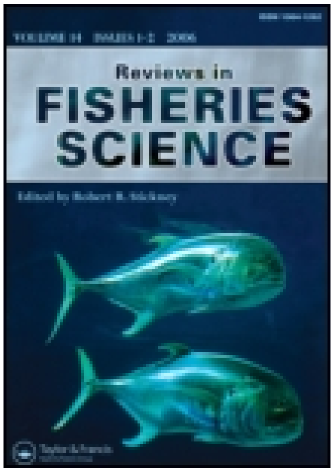
This article was downloaded by: [Acadia University]
On: 04 July 2014, At: 05:53
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Reviews in Fisheries Science & Aquaculture
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/brfs21

# Use of the SAFE Index to Evaluate the Status of a Summer Aggregation of Atlantic Sturgeon in Minas Basin, Canada, and the Implication of the Index for the USA Endangered Species Designation of Atlantic and Shortnose Sturgeons

Kevin D. E. Stokesbury[a], Michael J. W. Stokesbury[b], Matthew T. Balazik[c] & Michael J. Dadswell[b]

[a] Department of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts Dartmouth, Fairhaven, Massachusetts, USA

[b] Department of Biology, Acadia University, Wolfville, Nova Scotia, Canada

[c] Center for Environmental Studies, Virginia Commonwealth University, Richmond, Virginia, USA

Published online: 02 Jul 2014.

To cite this article: Kevin D. E. Stokesbury, Michael J. W. Stokesbury, Matthew T. Balazik & Michael J. Dadswell (2014) Use of the SAFE Index to Evaluate the Status of a Summer Aggregation of Atlantic Sturgeon in Minas Basin, Canada, and the Implication of the Index for the USA Endangered Species Designation of Atlantic and Shortnose Sturgeons, Reviews in Fisheries Science & Aquaculture, 22:3, 193-206

To link to this article: http://dx.doi.org/10.1080/23308249.2014.913005

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

*Reviews in Fisheries Science & Aquaculture*, 22:193–206, 2014
Copyright © Taylor & Francis Group, LLC
ISSN: 2330-8249 print / 2330-8257 online
DOI: 10.1080/23308249.2014.913005

# Use of the SAFE Index to Evaluate the Status of a Summer Aggregation of Atlantic Sturgeon in Minas Basin, Canada, and the Implication of the Index for the USA Endangered Species Designation of Atlantic and Shortnose Sturgeons

**KEVIN D. E. STOKESBURY,[1] MICHAEL J. W. STOKESBURY,[2] MATTHEW T. BALAZIK,[3] and MICHAEL J. DADSWELL[2]**

[1]Department of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts Dartmouth, Fairhaven, Massachusetts, USA
[2]Department of Biology, Acadia University, Wolfville, Nova Scotia, Canada
[3]Center for Environmental Studies, Virginia Commonwealth University, Richmond, Virginia, USA

*Sturgeon species worldwide have undergone population declines due to habitat alteration and overexploitation and many are listed by the International Union for Conservation of Nature (IUCN) and national agencies. Atlantic and shortnose sturgeon on the east coast of North America are listed as "endangered" or "threatened" over most of their ranges. It has been proposed, however, that IUCN risk categories are ambiguous and do not consider the threat status of a species in relation to a minimum viable population level. Here, we examine the Species Ability to Forestall Extinction (SAFE) Index, which is a heuristic measure of a species relative distance from extinction, and other available information on Atlantic and shortnose sturgeon with regard to the risk status of the two species. To move beyond a 'tipping point' designation of threatened, the SAFE Index requires a species abundance of 5000 adults (SAFE Index = 0.0). DNA and mark-recapture data for Atlantic sturgeon in Minas Basin, Canada indicates a USA/Canada mixed stock of ∼10,000 fish aggregate there in summer. The SAFE Index for this population is 0.28 indicating abundance is within the "vulnerable" threshold range for the Index although it includes but a small portion of the Atlantic sturgeon in the western Atlantic. Estimates for the east coast of North America suggest the Atlantic sturgeon population could consist of ∼177,000 sub adults and adults for a SAFE Index of 1.55. Additionally, the present spawning range of Atlantic sturgeon in North America is ∼99% of the historically known range and the number of stocks is near the historic level (33+) which means the species does not meet IUCN criteria for listing. Similarly, shortnose sturgeon has an Atlantic coast population of ∼96,800 adults (SAFE Index of 1.29) and a species range and number of stocks (26+) that has not changed substantially from the historical situation. Since the abundance of Atlantic and shortnose sturgeon are well above the SAFE threshold for "threatened" and they lack other accepted criteria for endangered or threatened designation, we conclude that the risk status of both species should be reconsidered.*

**Keywords** population sizes, risk status, SAFE index, sturgeons

Address correspondence to Kevin D. E. Stokesbury, Department of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts Dartmouth, 200 Mill Road, Suite 325, Fairhaven, MA 02744-1221, USA. E-mail: kstokesbury@umassd.edu

Color versions of one or more figures in this article can be found online at www.tandfonline.com/brfs.

## *INTRODUCTION*

Sturgeon species worldwide have undergone population declines because of habitat alteration and overexploitation and many species are listed in the International Union for Conservation of Nature (IUCN) Red List and by national agencies. It has been proposed that the IUCN threat categories are ambiguous and do not define a risk status for a species in relation to a minimum viable population (MVP) size (Thomas, 1990; Traill et al., 2010). Recently, Clements et al. (2011) proposed a heuristic measure, the Species Ability to Forestall Extinction or "SAFE" Index, which they demonstrated was a better predictor of IUCN threat categories than percentage range loss. The SAFE Index predicts a species distance from extinction by incorporating population size as a variable. For some sturgeon species where population sizes have been estimated, such as Atlantic sturgeon, *Acipenser oxyrinchus* (Mitchill, 1814), and the shortnose sturgeon, *Acipenser brevirostrum* (LeSueur, 1818), the SAFE Index may be a valuable tool to either corroborate or bring into question decisions concerning their proposed risk status.

The Atlantic sturgeon is an anadromous fish which occurs in rivers and seaward to the edge of the continental shelf from Ungava Bay, Labrador, Canada to the northern coast of South America (Vladykov and Greeley, 1963; Dadswell, 2006) and formerly occurred in the Baltic Sea (Ludwig et al., 2002). Although a few Atlantic sturgeon stocks have been extirpated because of dams and perhaps pollution (ASSRT, 2007; Oakley and Hightower, 2007) a large number of stocks are known and their oceanic migration routes and marine feeding grounds are rapidly being described (Fox et al., 2002; Laney et al., 2007; Erickson et al., 2011; McLean et al., 2013).

The shortnose sturgeon is also an anadromous species which occurs in watersheds along eastern North America from the Saint John River, New Brunswick, Canada to the St. Johns River, Florida (Kynard, 1997; NMFS, 1998). Unlike the Atlantic sturgeon, shortnose populations are more closely confined to their natal watersheds and move shorter distances seaward (Fernandes et al., 2010; Peterson and Farrae, 2011; Dadswell et al., 2014). They can become landlocked in freshwater by dams (Root, 2002; Collins et al., 2003). The biology and population size of shortnose sturgeon stocks were poorly known before the 1970s but in response to its listing as 'endangered' by the USA Endangered Species Act (ESA) in 1973 numerous studies have greatly expanded our knowledge in these areas (Dadswell et al., 1984a; NMFS, 1998, 2010).

Atlantic sturgeon supported fisheries along the east coast of North America from the pre-colonial era until the present (Smith, 1985; Cobb, 1900; Smith and Clugston, 1997; Holzkamm and Waisberg, 2004; Bradford et al., 2013). Due to declining abundance the USA fisheries were closed incrementally since 1973 (Dadswell and Nack, 2012) and in 1998 the entire USA Atlantic coast was placed under a 20–40-year fishing moratorium by the Atlantic States Marine Fisheries Commission (ASMFC; Secor and Waldman, 1999; Secor, 2002; Patrick and Damon-Randall, 2008). Following further study USA National Marine Fisheries Service (NMFS) grouped the USA Atlantic coast Atlantic sturgeon into five distinct population segments; four of which were designated "endangered," (New York Bight, Chesapeake Bay, Carolina and South Atlantic segments), and the fifth "threatened," (Gulf of Maine; USA Fed. Regs., 2012a,b). As the proportion of mixing in the marine environment is unknown all Atlantic sturgeon in marine, USA waters were designated "endangered" by the NMFS. The Committee on the Status of Endangered Wildlife in Canada recommended that the Atlantic sturgeon be designated as 'threatened' (COSEWIC, 2011) but this designation is non-binding unless the species is included in the Canadian Species at Risk Act (SARA) registry. Currently, the species is unlisted in Canada and small commercial fisheries remain in the St. Lawrence River, Quebec and the Saint John River, New Brunswick (Dadswell, 2006).

In the USA the shortnose sturgeon landings were always mixed with Atlantic sturgeon landings and reported as a single category "sturgeons" (Dadswell et al., 1984a). Shortnose sturgeon were listed as "endangered" because of limited knowledge concerning their distribution and abundance (Miller, 1972) and remains so despite evidence suggesting it is widespread and often abundant (NMFS, 1998, 2010; Bain et al., 2007). In Canada, shortnose sturgeon were seldom landed because harvesting sturgeon less than 123 cm total length (TL) was prohibited and shortnose rarely reached this size (Dadswell et al., 1984a). Shortnose sturgeon were designated as a "species of concern" by COSEWIC and listed by SARA in this category because spawning is only known to occur in the Saint John River, New Brunswick (Dadswell, 1979; Usvyatsov et al., 2013).

There is considerable new information available on population estimates of both Atlantic and shortnose sturgeon stocks in their natal watersheds and at sea. Here, we examine recent information concerning the size and stock composition of the marine aggregation of Atlantic sturgeon which occurs annually in Minas Basin, inner Bay of Fundy. We use these data to determine SAFE indices for the summer aggregation of Atlantic sturgeon in Minas Basin and for the estimated population sizes of both species on the east coast of North America. Using the SAFE Index in conjunction with the IUCN Percentage Range Loss Method (Ceballos and Ehrlich, 2002) enables us to re-examine the Atlantic and shortnose sturgeon risk status.

## *METHODS*

### *The Study Site*

Minas Basin is a large (822 km$^2$), mega-tidal embayment at the head of the Bay of Fundy, Nova Scotia, Canada, that reaches temperatures of 18–20°C in the summer (Figure 1). Minas Basin has the world's largest tidal range (16m+ on spring tides) and approximately one-third of its surface area is exposed as sand, mud flats, or salt marshes at low tide (Bousfield and Leim, 1959). The tide flats and salt marshes support a diverse benthic community (Bromley and Bleakney, 1985), which in turn feed large numbers of fish and birds (Dadswell et al., 1984b; Hicklin and Smith, 1984;

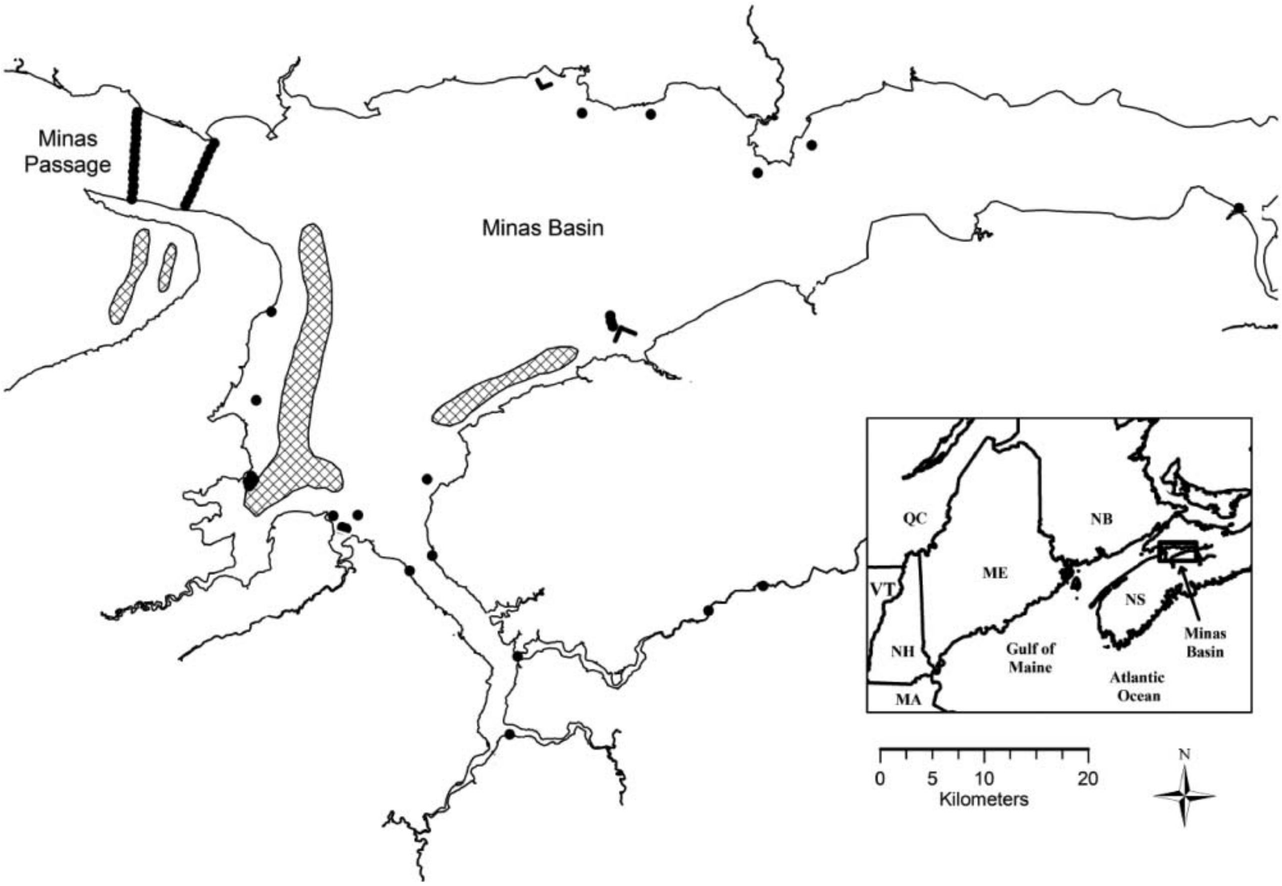


**Figure 1** Minas Basin indicating acoustic receivers deployed during 2005–2013 (dots and lines of dots), weirs (right angles), and trawling area (hashed areas).

McLean et al., 2013). Minas Basin has supported a traditional multi-species fishery since the 1700s using intertidal weirs (Figure 2), gill nets, and otter trawls (Dadswell et al., 1984b; Gordon, 1993; Wehrell, 2005). The extreme tides provide a potential for tidal power (Dadswell and Rulifson, 1994), which has resulted in a closer examination of the fish fauna since the 1980's (Dadswell et al., 1984b; Scott and Scott, 1988; Wehrell, 2005). Interest in tidal power has recently increased and an experimental turbine was deployed for a year in Minas Passage (AECOM, 2009). Wirgin and coworkers (2012) found that 60% of the Atlantic sturgeon in Minas Basin were from the Saint John River, NB, stock and ~36% were from USA stocks, all of which could be impacted if tidal turbines were installed in the future.

### *Atlantic Sturgeon Tagging in Minas Basin*

A mark-recapture population estimate was conducted to determine the size of the summer aggregation of Atlantic sturgeon in Minas Basin. Atlantic sturgeon was taken as bycatch in commercial fisheries during May to August from 2004 to 2013 using intertidal weirs (Figure 2) sited around the shores of the Minas Basin or by otter trawl (Figure 3; Wirgin et al., 2012). Both fishing techniques were considered nonselective for sturgeon because net mesh sizes used (2.5–12.5 cm) would capture all available individuals (Ricker, 1975). Permits for collecting and tagging fish were obtained from the Department of Fisheries and Oceans, Canada (Scientific License to Fish #322595 and 330657).

Although different capture techniques were used, Atlantic sturgeon were handled in a similar manner. Captured fish were examined for any external damage, and fork length (FL) was measured. Individuals were marked with an internal Passive Integrated Transponder Tag (PIT, 134.2 kHz) and numbered, yellow, Floy FT-1-94 spaghetti dart tag. The dart tags were 16 cm long and anchored deep in the pterygiophores below the dorsal fin (Figure 3). Additionally, a sub-sample of sturgeon (114 of 192) captured between 2010 and 2012 were tagged with an internal, coded acoustic tag (VEMCO V16, 4-y battery life; Mclean et al., 2014). These Atlantic sturgeon were sedated with 0.5 mg/L MS-222 and the acoustic tag was implanted in the abdomen following the methods outlined in our Acadia University Animal Care Committee Protocol #07-11. A 3–4 cm incision was made with a scalpel in the abdomen on either side of the *linea alba* (Panther et al., 2011) anterior to the pelvic girdle after sterilization of the area with 10% Betadine solution. The incision was closed with sterile,

**Figure 2** A catch of 12 Atlantic sturgeon from a traditional intertidal fishing weir in Minas Basin.

**Table 1** Survival and fidelity of Atlantic sturgeon to the summer aggregation in Minas Basin based on acoustic tag recoveries

| | | Year and number (% recovered) | | |
|---|---|---|---|---|
| Year tagged | # Tagged | 2010 | 2011 | 2012 |
| 2010 | 30 | 28 (93%) | 26 (93%) | 21 (81%) |
| 2011 | 54 | — | 53 (98%) | 35 (66%) |
| 2012 | 33 | — | — | 33 (100%) |

Mean minimum tagging survival rate during the first summer at large was 97.0% (see Beardsall et al., 2013) and mean minimum annual return rate in subsequent years was 80.0%.

absorbable 1/0 Ethilon monofilament nylon sutures and the incision again sterilized with Betadine. All instruments and equipment, including transmitters, were sterilized with Betadine followed by a saline rinse. Postsurgery, Atlantic sturgeon were held in a circular recovery tank with freshly pumped, local seawater and released once the fish began swimming normally (∼5–10 min). Based on the recovery of acoustic signals from receivers placed around the shores of Minas Basin and across Minas Passage (Figure 1), survival of these Atlantic sturgeon was at least 97% during the year of tagging and the minimum mean return rate over a two-year period was 80% (Tables 1 and 2; Beardsall et al., 2013). Spaghetti tag loss during the study was minimal since only three recaptured sturgeon (0.2%) were observed with tag wounds or retained only their PIT tag, tags were recovered after long time periods (up to 8 years), and all recaptured sturgeon double tagged with an internal acoustic tag retained their spaghetti tag except one (Amstrup et al., 2005). Tag returns were from commercial fishing operations and our continuing tagging study (using commercial fishers) using capture gear (weirs and trawls; Ricker, 1975) that was not size-selective. Only tagged sturgeon at large 15 or more days were considered randomly mixed with the population and used in the population estimates.

**Figure 3** An Atlantic sturgeon tagged with an individually numbered yellow, spaghetti tag anchored deep in the pteriogophores below the dorsal fin, and recaptured in a commercial otter trawl along with winter flounders and skates.

### *Modified Schnabel Mark-Recapture Model*

To estimate the size of the Atlantic sturgeon summer aggregation in Minas Basin, we used the modified Schnabel, mark-recapture model (Ricker, 1975) calculated as:

$$N = \frac{\sum C_t M_t}{\sum R_t + 1}, \tag{1}$$

where:

$N$ = number of sturgeon estimated in the population

**Table 2** Fidelity of Atlantic sturgeon to the summer aggregation in Minas Basin based on external marks, 2004–2013

| | | | | | | Year recovered | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Mark | 2004 | 2005 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | Total | % |
| 2004 | 24 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 4.2 |
| 2005 | 10 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 2 | 20.0 |
| 2007 | 121 | | | 2 | 6 | 1 | 0 | 0 | 0 | 0 | 9 | 7.4 |
| 2008 | 412 | | | | 9 | 2 | 1 | 3 | 5 | 4 | 24 | 5.8 |
| 2009 | 66 | | | | | 0 | 0 | 2 | 1 | 1 | 4 | 6.1 |
| 2010 | 30 | | | | | | 0 | 0 | 2 | 1 | 3 | 10.0 |
| 2011 | 86 | | | | | | | 0 | 0 | 5 | 5 | 5.8 |
| 2012 | 76 | | | | | | | | 2 | 4 | 6 | 7.9 |
| 2013 | 374 | | | | | | | | | 5 | 5 | 1.3 |
| Total | 1199 | 0 | 0 | 2 | 17 | 3 | 1 | 5 | 10 | 21 | 59 | 4.9 |

Recoveries include those from fishers where total catch information was not available and are not included in population estimates in Table 4. Recoveries must be at large more than 15 days.

$C$ = total number of sturgeon caught in sample $t$
$M$ = number of marked sturgeon at large at sample $t$
$R$ = number of sturgeon already marked when caught in sample $t$

Only a fraction of the total population was caught in each sample ($C_t/N$) and the marked to total population ratio ($M_t/N$) was always $<0.1$. Schnabel abundance 95% confidence intervals were calculated as:

$$N \pm \frac{\sum CM}{df}, \tag{2}$$

where:

$df$ = poisson value at $t = 0.05$ degrees of freedom (# recaptures), the upper and lower limits are asymmetric around $N$ because recaptures were about 50 or less (Krebs, 1989).

We used a closed-population Schnabel model in this study because when sturgeon enter the Minas Basin cul-de-sac (Figure 1) they remain for the summer (e.g., a closed population) and there was a consistent return rate of externally tagged sturgeon over all tagging years to the Basin in years following tagging (∼5%; Table 2). Additionally, based on our acoustic returns most or all sturgeon exit the Basin during late autumn (Stokesbury et al., unpublished data), but there was a high return rate in the spring (∼80; Table 1). This latter fact precluded the use of a Jolly-Seber population model, which assumes permanent emigration (Amstrup et al., 2005).

### *Estimated Population Sizes for Atlantic and Shortnose Sturgeon, East Coast North America*

Population estimates, other than the Minas Basin aggregation, for Atlantic sturgeon, *Acipenser oxyrinchus* (we have included both subspecies *oxyrinchus* and *desotoi*), and the shortnose sturgeon, *Acipenser brevirostrum* were collected from the most recent**,** peer-reviewed scientific sources available. We assumed that Atlantic sturgeon river abundance estimates were additive to at-sea abundance estimates. We considered at-sea Atlantic sturgeon “virtual” adults as natural mortality rates decline and growth rates increase once the sturgeon have successfully entered the marine environment (Gross et al., 1988; Sulak and Randall, 2002; Kahnle et al., 2007; Balazik et al., 2012b). Given this assumption, at-sea population estimates are comparable to river population estimates of adults and are mutually exclusive because of the intermittent nature and extended run duration of spawning (Van Eenennaam et al., 1996; Sulak and Clugston, 1999; Balazik et al., 2012a,b; Bradford et al., 2013) which occurs at the same time as most at-sea abundance studies (Erickson et al., 2011; Kocik et al., 2013).

Bain et al. (2007) recently estimated the Hudson River population of shortnose sturgeon. We recalculated the Delaware shortnose sturgeon population estimate using a modified Schnabel estimate based on Hastings et al. (1987) mark-recapture data. The adult shortnose sturgeon population size used for the Altamaha River was the mean of annual population estimates made over the four-year period from 2004–2007 (Peterson and Bednarski, 2013). We did not include the landlocked, upper Connecticut River population in the carrying capacity assessment as its biological characteristics indicate the population has a low condition factor and slow growth indicating sub-optimal freshwater habitat (Taubert, 1980).

### *The SAFE Index*

The SAFE index (Clements et al., 2011) was calculated as:

$$\text{SAFEindex} = \log_{10}(N) - \log_{10}(\text{MVP}_t)$$

where:

$N$ = the species population estimate throughout the species known range (e.g., all populations combined)
$\text{MVP}_t$ = an empirically supported minimum viable population threshold which is currently set at 5000 individuals according to median demographic and genetic estimates of size requirements among widely different taxonomic groups (Traill et al., 2007, 2010).

### *Percent Range Change from Historic Levels*

Percent range change for both species was estimated as the percent of the total known historic spawning range (km of coastline distance) on the east coast of North America (ASSRT, 2007; Patrick and Damon-Randall, 2008). The Atlantic sturgeon was found in the Baltic Sea region of Europe before 1900 (Ludwig et al., 2002, 2008) and the northern coast of South America (Vladykov and Greeley, 1963) but these aggregations are not included in our study.

### *Carrying Capacity of Shortnose Sturgeon Estuarine Watersheds*

The Saint John River, New Brunswick was used as the baseline against which other estuaries on the east coast of North America were compared because it is the only estuarine system where adult population size of shortnose sturgeon is known to be relatively stable over the last 40 years (Dadswell, 1979; Li et al., 2007; Usvyatsov et al., 2012). Additionally, the Saint John River shortnose population is not exploited by a commercial fishery and the estuary is relatively free of human impacts. The carrying capacity of adult shortnose sturgeon

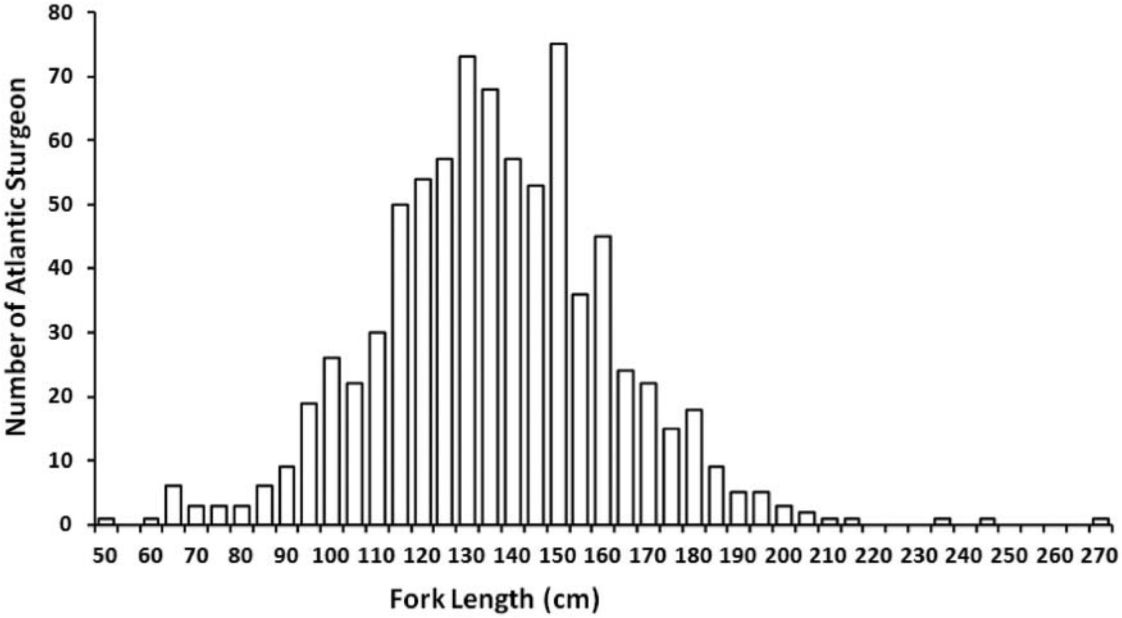


**Figure 4** Fork length frequency of Atlantic sturgeon captured in the Walton weir, Minas Basin during 2005–2013 ($n = 805$, mean = 136.1 cm FL).

was determined as:

$$\text{Carrying Capacity (adults/ha)} = \text{Estimated Adult Population/Estuarine Surface Area(ha)}.$$

Estuarine surface area was determined using a planimeter and large scale maps (1:50,000) from the head of tide to the ocean (~25ppt).

## RESULTS

### *Modified Schnabel Mark-Recapture Estimate for the Minas Basin Atlantic Sturgeon Summer Aggregation*

Atlantic sturgeon from the summer aggregation in Minas Basin ranged in size from 46–267 cm FL but ~95% were in the range 100–160 cm FL (Figure 4). Most Atlantic sturgeon aged with pectoral ray sections were between 10 and 25 years (range 3–64 years; M. J. Dadswell, Acadia University, unpublished data).

During 2004–2013 a total of 1,655 Atlantic sturgeon were captured, 1199 were tagged with dart tags and there were 51 recaptures from the same or previous years that had been at large 15 days or more. We had sufficient tag returns for the summers of 2008 and 2013 and the period 2004–2013 to perform two, one-summer estimates (Table 3) and a multiyear estimate (Table 4) that were valid (4+ returns; Ricker, 1975) which demonstrate that the estimated size of the aggregation is relatively consistent.

Mark-recapture estimates from Atlantic sturgeon in Minas Basin during the summers of 2008 and 2013 were 8804 and 9244, respectively, (Table 3) and the multiyear estimate was 12,754 fish (Table 4). The three estimates suggest a population of ~10,000 fish aggregates in the Basin annually between May and October. A regression of marked at large for time ($M_t$) compared to recaptures at time ($t$) divided by catch at time ($C_t$) for the multiyear estimate was significant with an $r^2$ of 0.69 ($y = 4 \times 10^{-5} + 0.0066$) indicating these data met the assumptions for the Schnabel method.

**Table 3** Atlantic sturgeon population estimates for Minas Basin using a modified Schnabel model during the summers of 2008 and 2013

| 2008 | $C_t$ | $R_t$ | $M$ | $M_t$ | $C_tM_t$ |
|---|---|---|---|---|---|
| May | 8 | 0 | 8 | 0 | 0 |
| June | 33 | 1 | 33 | 8 | 264 |
| July | 461 | 5 | 227 | 41 | 18,901 |
| August | 257 | 3 | 114 | 268 | 68,876 |
| Sum | 759 | 9 | 382 | | 88,041 |
| Population estimates | | | Lower | N | Upper |
| Modified Schnabel method | | | 4108 | 8804 | 15,443 |
| 2013 | $C_t$ | $R_t$ | $M$ | $M_t$ | $C_tM_t$ |
| May | 69 | 0 | 52 | 0 | 0 |
| June | 157 | 2 | 130 | 52 | 8164 |
| July | 102 | 1 | 99 | 182 | 18,564 |
| August | 61 | 1 | 60 | 281 | 17,141 |
| September | 34 | 1 | 33 | 341 | 11,594 |
| Sum | 423 | 5 | 374 | | 55,463 |
| Population estimates | | | Lower | $N$ | Upper |
| Modified Schnabel method | | | 4962 | 9244 | 28,154 |

Following Ricker (1975); $C_t$ is catch at time ($t$), $R_t$ is recapture at time ($t$), $M$ is number marked, and $M_t$ is number marked at large for time ($t$); $N$ equals population estimate, $L$ (lower) and $U$ (upper) represent the 95% confidence limits. Recoveries must be at large 15 days.

**Table 4** Atlantic sturgeon population estimates for Minas Basin using a multiyear Modified Schnabel model for the period from 2004 to 2013

| Year | $C_t$ | $R_t$ | $M$ | $M_t$ | $C_tM_t$ |
|---|---|---|---|---|---|
| 2004 | 39 | 0 | 24 | 0 | 0 |
| 2005 | 18 | 0 | 10 | 24 | 432 |
| 2007 | 144 | 2 | 121 | 34 | 4896 |
| 2008 | 750 | 17 | 412 | 155 | 116,250 |
| 2009 | 77 | 3 | 66 | 567 | 43,659 |
| 2010 | 31 | 1 | 30 | 633 | 19,623 |
| 2011 | 89 | 3 | 86 | 663 | 59,007 |
| 2012 | 94 | 4 | 76 | 749 | 70,406 |
| 2013 | 423 | 21 | 374 | 825 | 348,975 |
| Sum | 1665 | 51 | 1199 | 3650 | 663,248 |
| Population estimates | | | Lower | $N$ | Upper |
| Modified Schnabel method | | | 9935 | 12,754 | 17,607 |

Following Ricker (1975); $C_t$ is catch at time ($t$), $R_t$ is recapture at time ($t$), $M$ is number marked, and $M_t$ is number marked at large for time ($t$); $N$ equals population estimate, $L$ (lower) and $U$ (upper) represent the 95% confidence limits. Recoveries must be at large 15 days.

### Population Estimates or Captures of Atlantic and Shortnose Sturgeon

Since the 1970s, there have been numerous studies conducted on almost every river on the east coast of North America with a stock of Atlantic or shortnose sturgeon that either provides a population estimate or a discrete number of captures (tagged fish). All of the stocks that had been previously fished have been unexploited for at least one generation (Table 5). Recently, two estimates of Atlantic sturgeon abundance from Cape Hatteras, NC, to Cape Cod, MA, were derived using two data sets; one from the Virginia Institute of Marine Science's North East Area Monitoring and Assessment Program (NEAMAP) survey, which provides a catch-per-unit-effort minimum swept-area estimate; the second from a tagging model using observer data and total fishery discards by an exploitation rate and included the Gulf of Maine (Eyler et al., 2009; Kocik et al., 2013). For the NEAMAP survey, minimum swept area estimates from the fall survey ranged from 6980 to 42,160 sturgeon and the spring survey from 25,540 to 52,990. The fishery discards model provided an estimate of 139,000 sturgeon with CV's of 21 and 39% for moving three-year and five-year averages, respectively (Kocik et al., 2013). The area sampled by NEAMAP is a subset of the area sampled by the discards model so these estimates are consistent. When riverine and at-sea estimates and captures are summed they indicate that there is probably a minimum population of ∼177,000 "virtual" adult Atlantic sturgeon on the east coast of North America (Table 6; note the NEAMAP were excluded in the total estimate as it is a subset of the larger fishing discard estimate). Similarly, the minimum Atlantic coast population of adult, shortnose sturgeon based on watershed estimates is ∼96,800 (Table 7).

**Table 5** Date of closure of the commercial fishery and number of unexploited year classes of Atlantic sturgeon by USA State with known Atlantic sturgeon populations

| State | Closure Date | Females 50% Maturity (year) | Unexploited as of 2012 Year classes | Generations |
|---|---|---|---|---|
| Maine | 1992 | 20 | 20 | 1.0 |
| Connecticut | 1998 | 15 | 14 | 1.0 |
| New York | 1996 | 15 | 16 | 1.1 |
| New Jersey | 1996 | 15 | 16 | 1.1 |
| Pennsylvania | 1990 | 15 | 22 | 1.6 |
| Delaware | 1998 | 15 | 14 | 1.0 |
| Maryland | 1996 | 15 | 16 | 1.1 |
| Virginia | 1973 | 15 | 39 | 2.6 |
| North Carolina | 1991 | 10 | 21 | 2.1 |
| South Carolina | 1985 | 10 | 27 | 2.7 |
| Georgia | 1997 | 10 | 15 | 1.5 |

Number of unexploited year classes for each state is based on closure date and the approximate time when 50% of the female sturgeon in the region reach maturity.

### SAFE Indices

The SAFE Index calculated for the summer aggregation of Atlantic sturgeon in Minas Basin was 0.28 (Tables 6 and 7, Figures 5 and 6). The SAFE index for the "virtual" adult metapopulation of Atlantic sturgeon in Northeast USA coastal waters was 1.44 (∼139,000 fish, Kocik et al., 2013; Figure 5). SAFE indices for adults in individual populations of shortnose sturgeon range from −1.00 for the Altamaha River (∼1500 adults; Peterson and Bednarski, 2013) to +1.05 for the population in the Hudson River (∼57,000 adults; Bain et al., 2007; Figure 6). The SAFE Indices determined for the total North American east coast populations of adult and sub-adult Atlantic sturgeon and adult shortnose sturgeon were 1.55 and 1.29, respectively (Tables 6 and 7; Figures 5 and 6).

### Percent Range Changes from Historic Levels

The historic spawning range of Atlantic sturgeon, *Acipenser oxyrinchus,* on the east coast of North America was from the Mississippi River, LA to the Saint Lawrence River, PQ (Vladykov and Greeley, 1963; Dadswell, 2006; note in this analysis we have included the subspecies Gulf sturgeon *desotoi*). A spawning population exists in the Pearl River, LA which is approximately 140 km east of the Mississippi (Morrow et al., 1998) and spawning has been recently described from the Saint Lawrence River, PQ (Trencia et al., 2002) which means the spawning range is still ∼99% of the historic range and contains ∼33 stocks (Wirgin et al., 2000). Although free-flowing big river sturgeon habitats were altered drastically in the 1930s through the 1980s (Dynesius and Nilsson, 1994; Collins et al., 2000a,b; Sulak and Randall, 2002), Patrick and Damon-Randall (2008) estimated that 91% of the freshwater natal spawning habitat is still available (ASSRT, 2007). Recently, Atlantic sturgeon populations have been described

**Table 6** Minimum estimated population size or captures of Atlantic sturgeon in at-sea aggregations or riverine stocks on the east coast of North America

| Location | Estimate | Captures | Source |
|---|---|---|---|
| St. Lawrence R., PQ | | 4800 | Trencia et al., 2002[1] |
| Saint John R., NB | 2000[3] | | Bradford et al., 2013 |
| Annapolis R., NS | | 10 | Dadswell, 2006; M. J. Dadswell, Acadia University, unpublished data[2] |
| Minas Basin, NS | 10,000 | | This study |
| Kennebec R., ME | | 570 | G. Wippelhauser, Maine Department of Marine Resources, personal communication |
| Hudson River, NY | 2200[3] | | Dadswell and Nack, 2012 |
| USA Coastal Observer | 139,000 | | Kocik et al., 2013 |
| James R., VA | 7720[3] | | M. T. Balazik, Virginia Commonwealth University, unpublished data |
| Cape Fear R., NC | | 100 | Moser and Ross, 1995 |
| Waccamaw R.-Winyah Bay, SC | | 100 | Collins and Smith, 1997 |
| Edisto-Combahee R., SC | | 40 | Collins et al., 2000b |
| Altamaha, GA | 1020 | | ASSRT, 2007 |
| Suwannee R., FL | 7650 | | Sulak and Clugston, 1999 |
| Apalachicola R., FL | 1000 | | Flowers et al., 2009 |
| Yellow R., FL | 700 | | Berg and Allen, 2007 |
| Choctawhatchee R., FL | | 50 | Fox et al., 2002 |
| Pascagoula R., MI | | 50 | Heise et al., 2004 |
| Sum | 171,290 | 5670 | |
| Total | 176,960 | | Safe index = 1.55 |

Estimates are rounded to the nearest ten to account for uncertainty. The NEAMAP estimate was excluded in the sum as it is a subset of the USA Coastal Observer estimate.

[1] Population size of annual quota of 4800 sturgeon, 100–150 cm FL (Trencia et al., 2002).

[2] Mortalities of adult sturgeon recovered below the Annapolis Royal Tidal turbine, 1985–2012.

[3] Estimate based on spawning run size only.

from a number of rivers where it was previously unknown (Annapolis River, NS; Dadswell, 2006) or where it was thought to be extirpated (Figure 7; James River, VA; Balazik et al., 2012a,b). Relict or undescribed stocks may occur in numerous other watersheds (Dadswell, 2006; ASSRT, 2007; Wirgin et al., 2007).

The historical range of shortnose sturgeon extended from the Saint John River, NB, Canada to the St. Johns River, FL,

**Table 7** Minimum estimated adult population size or captures for North American east coast stocks of shortnose sturgeon

| Stock | Estimate | Captures | Source |
|---|---|---|---|
| Saint John R., NB | 18,000 | | Dadswell, 1979 |
| Penobscot R., ME | | 150 | Fernandes et al., 2010 |
| Kennebec R., ME | 7200 | | Dadswell et al., 1984a |
| Upper Connecticut R., CT[1] | 500 | | Taubert, 1980 |
| Lower Connecticut R., CT | 900 | | NMFS, 1998 |
| Merrimack R., MA | 30[2] | | Kieffer and Kynard, 1993 |
| Hudson R., NY | 57,000 | | Bain et al., 2007 |
| Delaware R., PA | 10,000 | | Hastings et al., 1987 |
| Upper Chesapeake Bay | | 13 | Welsh et al., 2002 |
| Potomac R., VA | | 2 | Kynard et al., 2009 |
| Cape Fear R., NC | | 10 | Moser and Ross, 1995 |
| Waccamaw R.-Winyah Bay, SC | | 320 | Collins and Smith, 1997 |
| Lake Marion, SC[1] | | 24 | Collins et al., 2003 |
| Cooper R., SC | 200[2] | | Cooke et al., 2002 |
| Edisto R., SC | | 26 | Collins and Smith, 1997 |
| Savannah R., SC | | 600 | Collins and Smith, 1993 |
| Ogeechee R., GA | 290 | | Peterson and Farrae, 2011 |
| Altamaha R., GA | 1500 | | Peterson and Bednarski, 2013 |
| St. John's R., FL | | 10 | NMFS, 1998 |
| Sum | 95,620 | 1155 | |
| Total | 96,775 | | Safe index = 1.29 |

[1] Land-locked population.

[2] Spawning run.

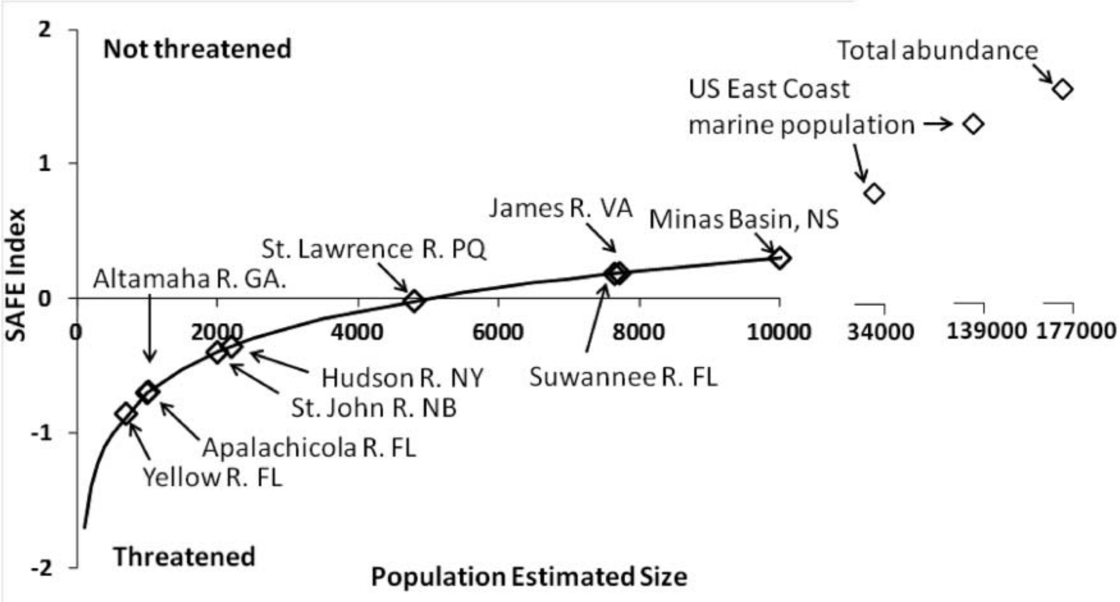


**Figure 5** The "Species Ability to Forestall Extinction" (SAFE) Index verses population size for Atlantic sturgeon and using an empirically supported minimum viable population threshold of 5000 individuals (see Traill et al., 2010).

USA, and the species still occupies 100% of its range and has ~26 stocks (Dadswell et al., 1984a; NMFS, 1998, 2010). Additionally, new populations (Collins et al., 2003; Kynard et al., 2009) and range extensions are being discovered such as the first verified occurrence in Minas Basin, NS in June 2013, a northward range extension of ~165 km for this species (Dadswell et al., 2014).

### *Carrying Capacity of Shortnose Sturgeon Estuaries*

The estimate for the Hudson River estuary was 1.28 adults/ha or more than twice that of the Saint John River (0.51 adults/ha), whereas the carrying capacity for the Delaware River estuary (0.64 adults/ha) was similar to the Saint John River, and that for the Altamaha River estuary was 0.21 adults/ha or less than half that of the Saint John River (Table 8).

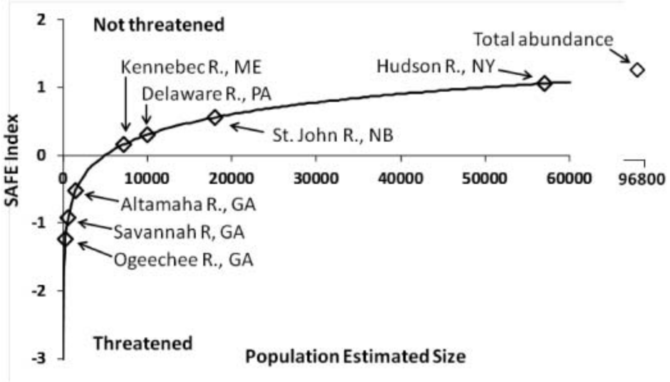


**Figure 6** The "Species Ability to Forestall Extinction" (SAFE) Index verses population size for shortnose sturgeon using an empirically supported minimum viable population threshold of 5000 individuals (see Traill et al., 2010).

## *DISCUSSION*

An extinct species would have a SAFE index of −3.7 and a threatened or endangered species would have a value of zero or lower (Clements et al., 2011). The SAFE index uses an MVP of 5,000 adults for a baseline (i.e., SAFE Index = 0.00). Traill et al. (2010) concluded that both the evolutionary and demographic constraints on populations require sizes to be at least 5000 adults. This value is based on a number of studies; the median MVP derived from population viability analysis of 102 vertebrate species was 5816 individuals (Reed et al.,

**Figure 7** A 50-min catch of adult, male Atlantic sturgeon with 60 m of 33-cm stretched-mesh gillnet during the fall spawning run on the James River, VA, September 2013. The holding tank is being refilled after the researcher cleared approximately 900 kg of sturgeon from the net as quickly as possible.

**Table 8** Carrying capacity of shortnose sturgeon in the estuarine portion of their respective watersheds (from inland tidal limit to ~25 ppt)

| Estuary | Population | Adults/ha |
|---|---|---|
| Saint John R., NB | 18,000 | 0.51 |
| Hudson R., NY | 57,000 | 1.28 |
| Delaware R., PA | 10,000 | 0.64 |
| Altamaha R., GA | 1500 | 0.21 |

2003), MVP equaled 4,169 individuals from a meta-analysis of 212 species (Traill et al., 2007), a census-based MVP provided an estimate of 5500 individuals (Thomas, 1990), and all of these are similar to the recommended effective population size of 4500 individuals based on genetic data (Frankham, 1995). Few fish were used in these studies and how effectively an MVP value of 5000 individuals can be applied to fish species is unclear.

An MVP of 5000 individuals for sturgeon was used because, similar to mammals studied for the MVP calculation, these sturgeon have a long life span of 20–25 years with a maximum age of 35 in southern waters and >60 in northern waters (Magnin, 1964; Dadswell, 1979; Sulak and Randall, 2002), and have an age of maturity of at least five years or older (Dadswell et al., 1984a; Sulak and Randall, 2002; ASSRT, 2007). Atlantic sturgeon have large ovaries and produce 0.8 to 3.76 million eggs with females spawning about every three years (Van Eenennaam et al., 1996) but overall maximum fecundity values are low, with 50% of the lifetime egg production occurring later in life (Boreman, 1997). Both Atlantic and shortnose sturgeon are considered k-selected species similar to mammals under the USA ESA (Fed. Reg., 2012a,b). Utilizing a SAFE index with values derived from mammal populations seems applicable although further development specifically for fish species would be useful.

Sturgeon do seem to have a remarkable ability to rebuild a population from a depleted population size. The MVP calculated for lake sturgeon, *Acipenser fulvescens* (Rafinesque, 1817) is only 80 adults (Schueller and Hayes, 2011). The sturgeon population in the Suwannee River has rebound from about 1000–2000 individuals in the 1980s to 7650 in 1998 (Sulak and Clugston, 1999). Ludwig et al. (2008) estimated that 10 Atlantic sturgeon from northern portion of their range colonized the Baltic Sea about 1200 years ago. Sturgeon are polyploidy and an intriguing hypothesis is that this condition provides a special hedge against the small-population-size genetic bottleneck (Ludwig et al., 2001; Krieger and Fuerst, 2002; Krieger et al., 2006; hypothesis proposed by K Sulak). These studies suggest that 5000 adult individuals in a sturgeon population are probably more than minimally viable.

The modified Schnabel mark-recapture model requires meeting the following assumptions: all recaptured tags are reported; animals do not lose their tags or tag loss can be estimated; marking animals does not affect their catchability; all tags have the same chance of being caught; and the population is closed (Krebs, 1998). We conclude our data met the assumptions for a modified Schnabel estimate (Ricker, 1975) based on monthly or yearly increments and can be used to estimate the size of a virtual, adult population of Atlantic sturgeon in Minas Basin. Our acoustic tag returns indicated an average of 97% survival over one summer and an average of 80% acoustic recovery over subsequent years (Table 1; Beardsall et al., 2013). Although the population is open to the east coast of North America, the single passage to the ocean was monitored year round with the acoustic lines and sturgeon remained mostly in the Basin during the summer months, generally returned the following year (M. Stokesbury unpublished data). Only a few tagged sturgeon released in the Minas Basin have been recovered either from tag returns or acoustically from USA waters (one off Cape Cod, one off Maine) or distant Canadian locations (one off Gaspe, PQ) and most tag returns (16) have been from the Saint John River, NB the source of 60% of the Minas Basin summer aggregation (Wirgin et al., 2012). Additionally, the percentage of total recaptures from subsequent years for tags applied in a discrete year were similar (~5%) and the total number of recaptured tags in subsequent years were proportional to the number of tags applied in a given year (Table 2).

The SAFE index was calculated for the metapopulation of Atlantic sturgeon observed in Minas Basin because it is the only marine aggregation with a mark-recapture abundance estimate. Preferably the SAFE index should incorporate an abundance estimate for the entire species including all marine aggregations and the adults that are in each spawning river during summer (USA Fed. Regs., 2012a,b). There are other marine metapopulations along the USA Atlantic coast in summer and winter (Laney et al., 2007; Dunton et al., 2012; Kocik et al., 2013) and it is unlikely the aggregation in Minas Basin is the only one in the Bay of Fundy during summer. Pearson et al. (2007) found that Atlantic sturgeon were the most important source of bio-turbation of intertidal flats during summer in Chignecto Bay, the megatidal embayment west of Minas Basin. A SAFE index of 0.28 for the Minas Basin metapopulation alone, which is clearly a subsample of the true population of the species, suggests that Atlantic sturgeon are at least at or above a vulnerable threshold, or "tipping point," since this designation falls between −1 and 1 (Clements et al., 2011).

A compilation of the abundance of Atlantic sturgeon on the east coast of North America based on available, recent studies suggests the minimum adult population is ~177,000 virtual adults for a SAFE Index of 1.55 (Table 6). While several Atlantic sturgeon river populations, particularly in the southern portion of the geographic range have estimated numbers that would classify them as "threatened" the population estimates for several large rivers are above the threshold, while the summer aggregation in the Minas Basin and the US East Coast population estimates are well above the 5000 MVP threshold (Figure 5). The overall estimate for Atlantic sturgeon on the east coast of North America is above the "tipping point" designation.

Similarly, when all recent population estimates or captures of shortnose sturgeon along the east coast of North America are compiled, the minimum adult abundance is ∼97,000 for a SAFE Index of 1.29. Shortnose sturgeon are clearly above the tipping point for a threatened species as well.

When present ranges of both sturgeon species are compared to their historic ranges neither species meet the IUCN, USA Endangered Species Act or Canadian SARA regulation of endangered or threatened criteria for range loss. Although the abundance of adult Atlantic sturgeon is reduced from its former level (Secor, 2002) with 91% of its former natal habitat (Patrick and Damon-Randall, 2008) and ∼99% of its former spawning range available on the east coast of North America, the species has adequate scope for complete recovery to exploitable levels of abundance with proper management. Atlantic sturgeon fisheries have been closed in many USA states for much longer than the 1998 federal closure resulting in two or more unexploited generations in many populations (Table 5). Similarly, shortnose sturgeon still occupy 100% of their former spawning range and after 40 years of protection under the USA ESA populations appear to be near or at the carrying capacity of their estuarine habitat (Table 8).

Since any aquatic habitat has a maximum carrying capacity for a particular species, once populations reach this level they have recovered. Why the Hudson River estuary has such a high carrying capacity of 1.28 adults/ha may be explained by the fact this is the only estuary of the four examined that has a population of the introduced zebra mussel, *Dreissena polymorpha* (Woodland et al., 2009). Because molluscs are the preferred food of adult shortnose sturgeon (Dadswell et al., 1984a) the addition of zebra mussel to the Hudson River may have significantly expanded the prey base in this estuary allowing the population to increase to its present large size (Bain et al., 2007). This may be analogous to the dramatic increase in growth rate observed with individuals first become fully anadromous due to the abundance of invertebrate prey in marine compared to freshwater habitats (Sulak and Randall, 2002). A detailed experimental examination of this hypothesis could lead to insights aiding sturgeon enhancement plans.

Determining the risk status of aquatic species is difficult, especially for those whose biology and population characteristics are poorly known. However, determining that an aquatic species is recovered seems to be even more difficult and rare. No fish species declared endangered in the USA has ever been declared recovered (Doremus and Pagel, 2001; Stokstad, 2005). The Oregon chub (*Oregonichthys crameri*), listed as "endangered" in 1993 with less than 1000 individuals, will be the first officially recovered fish species as the population has grown to 160,000 individuals once the USFWS recommendation status change is approved (www.fws.gov/oregonfwo/species/data/oregonchub). Similarly, of the 279 species of freshwater Gastropoda in Canada and the USA that have been listed endangered, only one, the Tulotoma (*Tulotoma magnifica*) has been down-listed to threatened (Johnson et al., 2013).

The ecosystem approach to fisheries requires that managers take account of the environmental impacts of fishing. These fishing effects can be assessed at different biological scales from the "individual" (growth, energetic, physiology, injury, predation, and spatial distribution), to the "population" (abundance, spatial distribution, age structure, recruitment, and fertilization success) and to the "community" (recovery, resilience, recolonization, equilibrium shift, tropic levels, and physical/chemical shifts in habitat) (Mayr, 1997). The key advantage of the SAFE Index is that it enables us to examine these scales quantitatively, as they relate to one another and to the threat of extinction for a species. For Atlantic and shortnose sturgeon it provides a measure that can be used for evaluating risk potential by comparing estimates of abundance in rivers to marine aggregations to the overall population size for each species. We suggest that although individual sturgeon populations in some rivers may be threatened or may never have had large populations, overall the two species are outside the range of vulnerability and lack the characteristic criteria set out by numerous national and international agencies to be designated at risk. The status of both sturgeon species should be reassessed according to state, provincial, and federal jurisdictions in the USA and Canada.

## ACKNOWLEDGMENTS

We thank A. Redden and J. Broome of the Acadia Centre for Estuarine Research for deployment of the Acadia line of acoustic receivers in Minas Passage. We thank the Ocean Tracking Network (OTN) of Dalhousie University for their deployment of a Minas Passage line of receivers. We are grateful to T. Lewis, W. Linkletter, R. Wilcox and D. Porter for allowing us to sample in their fishing weirs. We thank Captain G. Travis and C. Travis for allowing us to sample their trawler catches. We thank S. Wehrell, A. Spares, G. Nau, M. McLean, W. Roberts, T. Gregoire, L. Boudreau, M. Gregoire, J. Breadsall, S. Munroe, D. Quinn, M. Baker, and J. Whidden for sturgeon tagging field work in all weather and at all times of the day and night. G. Wippelhauser provided us with unpublished data on the number of individually, acoustic tagged sturgeon in Maine. We thank P. Rago for insight on coastal population analysis; C. Chambers for discussion, sushi, and review; and K. Sulak for providing an excellent critical review full of ideas, suggestions, and further reading.

## FUNDING

Funding for students was provided by A. Redden through Nova Scotia Power and the Fundy Ocean Research Center for Energy and for T. Avery by the Department of Fisheries and Oceans Canada. M. Stokesbury's and M. Dadswell's students were funded by the Natural Sciences and Engineering

Research Council (NSERC) through OTN Canada, and the Acadia University Faculty Research Fund. M. Stokesbury was supported by the Canada Research Chairs Program. M. Balazik was supported by postdoctoral funding through the Virginia Commonwealth University.

## *REFERENCES*

AECOM. *Environmental assessment registration document – Fundy tidal energy demonstration project. Volume 1: Environmental Assessment*. Fundy Ocean Research Centre for Energy, Project #107405 (2009).

Amstrup, S. C., T. L. McDonald, and B. F. J. Manly. *Handbook of Capture-Recapture Analysis*, p. 313. Princeton, NJ: Princeton University Press (2005).

Atlantic Sturgeon Status Review Team (ASSRT). *Status Review of Atlantic Sturgeon (Acipenser Oxyrinchus Oxyrinchus)*. Gloucester, MA: National Marine Fisheries Service, NE Regional Office (2007).

Bain, M. B., N. Haley, D. L. Peterson, K. K. Arend, K. E. Mills, and P. J. Sullivan. Recovery of an US endangered fish. *PLos*, **2**:e168 (2007). Doi: 101371/journal.pone.0000168 2007.

Balazik, M. T., G. C. Garman, J. P. Van Eenennaam, J. Mohler, and L. C. Woods III. Empirical evidence of fall spawning by Atlantic sturgeon in the James River, Virginia. *Trans. Am. Fish. Soc.*, **141**: 1465–1471 (2012a).

Balazik, M. T., S. P. McIninch, G. C. Garman, and R. J. Latour. Age and growth of Atlantic sturgeon in the James River, Virginia. *Trans. Am. Fish. Soc.*, **140**: 1074–1080 (2012b).

Beardsall, J. W., M. F. McLean, S. J. Cooke, B. W. Wilson, M. J. Dadswell, A. Redden, and M. J. W. Stokesbury. Consequences of incidental otter trawl capture on survival and physiological condition of the threatened Atlantic sturgeon. *Trans. Am. Fish. Soc.*, **142**: 1202–1214 (2013).

Berg, J. J., and S. S. Allen. Population assessment of the Gulf of Mexico sturgeon in the Yellow River, Florida. *Am. Fish. Soc. Symp.*, **56**: 365–379 (2007).

Bromley, J. E. C., and J. S. Bleakney. *Keys to the Fauna and Flora of Minas Basin*. National Research Council of Canada Publication 2419 (1985).

Bradford, R. G., P. Bentzen, C. Ceappa, A. M. Cook, M. Curry, and P. LeBlanc. *Status of Atlantic Sturgeon in the Saint John River*, New Brunswick. Halifax: Canadian Science Advisory Secretariat (2013).

Bousfield, E. L. and A. H. Leim. The fauna of Minas Basin and Minas Channel. *Nat. Mus. Can. Bull.* 166 (1959).

Boreman, J. Sensitivity of North American sturgeons and paddlefish to fishing mortality. *Environ. Biol. Fish.*, **48**: 399–405 (1997).

Ceballos, G., and R. R. Ehrlich. Mammal population loses and the extinction crisis. *Science*, **296**: 904–906 (2002).

Clements, G. R., C. J. A. Bradshaw, B. W. Brook, and W. F. Laurance. The SAFE index: using a threshold population target to measure relative species threat. *Fron. Ecol. Environ.*, **9**: 521–525 (2011).

Cobb, J. N. The sturgeon fishery of the Delaware River and Bay. *U.S. Commission of Fish and Fisheries*, **25**: 369–381 (1900).

Collins, M. R., D. Cooke, B. Post, J. Crane, J. Bulak, T. I. J. Smith, T. W. Greig, and J. M. Quattro. Shortnose sturgeon in the Santee-Cooper Reservoir system, South Carolina. *Trans. Am. Fish. Soc.*, **132**: 1244–1250 (2003).

Collins, M. R., S. G. Rogers, T. I. J. Smith, and M. L. Moser. Primary factors affecting sturgeon populations in the southeastern United States: fishing mortality and degradation of essential habitats. *Bull. Mar. Sci.*, **66**: 917–928 (2000a).

Collins, M. R. and T. I. J. Smith. Characteristics of the adult segment of the Savannah River population of shortnose sturgeon. *Proc. Ann. Conf. SE Ass. Fish Wildl. Agen.*, **47**: 485–491 (1993).

Collins, M. R. and T. I. J. Smith. Management Briefs: distributions of shortnose and Atlantic sturgeons in South Carolina. *J. Fish. Manag.*, **17**: 995–1000 (1997).

Collins, M. R., T. I. J. Smith, W. C. Post, and O. Pashuk. Habitat utilization and biological characteristics of adult Atlantic sturgeon in two South Carolina rivers. *Trans. Am. Fish. Soc.*, **129**: 982–988 (2000b).

Cooke, D. W., S. D. Leach, and J. J. Isely. Behavior and lack of upstream passage of shortnose sturgeon at a hydroelectric facility and navigation lock complex. *Am. Fish. Soc. Symp.*, **28**: 101–110 (2002).

COSEWIC (Committee on the status of Endangered Wildlife in Canada). *Assessment and Status Report on the Atlantic Sturgeon, Acipenser Oxyrinchus, in Canada*. Ottawa: COSEWIC (2011).

Dadswell, M. J. Biology and population characteristics of the shortnose sturgeon, *Acipenser brevirostrum* LeSueur, 1818 (Osteichthyes: Acipenseridae), the Saint John River estuary, New Brunswick, Canada. *Can. J. Zool.*, **57**: 2186–2210 (1979).

Dadswell, M. J. A review of the status of Atlantic sturgeon in Canada, with comparisons to populations in the United States and Europe. *Fisheries*, **31**: 218–229 (2006).

Dadswell, M. J., R. Bradford, A. H. Leim, D. J. Scarratt, G. D. Melvin, and R. G. Appy. A review of research on fishes and fisheries in the Bay of Fundy between 1976 and 1983 with particular reference to its upper reaches. *Can. Tech. Rep. Fish. Aquat. Sci.*, **1256**: 163–294 (1984b).

Dadswell, M. J., and S. Nack. *An analysis of the scientific data used in the NOAA Listing of the USA Atlantic coast Atlantic sturgeon population as endangered*. Available from www/asmfc.org (2012).

Dadswell, M. J., G. Nau, and M. J. W. Stokesbury. First verified record of shortnose sturgeon, Acipenser brevirostrum LeSueur, 1818, in Minas Basin, Bay of Fundy, Nova Scotia, Canada. *Proc. Nova Scotia Inst.* Sci., **47**: 273–279 (2014).

Dadswell, M. J., and Rulifson, R. A. Macrotidal estuaries: a region of collision between migratory marine animals and tidal power development. *Biol. J. Linn. Soc.*, **51**: 93–113 (1994).

Dadswell, M. J., B. D. Taubert, T. S. Squiers, D. Marchette, and J. Buckley. Synopsis of the biological data on shortnose sturgeon, *Acipenser brevirostrum* LeSueur, 1818. NOAA Tech. Rep. NMFS 14, *FAO Fish. Syn.* **140** (1984a).

Doremus, H., and J. E. Pagel. Why listing may be forever: perspectives on delisting under the Endangered Species Act. *Conserv. Biol.*, **15**: 1258–1268 (2001).

Dunton, K. J., D. Chapman, A. Jordaan, K. Feldhein, S. J. O'Leary, K. A. McKown, and M. G. Frisk. Genetic mixed stock analysis of Atlantic sturgeon, *Acipenser oxyrinchus*, in a heavily exploited marine habitat indicates the need for routine genetic monitouring. *J. Fish Biol.*, **80**: 207–217 (2012).

Dynesius, M., and C. Nilsson. Fragmentation and flow regulation of river systems in the northern third of the world. *Science*, **266**: 753–762 (1994).

Erickson, D. L., A. Kahnle, M. J. Millard, E. A. Mora, M. Bryja, A. Higgs, J. Mohler, M. Dufour, G. Kenny, J. Sweka, and E. K. Pikitch. Use of pop-up satellite archival tags to identify oceanic-migratory patterns for adult Atlantic sturgeon, *Acipenser oxyrinchus* Mitchill, 1815. *J. App. Ichthy.*, **27**: 356–365 (2011).

Eyler, S., M. Mangold, and S. Minkkinen. *Atlantic Coast Tagging Database*. Annapolis, MD: US Fish and Wildlife Service (2009).

Fernandes, S. J., G. B. Zydlewski, J. D. Zydlewski, G. S. Wipplehauser, and M. T. Kinnison. Seasonal distribution and movements of shortnose sturgeon and Atlantic sturgeon in the Penobscot River estuary, Maine. *Trans. Am. Fish. Soc.*, **139**: 1436–1449 (2010).

Flowers, H. J., W. E. Pine III, A. C. Dutterer, K. G. Johnson, J. W. Ziewitz, M. S. Allen, and F. M. Paruka. Spawning site selection and potential implications of modified flow regimes on viability of Gulf sturgeon populations. *Trans. Am. Fish. Soc.*, **138**: 1266–1284 (2009).

Fox, D. A., J. E. Hightower, and F. M. Parauka. Gulf Sturgeon spawning migration and habitat in the Choctawhatchee River system, Alabama-Florida. *Trans. Am. Fish. Soc.*, **129**: 811–826 (2002).

Frankham, R. Effective population-size and adult-population size ratios in wildlife – a review. *Gene. Res.*, **66**: 95–107 (1995).

Gordon, J. *The Woven Weirs of Minas Basin*. Nova Scotia Museum Curatorial Report **73** (1993).

Gross, M. R., R. M. Coleman, and R. M. McDowall. Aquatic productivity and the evoluation of diadromous fish migration. *Science*, **239**: 1291–1293 (1988).

Hastings, R. W., J. C. O'Herron, K. Schick, and M. A. Lazzari. Occurrence and distribution of shortnose sturgeon, *Acipenser brevirostrum*, in the upper tidal Delaware River. Estuaries, **10**: 337–341 (1987).

Heise, R. J., W. T. Slack, S. T. Ross, and M. A. Dugo. Spawning and associated movement of Gulf sturgeon in the Pascagoula River drainage, Mississippi. *Trans. Am. Fish. Soc.*, **133**: 221–230 (2004).

Hicklin, P. W., and P. C. Smith. Studies of birds in the Bay of Fundy: a review. *Can. Tech. Rep. Fish. Aquat. Sci.*, **1256**: 295–319 (1984).

Holzkamm, T. E., and L. G. Waisberg. Native American utilization of sturgeon. pp. 22–39. In. *Sturgeons and Paddlefish of North America*. (LeBreton, G. T. O., F. W. Beamish, and R. S. McKinley, Eds.). Netherlands: Kluwer Academic Publishers (2004).

Johnson, P. D., A. E. Bogan, K. M. Brown, N. M. Burkhead, J. R. Cordeiro, J. T. Garner, P. D. Hartfield, D. A. W. Lepitzki, G. L. Mackie, E. Pip, T. A. Tarpley, J. S. Tiemann, N. V. Whelan, and E. E. Strong. Conservation status of gastropods of Canada and the United States. *Fisheries*, **38**: 247–267 (2013).

Kahnle, A. W., K. A. Hattala, and K. McKown. Status of Atlantic sturgeon (*Acipenser oxyrinchus*) of the Hudson River estuary, New York, USA. *Am. Fish. Soc. Sym.*, **56**: 347–364 (2007).

Kieffer, M., and B. Kynard. Annual movements of shortnose and Atlantic sturgeon in the Merrimack River. *Trans. Am. Fish. Soc.*, **122**: 1088–1103 (1993).

Kocik, J., C. Lipsky, T. Miller, P. Rago, and G. Shepard. *An Atlantic sturgeon population Index for ESA management analysis*. US Department of Commerce, NE Fisheries Science Centre Reference Document **13-06** (2013).

Krebs, C. J. *Ecological Methodology*. New York, NY: Harper & Row Publishers Inc. (1989).

Krieger, J., and P. A. Fuerst. Evidence of multiple alleles of the nuclear 18S ribosomal RNA gene in sturgeon (Family: Acipenseridae). *J. Appl. Ichthy.*, **18**: 290–297 (2002).

Krieger, J., A. K. Hett, P. A. Fuerst, V. J. Birstein, and A. Ludwig. Unusual intraindividual variation of the nuclear 18S rDNA gene is widespread within the Acipenseridae. *J. Hered.*, **97**: 218–225 (2006).

Kynard, B. Life history, latitudinal patterns and status of shortnose sturgeon. *Environ. Biol. Fish.*, **48**: 319–334 (1997).

Kynard, B., M. Breece, M. Atcheson, M. Keiffer, and M. Mangold. Life history and status of shortnose sturgeon (*Acipenser brevirostrum*) in the Potomoc River. *J. Appl. Ichth.* **25**(Suppl. 2): 34–38 (2009).

Laney, R. W., J. E. Hightower, V. R. Versak, M. F. Mangold, W. W. Cole Jr., and S. E. Winslow. Distribution, habitat use, and size of Atlantic sturgeon captured during cooperative winter tagging cruises, 1988–2006. *Am. Fish. Soc. Sym.*, **56**: 167–182 (2007).

Li, X., M. K. Litvak, and J. E. H. Clarke. Overwintering habitat use of shortnose sturgeon (*Acipenser brevirostrum*): defining critical habitat using a novel underwater video survey and modeling approach. *Can. J. Fish. Aquat. Sci.*, **64**: 1248–1257 (2007).

Ludwig, A., U. Arndt, S. Lippold, N. Benecke, L. Debus, T. L. King, and S. Matsumura. Tracing the first steps of American sturgeon pioneers in Europe. *BMC Evol. Bio.*, **8**: 221–235 (2008)

Ludwig, A., N. M. Belfiore, C. Pitra, V. Svirsky, and I. Jennecken. Genome duplication events and functional reduction of ploidy levels in sturgeon (Acipenser, Huso and Scaphirhynchus). *Genetics*, **158**: 1203–1215 (2001).

Ludwig, A., L. Debus, D. Lieckfeldt, I. Wirgin, N. Benecke, I. Jenneckens, P. Williot, J. R. Walden, and C. Pitra. When the American sea sturgeon swam east. *Nature*, **419**: 447–448 (2002).

Mayr, E. *This is Biology: The Science of the Living World*. Cambridge: Harvard University Press (1997).

Magnin, E. Croissance en longueur de troisesturgeonsd'Amerique du Nord: *Acipenser oxyrhynchus*, Mitchill, Acipenser fulvescens, Rafinesque, et Acipenser brevirostris LeSueur. Verh. *Int. Ver. Limnol.*, **15**: 968–974 (1964).

McLean, M. F., M. J. Dadswell, and M. J. W. Stokesbury. Feeding ecology of Atlantic sturgeon, *Acipenser oxyrinchus oxyrinchus* Mitchill, 1815 on the infauna of intertidal mudflats of Minas Basin, Bay of Fundy. *J. App. Ichthyol.*, **59**: 503–509 (2013).

McLean, M. F., C. A. Simpfendorfer, M. R. Heupel, M. J. Dadswell, and M. J. W. Stokesbury. Diversity of behavioural patterns displayed by a summer feeding aggregation of Atlantic sturgeon in the intertidal region of Minas Basin, Bay of Fundy, Canada. *Mar. Ecol. Prog. Ser.*, **496**: 59–69 (2014).

Miller, R. R. Threatened freshwater fishes of the United States. *Trans. Amer. Fish. Soc.*, **101**: 239–252 (1972).

Morrow, J. V. Jr., J. P. Kirk, K. J. Killgore, H. Rogillio, and C. Knight. Status and recovery potential of Gulf sturgeon in the Pearl River system, Louisiana-Mississippi. *N. Am. J. Fish. Manag.*, **18**: 798–808 (1998).

Moser, M. L., and S. W. Ross. Habitat use and movements of shortnose and Atlantic sturgeons in the lower Cape Fear River, North Carolina. *Trans. Am. Fish. Soc.*, **124**: 225–234 (1995).

NMFS (National Marine Fisheries Service). *Final Recovery Plan for the Shortnose Sturgeon, Acipenser Brevirostrum. Shortnose Sturgeon Recovery Team*, Gloucester, MA: NMFS, NOAA (1998).

NMFS. *Biological Assessment of Shortnose Sturgeon, Acipenser Brevirostrum, Status Review*. Gloucester, MA: NMFS (2010).

Oakley, N. C., and J. E. Hightower. Status of shortnose sturgeon in the Neuse River, North Carolina. *Am. Fish. Soc. Symp.*, **56**: 273–284 (2007).

Panther, J. L., R. S. Brown, G. L. Gaulke, K. A. Deters, C. M. Woodley, and M. B. Eppard. Influence of incision location on transmitter lose: healing, survival, growth, and suture retention of juvenile Chinook salmon. *Trans. Am. Fish. Soc.*, **140**: 1492–1503 (2011).

Patrick, W. S., and K. Damon-Randall. Using a five factorial structured decision analysis to evaluate the extinction risk of Atlantic sturgeon (Acipenser oxyrinchus oxyrinchus). *Biol. Conserv.*, **141**: 2906–2911 (2008).

Pearson, W. S., M. K. Gingras, I. A. Armitage, and S. G. Pemberton. Significance of Atlantic sturgeon feeding excavations, Mary's Point, Bay of Fundy, New Brunswick, Canada. *Palaios*, **22**: 457–464 (2007).

Peterson, D. L., and M. S. Bednarski. Abundance and size structure of shortnose sturgeon in the Altamaha River, Georgia. *Trans. Am. Fish. Soc.*, **142**: 1444–1452 (2013).

Peterson, D. L., and D. J. Farrae. Evidence of metapopulation dynamics in shortnose sturgeon in the southern part of their range. *Trans. Am. Fish. Soc.*, **140**: 1540–1546 (2011).

Reed, D. H., J. J. O'Grady, B. W. Brook, J. D. Ballou, and R. Frankham. Estimates of minimum viable population sizes for vertebrates and factors influencing those estimates. *Biol. Conserv.*, **113**: 23–34 (2003).

Ricker, W. E. Computation and interpretation of biological statistics of fish opulations. *Bull. Fish. Res. Board Can.*, **191** (1975).

Root, K. V. Evaluating risks for threatened species: the shortnose sturgeon in the Connecticut River. *Am. Fish. Soc. Sym.*, **28**: 45–54 (2002).

Schueller, A. M., and D. B. Hayes. Minimum viable population size for lake sturgeon (*Acipenser fulvescens*) using an individual-based model of demographics and genetics. *Can. J. Fish. Aquat. Sci.*, **68**: 62–73 (2011).

Scott, W. B. and M. G. Scott. Atlantic fishes of Canada. *Can. Bull. Fish.Aquat. Sci.*, **219** (1988).

Secor, D. H. Atlantic sturgeon fisheries and stock abundances during the late nineteenth century. *Am. Fish. Soc. Sym.*, **28**: 89–98 (2002).

Secor, D. H., and J. R. Waldman. Historical abundance of Delaware Bay Atlantic sturgeon and potential rate of recovery. *Am. Fish. Soc. Sym.*, **23**: 203–216 (1999).

Smith, T. I. J. The fishery, biology, and management of Atlantic sturgeon, *Acipenser oxyrhynchus*, in North America. *Environ. Biol. Fish.*, **14**: 61–72 (1985).

Smith, T. I. J., and J. P. Clugston. Status and management of Atlantic sturgeon, *Acipenser oxyrinchus*, in North America. *Environ. Biol. Fish.*, **48**: 335–346 (1997).

Stokstad, E. What's wrong with the Endangered Species Act. *Science*, **309**: 2150–2152 (2005).

Sulak, K. J., and J. P. Clugston. Recent advances in life history of the Gulf of Mexico sturgeon, *Acipenser oxyrinchus* desotoi, in the Suwanee River, Florida: a synopsis. *J. App. Ichtyol.*, **15**: 116–128 (1999).

Sulak, K. J., and M. Randall. Understanding sturgeon life history: enigmas, myths, and insights from scientific studies. *J. Appl. Ichtyol.*, **18**: 519–528 (2002).

Taubert, B. D. Reproduction of shortnose sturgeon, *Acipenser brevirostrum*, in the Holyoke Pool, Connecticut River, Massachusetts. *Copeia*, **1980**: 114–117 (1980).

Thomas, C. D. What do real populations tell us about minimum population sizes. *Conserv. Biol.*, **4**: 324–327 (1990).

Traill, L. W., C. J. A. Bradshaw, and B. W. Brook. Minimum viable population size: a meta-analysis of 30 years of published estimates. *Biol. Conserv.*, **139**: 159–166 (2007).

Traill, L. W., B. W. Brook, R. R. Frankham, and C. J. A. Bradshaw. Pragmatic population viability targets in a rapidly changing world. *Biol. Conserv.*, **143**: 28–34 (2010).

Trencia, G., G. Verault, S. George, and P. Pettigrew. Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) fishery management in Quebec. *J. App. Ichth.*, **18**: 594–599 (2002).

USA Federal Regulations. *Endangered and threatened wildlife and plants: final listing for two distinct population segments of Atlantic Sturgeon (Acipenser oxyrinchus oxyrinchus) in the southeast. USA Fed Reg* **77**:5914–5982, 6 February 2012, 50 CFR Part 224 (2012a).

USA Federal Regulations. *Endangered and threatened wildlife and plants; threatened and endangered status for distinct population segments of Atlantic Sturgeon in the Northeast. USA Fed Reg* **77**:5880–5912, 6 February 2012, 50 CFR Parts 223 and 224 (2012b).

Usvyatsov, S., J. Picka, A. Taylor, S. Watmough and M.K. Litvak. Timing and extent of drift of shortnose sturgeon larvae in the Saint John River, New Brunswick, Canada. *Trans. Am. Fish. Soc.*, **142**: 717–730 (2013).

Usvyatsov, S., J. Watmough, and M. K. Litvak. Age and population size estimates of overwintering shortnose sturgeon in the Saint John River, NB, Canada. *Trans. Am. Fish. Soc.*, **141**: 1126–1136 (2012).

Van Eenennaam, J. P., S. I. Doroshov, G. P. Moberg, J. G. Watson, D. S. Moore, and J. Linares. Reproductive conditions of the Atlantic sturgeon (*Acipenser oxyrinchus*) in the Hudson River. *Estuaries* **19**: 769–777 (1996).

Vladykov, V. D., and J. R. Greeley. Fishes of the Western North Atlantic: order Acipenseroidei. *Memoir Sears Foundation for Marine Research Part III*, **1**: 24–60 (1963).

Wehrell, S. *A survey of the groundfish caught by the summer trawl fishery in Minas Basin and Scots Bay. Honours Thesis, Department of Biology, Acadia University*, Wolfville, Canada (2005).

Welsh, S. A., M. F. Mangold, J. S. Skjeveland, and A. J. Spells. Distribution and movement of shortnose sturgeon (*Acipenser brevirostrum*) in the Chesapeake Bay. *Estuaries*, **25**: 101–104 (2002).

Wirgin, I., C. Grunwald, J. Stabile, and J. Waldman. Genetic evidence for relict Atlantic sturgeon stocks along the Mid-Atlantic Coast of the USA. N. *Am. J. Fish. Manag.*, **27**: 1214–1229 (2007).

Wirgin, I., L. Maceda, J. Waldman, S. Wehrell, M. J. Dadswell, and T. King. Stock origin of migratory Atlantic sturgeon in the Minas Basin, Inner Bay of Fundy, Canada, determined by microsatellite and mitochondrial DNA analyses. *Trans. Am. Fish. Soc.*, **141**: 1389–1398 (2012).

Wirgin, I., J. R. Waldman, J. Rosko, R. Gross, M. R. Collins, S. G. Rogers, and J. Stabile. Genetic structure of Atlantic sturgeon populations based on mitochondrial DNA control sequences. *Trans. Am. Fish. Soc.*, **129**: 476–486 (2000).

Woodland, R. J., D. H. Secor, and E. D. Nikitschek. Past and future habitat suitability for the Hudson River population of shortnose sturgeon: a bioenergetic approach to modeling habitat suitability for an endangered species. *Am. Fish. Soc. Sym.*, **69**: 589–604 (2009).