. The bycatch rates for a gear were a combination of mean rates for the study period and annually observed rates, both of which were partitioned into a state × month matrix. The matrix of mean rates was derived from bycatch and monitored landings matrices for a given gear type, which were filled using a form of iterative proportional fitting (Deming and Stephan 1940; Bishop et al. 1975). The matrix of accumulated bycatch for the entire study contained cells without data; therefore, proportional fitting was used to estimate missing cells and provide a smoothed version of the matrix. We completed the bycatch matrix by replacing each cell with a proportionally fit value calculated from the following equation:

$$B_{sm} = (B_{\bullet s} \times B_{m\bullet})/B_{\bullet\bullet}.$$

Here, B_{sm} is the bycatch for the month and state cell, $B_{\bullet s}$ and $B_{m\bullet}$ are column and row sums, respectively, and $B_{\bullet\bullet}$ is the matrix sum (sum of all bycatch for the gear). The same procedure was followed for the monitored landings matrix; thus, the bycatch rate for the gear was simply the matrix of proportionally fit bycatch divided by the matrix of proportionally fit landings.

To test the sensitivity of our inferences for the year-to-year fluctuations in the rate structure, we explored three weighting schemes for estimating bycatch based on the combination of the mean and

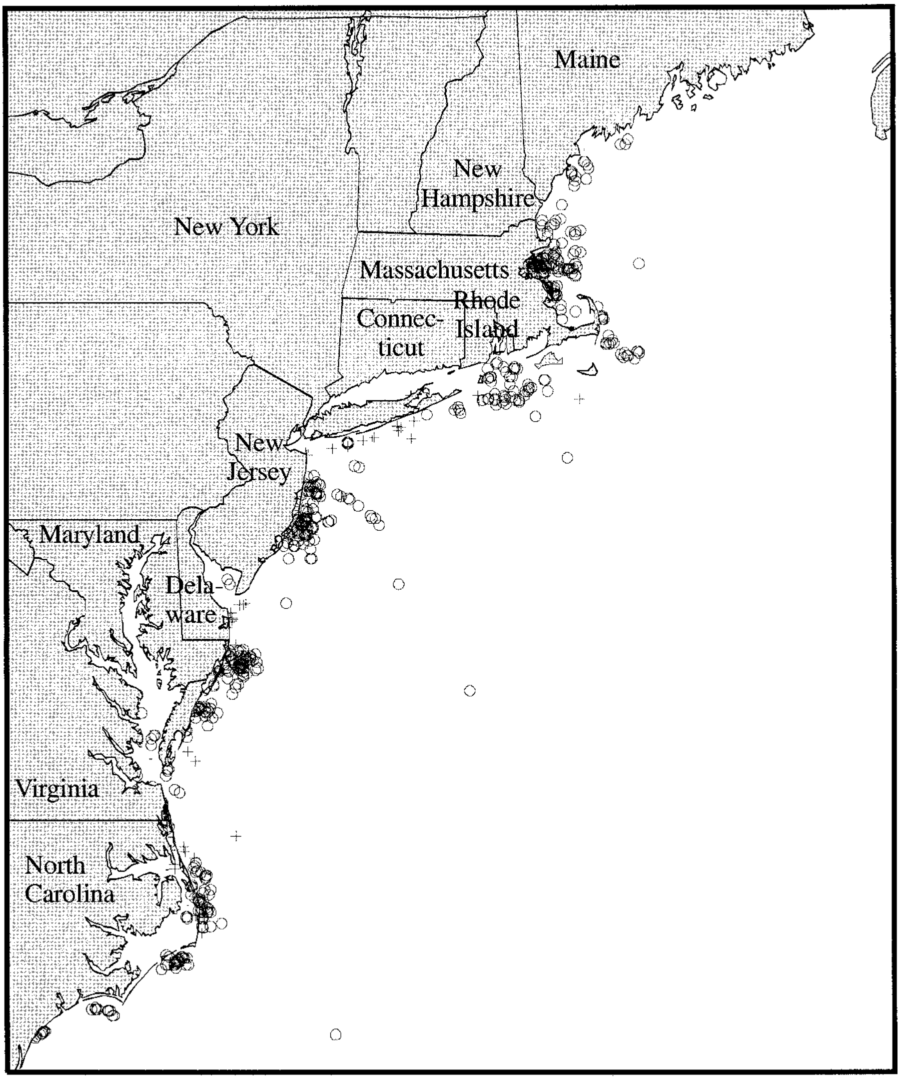

FIGURE 1.—Map of the northeast coast of the USA, showing locations of Atlantic sturgeon bycatch within National Marine Fisheries Service-monitored trips (''+'' indicates captures in otter trawls; '' ◊ '' indicates captures in drift gill nets; ''O'' indicates captures in sink gill nets).

annually observed bycatch rates. We calculated weighted averages between the mean and annual rates by applying 25%, 50%, and 75% weights to the mean rates:

$$R^e = \left[R^o \times W + R^m \times (1 - W)\right],$$

where R^e is the weighted mean bycatch rate, R^o is the annually observed bycatch rate, R^m is the mean bycatch rate, and W is the weight of 0.25, 0.5, or 0.75. The weighted mean bycatch rates were applied to the annual landings for each gear, again organized in a month × state matrix.

The precision of bycatch estimates was examined by use of a resampling technique based on the observed variation in bycatch rates throughout the time series. We calculated the ratio between the standard deviations and the mean bycatch rates by gear, month, and state. The ratios were applied to the weighted bycatch rates to estimate a standard deviation for use in the resampling. Empirical confidence intervals were computed from 500 realizations based on Monte Carlo resampling methods, assuming a truncated normal distribution for the bycatch estimates. The distributions were truncat-

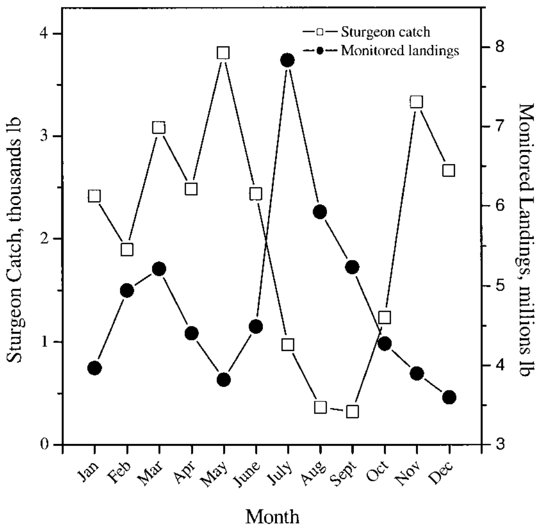

FIGURE 2.—Atlantic sturgeon bycatch and landings from monitored trips for all gears (otter trawls, sink gill nets, and drift gill nets), by month, 1989–2000.

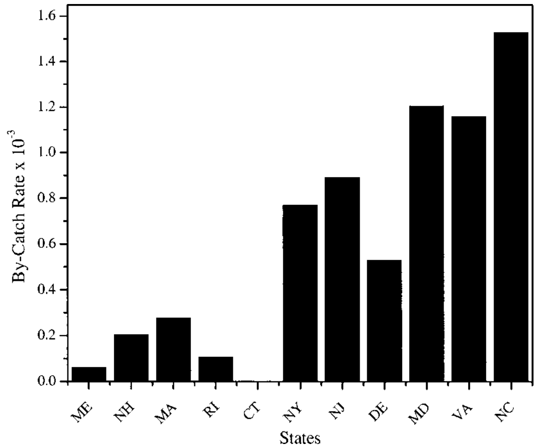

FIGURE 3.—Bycatch rate of Atlantic sturgeon (lb sturgeon/lb landings) for all gears (otter trawls, sink gill nets, drift gill nets) from monitored trips, by state.

ed to avoid negative rates in the resampling. We calculated the means and quartile ranges from the resampled estimates.

Gear mortality.—Minimum mortality estimates were calculated from individual records of dead Atlantic sturgeon landed during monitored fishing trips. For each gear involved, we estimated the immediate mortality associated with that gear, calculated from the observed mortalities. The sturgeon mortality rates were calculated from the individual animal records collected in the sea sampling/observer database from April 1994 to April 2000, and were expressed as a ratio of the number of individuals killed in the particular gear divided by the total number captured. For the minimum mortality estimates, the mortality rates were applied to the sturgeon bycatch estimates, and the bycatch rates were weighted evenly between the individual years and mean rates to determine the total sturgeon mortality by year. The estimated number of individuals killed was calculated from the mean weights of captured sturgeon in each gear.

Results

Characterization of Bycatch

Monitored commercial fishing trips caught 25,033 lb of Atlantic sturgeon during the period 1989–2000 (Table 2). Sturgeon were captured along the coast from the Gulf of Maine to the Carolina Capes (Figure 1). The bycatch occurred in distinct areas of the coast; however, monitoring effort was not randomly distributed. Bycatch peaked in 1995 and 1996, during which over one-third of all the sturgeon catch was recorded. Seasonal bycatch trends displayed an increase during the winter and spring (Figure 2). While sturgeon catch was lowest in the summer, fishing effort was at its highest point. Despite the increase in landings in July, the landings for monitored trips exceeded 3.5 million pounds per month throughout the time series.

Bycatch by States

The bycatch rates were not uniform along the coast (Figure 3). The highest rates were associated with landings in the states of Maryland, Virginia, and North Carolina. Despite lower bycatch rates, the highest cumulative Atlantic sturgeon catches included ports in the states of New Jersey and Massachusetts. The total sturgeon catch from Massachusetts, New Jersey, and North Carolina accounted for 64% of the total observed sturgeon bycatch during the study period. The states associated with the lowest observed sturgeon bycatch were Connecticut and Delaware (combining for a total of 8 lb). While New Jersey and Massachusetts hosted the greatest percentages of monitored landings, totaling 42.3% of the observed landings, Connecticut and Delaware hosted only 0.6% of the total observed landings. The mean rates for each gear supported this latitudinal trend, with sturgeon bycatch rates increasing from the northern states to the southern states (Table 3).

TABLE 3.—Matrix of mean bycatch rate of Atlantic sturgeon (1989–2000) stratified by fishing gear, month, and state. Units are sturgeon pounds per 1,000 lb of monitored landings.

State	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Otter trawl												
Maine	1.545	0.229	0.021	0.173	1.038	2.367	0.034	0.003	0.294	1.460	2.280	0.788
New Hampshire	2.133	0.317	0.032	0.239	1.432	3.267	0.047	0.046	0.405	2.017	3.147	1.088
Massachusetts	1.545	0.229	0.021	0.173	1.038	2.367	0.034	0.034	0.294	1.460	2.280	0.788
Rhode Island	0.010	0.002	0.000	0.001	0.007	0.016	0.000	0.000	0.002	0.010	0.015	0.005
Connecticut	1.545	0.229	0.021	0.173	1.038	2.367	0.034	0.034	0.294	1.460	2.280	0.788
New York	1.536	0.228	0.023	0.172	1.032	2.353	0.034	0.033	0.292	1.453	2.267	0.784
New Jersey	0.416	0.062	0.006	0.047	0.279	0.637	0.009	0.009	0.079	0.393	0.614	0.212
Pennsylvania	1.545	0.229	0.021	0.173	1.038	2.367	0.034	0.003	0.294	1.460	2.280	0.788
Delaware	1.545	0.229	0.021	0.173	1.038	2.367	0.034	0.003	0.294	1.460	2.280	0.788
Maryland	2.946	0.437	0.044	0.330	1.979	4.514	0.065	0.064	0.560	2.787	4.348	1.503
Virginia	1.557	0.231	0.023	0.174	1.046	2.386	0.035	0.034	0.296	1.473	2.298	0.794
North Carolina	2.218	0.329	0.033	0.248	1.490	3.399	0.049	0.048	0.422	2.098	3.274	1.132
Sink gill nets												
Maine	0.147	0.132	0.228	0.211	0.260	0.085	0.042	0.016	0.009	0.057	0.184	0.180
New Hampshire	0.440	0.394	0.682	0.630	0.778	0.255	0.125	0.049	0.028	0.170	0.551	0.536
Massachusetts	1.042	0.933	1.613	1.491	1.839	0.604	0.297	0.115	0.066	0.401	1.303	1.268
Rhode Island	2.201	1.971	3.408	3.150	3.886	1.275	0.627	0.244	0.140	0.848	2.753	2.680
Connecticut	2.770	2.480	4.290	3.960	4.890	1.600	0.790	0.300	0.180	1.100	3.460	3.370
New York	3.261	2.919	5.048	4.666	5.757	1.889	0.929	0.361	0.207	1.256	4.078	3.970
New Jersey	9.156	8.198	14.177	13.102	16.165	5.304	2.609	1.013	0.582	3.527	11.453	11.147
Delaware	2.770	2.480	4.290	3.960	4.890	1.600	0.790	0.300	0.180	1.100	3.460	3.370
Maryland	3.057	2.737	4.733	4.374	5.397	1.771	0.871	0.338	0.194	1.177	3.823	3.721
Virginia	2.407	2.155	3.727	3.444	4.249	1.394	0.686	0.266	0.153	0.927	3.010	2.930
North Carolina	3.201	2.866	4.956	4.580	5.651	1.854	0.912	0.354	0.204	1.233	4.003	3.897
Drift gill nets												
Maine	5.9		2.2	53.7				3.0			5.9	
New Hampshire	5.9										5.9	
Massachusetts	5.9										5.9	
Rhode Island	5.9		2.2	53.7				3.0			5.9	
Connecticut	5.9		2.2	53.7				3.0			5.9	
New York	5.9										5.9	
New Jersey	5.9		0.288	7.016				0.390			5.9	
Delaware	5.9		0.146	3.558				0.198			5.9	
Maryland	5.9		0.179	4.353				0.242			5.9	
Virginia	5.9		17.003	414.428				23.017			5.9	
North Carolina	5.9										5.9	

Bycatch by Target Species

High cumulative bycatch and bycatch rates were associated with distinct target species (Figure 4). When goosefish and spiny dogfish were the targeted species, gears used in these fisheries captured over 60% of the observed sturgeon recorded (Table 4). Substantial bycatch also occurred in fisheries targeting Atlantic cod and summer flounder. The calculated bycatch rates also highlighted several different target species, including weakfish, striped bass, smooth dogfish, American shad, northern kingfish, and southern flounder. When American shad and scup were targeted, the high sturgeon bycatch was coupled with high sturgeon bycatch rates. Vessels targeting American shad caught 540 lb of sturgeon, the eighth highest biomass of sturgeon caught by an observed fishery, while recording a bycatch rate of 2.4%. Gears targeting scup caught 570 lb of sturgeon and had the ninth highest bycatch rate.

Bycatch by Gear

Atlantic sturgeon capture was recorded in both active and passive gears. Bycatch was observed for gears categorized in five different gear codes, including sink gill nets (code 100), drift gill nets (code 110), and three otter trawls (codes 50, 58, and 59) (Table 1). Sturgeon catch varied with the different gear types and target species. Otter trawl codes 50 and 59 were used for similar species and similar states, capturing 1,938 and 1,790 lb, respectively. Otter trawl code 58 was used specifically for the shrimp fishery and captured a total of 56 lb of sturgeon during the time series. Sink gill nets were used to target spiny dogfish, goosefish, and Atlantic cod. The sink gill nets caught

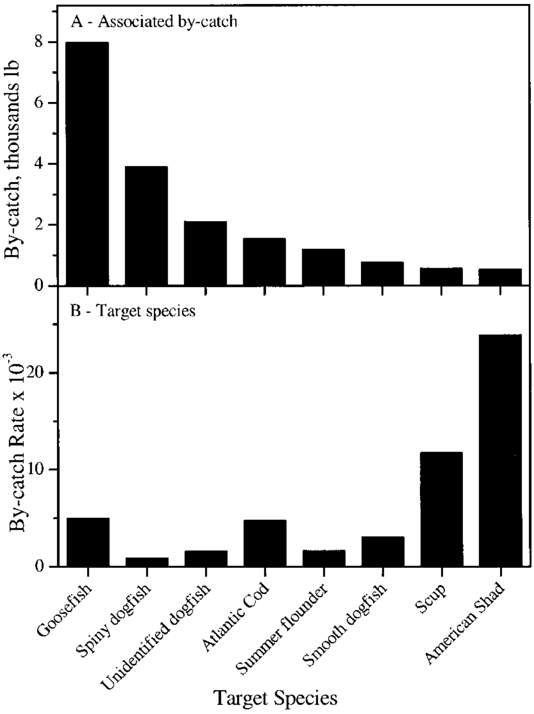

FIGURE 4.—(A) Bycatch of Atlantic sturgeon on monitored trips made by otter trawls, sink gill nets, and drift gill nets, and (B) the associated bycatch rates, for each target species.

20,891 lb of sturgeon. Drift gill nets were used to target bluefish and American shad, and captured 357 lb of sturgeon. Each gear selectively captured sturgeon of significantly different sizes (Figure 5). Otter trawls caught sturgeon at a mean size of 63.56 lb, sink gill nets captured a mean size of 34.60 lb, and drift gill nets caught a mean size of 13.14 lb (ANOVA, $P < 0.05$).

Gear Bycatch Rates and Estimated Sturgeon Catch

Commercial landings.—The commercial landings of all species varied considerably between gear types (Figure 6). Otter trawl landings were highly variable, ranging from 231 to 330 million pounds from 1986 to 2000. Sink gill nets followed a steady increase from 32 million pounds in 1986 to 77 million pounds in 1998, with two distinct periods of decreased landings in 1991–1992 and 1999–2000. For drift gill nets, landings exhibited an overall increasing trend from 761,256 pounds in 1986 to 10 million pounds in 1998, and later decreasing to 6 million pounds in 2000.

Variation in Bycatch Rate

The fitted mean values and standard deviation ratios revealed gear-specific results. The resulting rates showed a difference in gear use and efficiency during particular months. For otter trawls, the overall mean bycatch rate was approximately 0.00085 (lb sturgeon/lb monitored landings), with Maryland fisheries consistently recording the highest bycatch rates and Rhode Island the lowest (Table 3). Sink gill nets recorded an overall mean rate of 0.00144. In sink gill nets, New Jersey had the highest bycatch rates for all months, while several states recorded seasonal low rates. Drift gill nets recorded an overall mean bycatch rate of 0.0059, with a noteworthy peak rate occurring during April in Virginia. Each gear displayed seasonal peaks. The peaks in otter trawl bycatch rates occurred during the winter and late spring, and sink gill nets recorded peak mean rates during the winter and spring. Particular catch events contributed to a large peak in bycatch rates in drift gill nets for the month of April.

The standard deviation ratios ranged considerably from gear to gear (Table 5). The mean ratio for otter trawls was 0.462 (lb sturgeon/1,000 lb monitored landings). The sink gill nets had a slightly higher mean rate of approximately 0.622 (lb sturgeon/1,000 lb monitored landings). The drift gill nets had a substantially higher mean ratio of 0.710 (lb sturgeon/1,000 lb monitored landings). For the most part, the ratio matrix cells were individually estimated for sink gill nets, while ratio matrix cells were mostly filled with the mean values for the otter trawls and drift gill nets. The number of filled cells reflects an absence of data coverage.

Estimated Sturgeon Bycatch

Coastwide estimates of Atlantic sturgeon bycatch were substantial and varied over the study period. Otter trawl estimates steadily declined from 200,000 lb to nearly 150,000 lb over the time series (Figure 7). In 1996, there was an anomalous increase in the bycatch estimates due to a prominent increase in the bycatch rate during one particular month. Excluding 1996, the analysis showed little variation between the different weighting schemes for each year. Sink gill net estimates steadily increased from 32,000 lb in 1986 to 150,000 lb in 2000 (Figure 8). Again, a substantial increase occurred in 1996, when the estimates reached 200,000 lb. There was a noticeable separation in the mean estimates for each weight-

TABLE 4.—Bycatch of Atlantic sturgeon (lb) and landings for monitored trips (lb) by declared target species. Associated bycatch rate was calculated as pounds of sturgeon per pound landed.

Target species	Sturgeon catch	Landings for monitored trips	Bycatch rate
Bluefish	169	257,215	0.000657
Butterfish *Peprilus triacanthus*	265	331,064	0.000800
Atlantic cod	1,542	323,795	0.004762
Atlantic croaker	373	749,476	0.000497
Haddock *Melanogrammus aeglefinus*	45	97,974	0.000459
Horseshoe crab	97	205,728	0.000471
Northern kingfish *Menticirrhus saxatilis*	85	3,511	0.024213
Longfin inshore squid	355	1,826,769	0.000194
Atlantic menhaden *Brevoortia tyrannus*	8	25,792	0.000291
Goosefish	7,975	1,599,948	0.004984
Pollock	75	717,607	0.000105
Red hake *Urophycis chuss*–silver hake	50	2,912	0.017170
Scup *Stenotomus chrysops*	570	48,525	0.011747
American shad	540	22,582	0.023899
Smooth dogfish *Mustelus canis*	760	246,244	0.003086
Southern flounder *Paralichthys lethostigma*	107	5,361	0.019959
Spiny dogfish	3,910	4,126,878	0.000947
Striped bass *Morone saxatilis*	456	58,874	0.007745
Summer flounder	1,196	720,499	0.001660
Tautog *Tautoga onitis*	10	8,906	0.001123
Unidentified dogfish	2,107	1,320,843	0.001595
Unidentified squid	50	519,933	0.000096
Unidentified tuna	8	843,336	0.000009
Weakfish *Cynoscion regalis*–bluefish	116	11,163	0.010391
Weakfish–Atlantic croaker	10	45,290	0.000221
Weakfish–Striped bass	35	210	0.166667
Winter flounder *Pleuronectes americanus*	277	108,613	0.002550
Winter skate *Raja ocellata*	105	7,008	0.014983
Witch flounder *Glyptocephalus cynoglossus*	341	20,628	0.016531
Yellowtail flounder *Pleuronectes ferrugineus*	230	434,270	0.000530

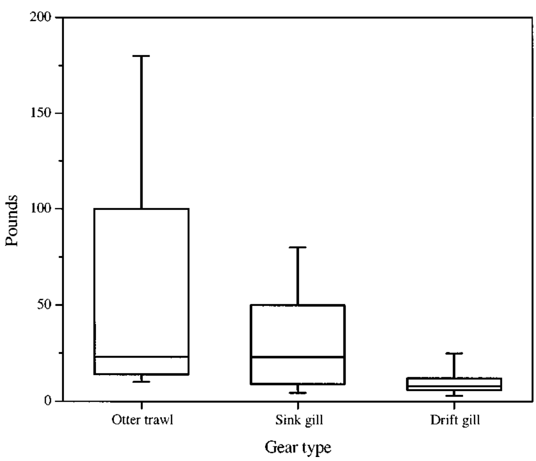

FIGURE 5.—Whole weights for individual Atlantic sturgeon from monitored trips made by otter trawls, sink gill nets, and drift gill nets. Boxes denote the quartile ranges, and whiskers denote the 90% confidence intervals.

ing scheme between 1997 and 1999. This separation showed an increased bycatch estimate when the weighted rates incorporated the rates for the individual years at 25% and the mean rates at 75%. Drift gill net estimates were stable at around 50,000 lb per year (Figure 9). Early in the time series, the estimates were below 1,000 lb, but they increased substantially in 1989 to approximately 150,000 lb due to an anomalous increase in the bycatch rates. The estimates leveled off and remained at around 50,000 lb throughout the final 11 years of the time series, with little variation between estimates for the three weighting schemes.

Gear Baseline Mortality Rates and Estimates

Based on observer data, substantial quantities of Atlantic sturgeon bycatch resulted in mortality, especially in the gill net gears. The baseline mortality rates for sink gill nets and drift gill nets were 22% and 10%, respectively. Over the time series, sink gill nets killed an estimated 236,292 lb of sturgeon, which represents approximately 1,000

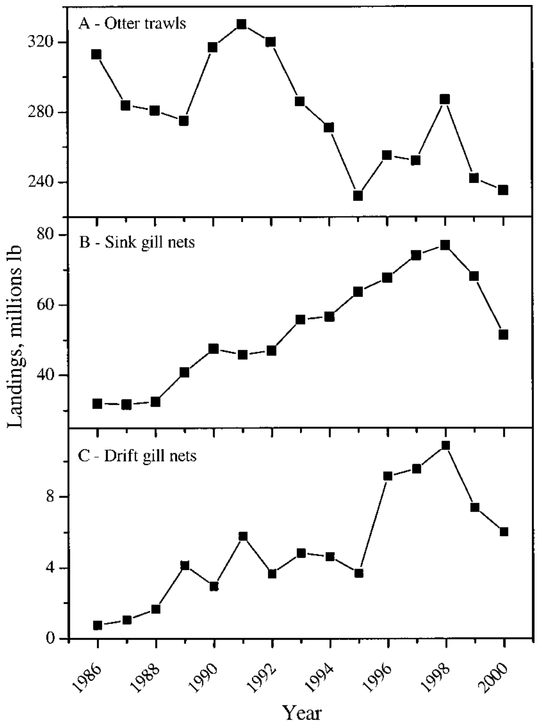

FIGURE 6.—Total landings of all species for all monitored trips, 1986–2000, for (A) otter trawls, (B) sink gill nets, and (C) drift gill nets.

individuals per year for the most contemporary years based on the mean weight from individual fish records (Figure 10). Drift gill nets killed an estimated 70,604 lb of sturgeon, which represents approximately 385 individuals per year in the latter 10 years of the analysis. Sturgeon mortality associated with both sink gill nets and drift gill nets increased through the time series. There were no records of immediate mortality for sturgeon caught in otter trawls in the observer data set.

Discussion

The continuum between target and nontarget species is problematic, especially when the nontargeted species have significant market values. Though the catches described in this study are termed bycatch, it is important to acknowledge that sturgeon must have been the subject of some level of targeting to account for the levels of catch and landings we report here. In fact, spatial patterns in bycatch and bycatch rates were associated with specific areas, such as the New York Bight, that were considered emergent areas of commercial fishing activity during the 1990s (Smith and Clugston 1997). This highlights the inadequacy of many standard databases to interpret fisher motivation and fleet behavior.

Bycatch appears to be a substantial source of chronic mortality for Atlantic sturgeon populations along the northeast coast of the USA. Sink gill nets are the most detrimental of the three studied gears, catching sturgeon at a high rate and causing mortality for at least 22% of captured individuals. Drift gill nets were monitored less frequently but still produced high bycatch rates as well. Drift gill net fisherman must frequently check their gear when in use, which reduces the time that nontarget species are tangled. Sturgeon and other nontarget species are often untangled and released alive. Although otter trawls have no recorded immediate sturgeon mortality, the effect of a fishing gear may last beyond initial contact and release (Boreman 1997; Kynard 1997; Caswell et al. 1998; Clark and Hare 1998). Fish can have a number of gear-related injuries after release, such as stress, scale damage, or disease, which can result in mortality for some time after release. Therefore, despite the reputed hardiness of sturgeon, it may be unadvised to assume sturgeon released from fishing gears do not suffer postrelease injury or mortality. Although it is difficult to quantify the effects and potential mortality related to capture and release, an estimate of delayed mortality is a necessary precaution for population management (Caswell et al. 1998; Crowder and Murawski 1998).

The Atlantic sturgeon bycatch rates were influenced by spatial and temporal trends in gear use. For example, otter trawls were used offshore on the continental shelf, while sturgeon bycatch apparently occurred closer to the coast; consequently, the otter trawl bycatch rates were substantially lower than those of the other gears. The sink gill net fisheries were situated along the coast, producing high bycatch rates and high sturgeon catch for the monitored trips. The bycatch rates for inshore drift gill nets were substantially higher than the rates for the otter trawls or sink gill nets. Each gear had anomalous catch events that increased estimates during individual years within the time series. For drift gill net bycatch, the mean values were also affected by anomalous catches. During the fitting procedure, a single catch event increased contiguous cells. The mean monitored landings were less than the actual monitored landings, substantially increasing the bycatch rate from 0.086 to 0.414 (lb sturgeon/lb monitored landings), which influenced the estimates through the weighting procedure. Therefore, these anomalous catch

TABLE 5.—Standard deviations of bycatch rates, for Atlantic sturgeon (1989–2000) by fishing gear, month, and state. Units are sturgeon pounds per 1,000 lb of monitored landings.

State	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Otter trawl												
Maine	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462
New Hampshire	0.707	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462
Massachusetts	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.333	0.316	0.316
Rhode Island	0.462	0.302	0.462	0.462	0.462	0.462	0.462	0.316	0.462	0.462	0.462	0.333
Connecticut	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462
New York	0.462	0.447	0.447	0.462	0.462	0.408	0.447	0.462	0.462	0.462	0.523	0.500
New Jersey	0.475	0.475	0.475	0.475	0.654	0.500	0.378	0.475	0.378	0.482	0.471	0.462
Pennsylvania	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462
Delaware	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462
Maryland	0.462	0.462	0.462	0.703	0.577	0.500	0.462	0.462	0.462	0.462	0.575	0.462
Virginia	0.378	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.408
North Carolina	0.447	0.577	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.462	0.500
Sink gill nets												
Maine	0.638	0.776	0.660	0.582	0.705	0.349	0.405	0.502	0.316	0.316	0.653	0.378
New Hampshire	0.638	0.776	0.316	0.302	0.705	0.611	0.414	0.316	0.434	0.434	0.643	0.664
Massachusetts	0.507	0.550	0.666	0.689	0.737	0.654	0.475	0.604	0.388	0.595	0.846	0.614
Rhode Island	0.354	0.378	0.660	0.442	0.574	0.570	0.447	0.456	0.408	0.378	0.463	0.546
Connecticut	0.638	0.776	0.660	0.582	0.705	0.611	0.442	0.598	0.600	0.600	0.653	0.664
New York	0.638	0.776	0.660	0.582	0.577	0.577	0.442	0.600	0.600	0.600	0.653	0.664
New Jersey	1.014	0.506	0.839	0.828	1.137	0.438	0.500	0.753	0.753	0.620	0.846	0.797
Delaware	0.638	0.776	0.660	0.582	0.705	0.611	0.442	0.600	0.600	0.600	0.653	0.664
Maryland	1.003	0.502	0.627	0.635	0.485	1.035	0.442	0.727	0.727	0.727	0.485	1.040
Virginia	0.408	1.267	0.651	0.577	0.719	0.655	0.408	0.674	0.674	0.674	0.786	0.591
North Carolina	0.543	1.450	0.860	0.599	0.705	0.611	0.442	0.749	0.749	0.749	0.500	0.681
Drift gill nets												
Maine	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
New Hampshire	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
Massachusetts	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
Rhode Island	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
Connecticut	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
New York	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
New Jersey	0.710	0.710	0.710	0.985	0.710	0.710	0.710	0.500	0.710	0.710	0.710	0.710
Delaware	0.710	0.710	0.710	0.707	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
Maryland	0.710	0.710	0.646	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
Virginia	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710
North Carolina	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710	0.710

events potentially affected the analysis by creating a bias in the estimates.

Analysis of state bycatch records revealed an increase in Atlantic sturgeon bycatch rates from north to south. Although there were regional differences in gear use within the observer database, the trend in state records remained even when each individual gear was examined. This latitudinal trend might be explained by a number of factors. First, differences in regional temperatures along the coast could influence sturgeon movements and migration patterns, thus affecting the length of time sturgeon spend in the marine environment and the potential for sturgeon to encounter marine gears (Kieffer and Kynard 1993; Bain 1997). Second, along the mid-Atlantic Bight, the edge of the continental shelf is relatively narrow, thus restricting the area in which sturgeon might venture and increasing the likelihood of encounters with commercial gears in these areas (Collins et al. 1996; Rochard et al. 1997). Third, differences in geographic formations could potentially influence sturgeon foraging while concurrently affecting gear use along the coast (Johnson et al. 1997).

Sturgeon capture within particular nontarget fisheries is a cause for concern. After reviewing sturgeon bycatch and bycatch rates for 30 target species, we focused on the target species that could potentially impact sturgeon population recovery. Where goosefish, spiny dogfish, Atlantic cod, summer flounder, American shad, and scup were targeted, bycatch was substantial. The eight target species that we focused on (Figure 4) were involved in 85% of all recorded sturgeon bycatch. When American shad and scup were targeted, the bycatch rates for sturgeon were among the highest

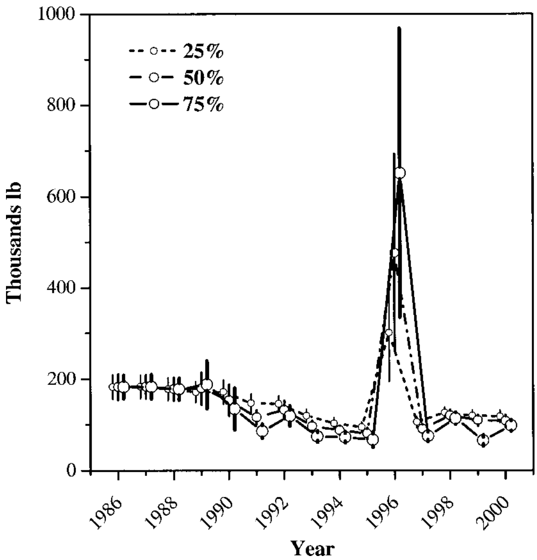

FIGURE 7.—Estimated bycatch of Atlantic sturgeon in otter trawls, 1986–2000, based on three weightings of bycatch rate. The percentages denote the weighting of the bycatch rates for each individual year, while the remaining percent reflects the weighting of the mean rates for that estimate. Error bars are the symmetrical quartile ranges.

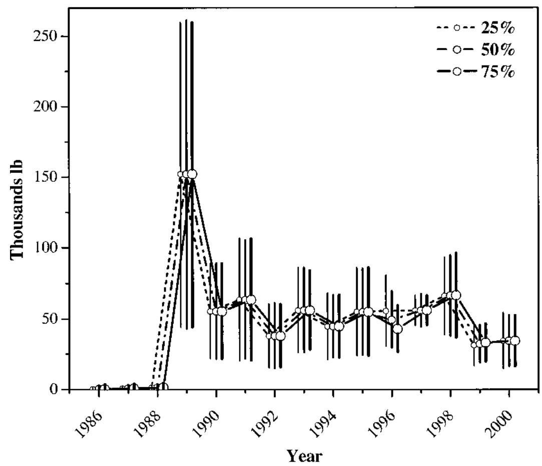

FIGURE 9.—Estimated bycatch of Atlantic sturgeon in drift gill nets, 1986–2000, based on three weightings of bycatch rate. The percentages denote the weighting of the bycatch rates for each individual year, while the remaining percent reflects the weighting of the mean rates for that estimate. Error bars are the symmetrical quartile ranges.

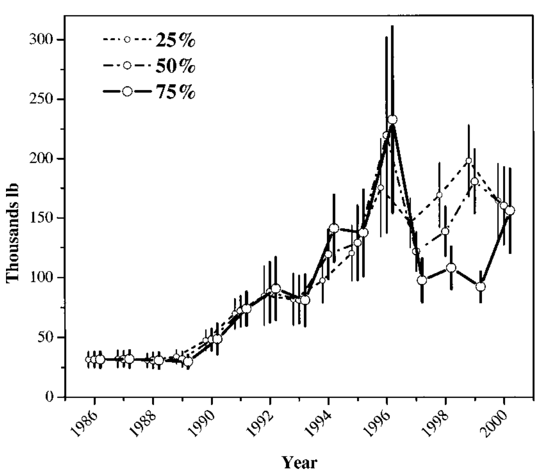

FIGURE 8.—Estimated bycatch of Atlantic sturgeon in sink gill nets, 1986–2000, based on three weightings of bycatch rate. The percentages denote the weighting of the bycatch rates for each individual year, while the remaining percent reflects the weighting of the mean rates for that estimate. Error bars are the symmetrical quartile ranges.

for any target species reviewed. The differences in target species do not highlight particular gears or regions, but show that there are a variety of potential impacts related to gear use and issues of selectivity.

Annual patterns of bycatch are likely related to the seasonal movements of nonspawning adult and juvenile sturgeon. Marine bycatch events occur most often during the fall, winter, and spring months, when spawning sturgeon undergo their

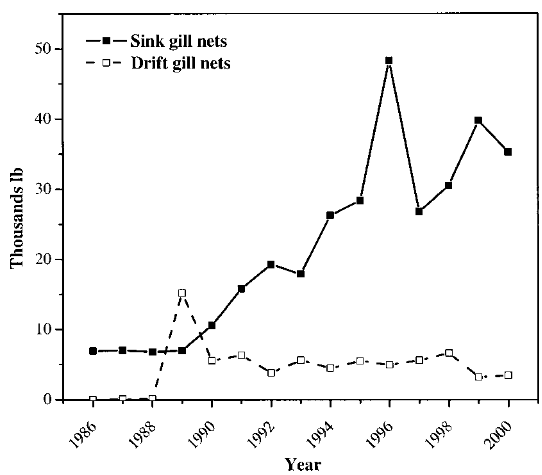

FIGURE 10.—Calculated mortality from estimated Atlantic sturgeon bycatch from 1986 to 2000 for sink gill nets and drift gill nets.

migration upstream (Bain 1997). Since sturgeon rarely spawn in successive years, juveniles and adults may remain in marine foraging areas in high numbers during fall through spring (Dadswell 1979; Kieffer and Kynard 1993; Moser and Ross 1995; Kynard 1997; Auer 1999). During the warm summer months, while marine bycatch is at its lowest point, sturgeon migrate into the estuaries and river systems, seeking thermal refuges (Kynard et al. 2000).

Within the marine and freshwater environments, bycatch is a serious problem that affects sturgeon populations. Along the coast, juveniles and nonspawning adults are captured in nontarget fisheries primarily during the fall, winter, and spring months. In addition to the bycatch documented here, bycatch in gill nets is a substantial cause of mortality in river systems for both east-coast sturgeon species (Collins et al. 1996; Kynard 1997). The marine bycatch data should be used in concert with the available information on sturgeon river bycatch to create a complete depiction of the impacts of bycatch on sturgeon populations (ASMFC 1998). In order to assess sturgeon population recovery, it is necessary to monitor marine commercial fishing effort—particularly for gill nets—along the mid-Atlantic Bight and North Carolina coast, and manage populations based on regulated takes, bycatch, and mortality.

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