HISTORICAL ATLANTIC BLUEFIN TUNA STOCK MIXING WITHIN FISHERIES OFF THE UNITED STATES, 1976-2012

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SUMMARY

Membership to natal population, Mediterranean Sea or Gulf of Mexico, was assigned for historical and recent samples of Gulf of Mexico spawners and U.S. Atlantic "school" size category juveniles collected during the past 36 years, 1976-2012. Maximum likelihood estimates of each sample's mixture were based on otolith stable isotope composition of $\delta^{18}O$ and $\delta^{13}C$. Gulf of Mexico spawners showed strong natal homing regardless of sampling period, although the most recent sample (2009-2010) showed slightly lower contribution rates from the Gulf of Mexico population (91.7% ±4.6% SD; N=80) than samples collected during 1999-2007 (97.0% ±3.9% SD; N=42) and 1978 (100.0%±0.01 SD %; N=60). The contribution of the Gulf of Mexico population has decreased substantially for school sized bluefin tuna (70-150 cm CFL) during the past four decades. School-sized bluefin were dominated by Gulf of Mexico members in 1976-1977 collections (84.8%±10.5% SD; N=26). Two decades (1997-2000) and three decades (2011-2012) later, Gulf of Mexico contributions were increasingly diminished: 38.9%±6.3% SD (N=120) and 15.8%±6.0% SD (N=86). These preliminary results indicate that the assessment assumption that US school bluefin CPUE represents western stock status is in error; CPUE trends likely reflect the varying contributions of the eastern and western stocks over time.

RÉSUMÉ

L'appartenance à une population natale, de la Méditerranée ou du Golfe du Mexique, a été assignée à des échantillons historiques et récents de reproducteurs du golfe du Mexique et de juvéniles susceptibles de se déplacer en bancs des États-Unis prélevés au cours de ces 36 dernières années, de 1976 à 2012. Les estimations de la vraisemblance maximale du mélange de chaque échantillon se sont basées sur la composition stable d'isotopes d'otolithes de $\delta^{18}O$ et $\delta^{13}C$. Les reproducteurs du golfe du Mexique manifestent un fort retour vers les frayères indépendamment de la période d'échantillonnage, même si l'échantillon le plus récent (2009-2010) a fait apparaître des taux de contribution de la population du golfe du Mexique légèrement plus faibles (91,7% ±4,6% SD; N=80) que les échantillons prélevés de 1999 à 2007 (97,0% ±3,9% SD; N=42) et en 1978 (100,0%±0,01% SD ; N=60). Au cours de ces quatre dernières décennies, la contribution de la population du golfe du Mexique a considérablement diminué en ce qui concerne le thon rouge susceptible de se déplacer en bancs (70-150 cm CFL). Les thons rouges susceptibles de se déplacer en bancs étaient dominés par les membres du golfe du Mexique lors des prélèvements de 1976-1977 (84,8%±10,5% SD; N=26). Deux décennies (1997-2000) et trois décennies (2011-2012) plus tard, les contributions du golfe du Mexique se sont de plus en plus réduites : 38,9%±6,3% SD (N=120) et 15,8%±6,0% SD (N=86). Ces résultats préliminaires indiquent que le postulat de l'évaluation selon lequel la CPUE du thon rouge des États-Unis susceptible de se déplacer en bancs représente l'état du stock Ouest est erroné ; les tendances de la CPUE reflètent vraisemblablement les contributions changeantes des stocks Est et Ouest dans le temps.

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RESUMEN

Se asignaron los miembros de población natal, mar Mediterráneo o golfo de México, en muestras históricas y recientes de reproductores del golfo de México y de juveniles de categoría de talla de cardumen del Atlántico estadounidense recopilados durante los 36 últimos años, 1976-2012. Las estimaciones de máxima verosimilitud de cada mezcla de muestras se basaron en la composición isotópica de otolitos estables de f $\delta^{18}O$ y $\delta^{13}C$. Los reproductores del golfo de México mostraron una fuerte conducta de retorno al lugar de nacimiento al margen del periodo de muestreo, aunque la muestra más reciente (2009-2010) mostraba tasas de contribución ligeramente inferiores de la población del golfo de México (91,7% ±4,6% SD; N=80) que las muestras recopiladas durante 1999-2007 (97,0% ±3,9% SD; N=42) y en 1978 (100,0%±0,01 % SD; N=60). Durante las cuatro últimas décadas la contribución del golfo de México ha descendido notablemente para los atunes rojos con talla de cardumen (70-150 cm). El atún rojo con talla de cardumen predominó entre los miembros del golfo de México en las muestras recopiladas en el periodo 1976-1977 (84,8%±10,5% SD; N=26). Dos décadas (1997-2000) y tres décadas (2011-2012) más tarde, las contribuciones del golfo de México fueron descendiendo cada vez más. 38,9%±6,3% SD (N=120) y15,8%±6,0% SD (N=86). Estos resultados preliminares indican que el supuesto de evaluación que postula que la CPUE de los atunes rojos de talla de cardumen representa el estado del stock es erróneo; las tendencias de la CPUE reflejan probablemente las contribuciones variables de los stocks oriental y occidental a lo largo del tiempo.

KEYWORDS

Otolith stable isotopes, stock composition, recruitment, tuna fisheries, Thunnus thynnus

1. Introduction

Atlantic bluefin tuna populations have experienced large changes in abundance during the past 50 years driven in part by the development of new fishery sectors throughout their range. In North America, the introduction of purse seine fisheries in the late 1950s targeting "school" size bluefin tuna (50-150 cm curved fork length (CFL)) was followed by rapid expansion of harvests. By the late 1960s, 22 large domestic and international vessels operated in US shelf waters (Cape Hatteras to Gulf of Maine) (Mather *et al*. 1995). Canneries drove demand and growth of the purse seine fishery, which mostly harvested fish between 1 and 2 years of age. As many as 300,000 small juveniles were removed per year during the late 1960s and early 1970s (**Figure 1**), but levels of harvests diminished rapidly in the 1970s due to the combined influence of lower recruitment and a shift in demand towards larger medium and giant size-class bluefin tuna, driven by Japanese markets (Fromentin and Powers 2005; Porch 2005). The crash in the school purse seine fishery was followed by three decades of persistently low recruitments by the western (Gulf of Mexico) population, leading to the question of whether recruitment overfishing in the 1960s and 1970s led to a threshold response by the population to a diminished demographic state.

To evaluate possible influences of historical fisheries on recruitment in the western population, harvests need to be weighted by where individuals originated - either the Mediterranean Sea (eastern stock) or the Gulf of Mexico (western stock). Recent evidence from natural markers supports that there are two populations of Atlantic bluefin tuna, both exhibiting high levels of natal homing to these spawning and nursery regions (Carlsson *et al*. 2007; Rooker *et al*. 2008; Dickhut *et al*. 2009). On the other hand, juvenile bluefin tuna are well known to undertake trans-Atlantic migrations as evidenced by conventional and electronic tagging studies (reviewed by Rooker *et al*. 2007). Further, otolith stable isotope analysis has indicated that during the past decade, more than 50% of juveniles harvested in US shelf waters originated from individuals spawned in the Mediterranean Sea (Rooker *et al*. 2008; Secor *et al*. 2011). Thus the historical US purse seine fishery likely included fish from both stocks. To determine the degree to which this fishery influenced subsequent recruitments by the western stock, we therefore need to know the degree of historical mixing.

Here we provide preliminary estimates of stock mixing rates by school bluefin tuna (70-150 cm CFL) harvested in North American waters for three periods, 1976-1977, 1997-2000, and 2011-2012 based on otolith stable isotope stock composition analysis. We hypothesized that the historically strong western stock recruitments, observed during the 1960s and 1970s, would be associated with dominant contributions of the western stock to North American school fisheries. In this paper, we also evaluated natal homing for adults sampled from the Gulf of Mexico in 1978 and 2009-2010, hypothesizing that natal homing would be near 100%, similar to that observed by Rooker *et al*. (2008) for samples collected during 1999-2007.

2. Methods

Bluefin tuna otoliths (sagittae) were collected during the Canadian purse seine fishery for juveniles off the eastern coast of the United States in 1976-1977. Unfortunately, precise locations of samples were not provided, but the available documentation indicated that the fish were caught off New England in 1976 and Virginia in 1977. Juveniles ranged from 75-150 cm FL and ages, estimated on the basis of CFL, ranged between 2 and 4 yrs. Juveniles for the 1997-2000 period were sampled as part of National Marine Fisheries Service's (NMFS) Large Pelagic Biological Survey conducted in US Atlantic shelf waters and made available by the NMFS Southeast Fisheries Science Center. These samples were previously analyzed for stable isotope analysis and supported stock mixing estimates reported in Rooker *et al*. (2008). Otoliths collected from adults sampled in the Gulf of Mexico in 1978 and 2009-2010 were provided by the Southeast Fisheries Science Center. Recent (2011-2012) juvenile samples were collected by University of Maryland Center for Environmental Science personnel from mid-Atlantic US fisheries (landed in North Carolina, Virginia, and Maryland). Recreational fisheries supplied school bluefin tuna sampled during the two later periods.

Otoliths were cleaned of adhering tissue, briefly rinsed and stored dry. A single otolith (right or left) was embedded in plastic resin and a 2.0 mm thick section cut from the center containing the juvenile and surrounding portions of the otolith (see Schloesser *et al*. 2010 for additional details on otolith processing). The juvenile portion of the otolith, specifically the area circumscribed by the first annulus, was identified with the aid of a template from measured juvenile otolith sections, which served to increase the consistency with which the first year of life was sampled (Rooker *et al*. 2008a). Carbonate material was rastered from that region using a New Wave Micromill ©. Powdered carbonate samples were analyzed for δ^{18}O and δ^{13}C at the University of Arizona Environmental Isotope Laboratory. Analytical precision was estimated at ± 0.1‰ and ±0.06‰ respectively for δ^{18}O and δ^{13}C (Schloesser *et al*. 2010). Otolith δ^{18}O and δ^{13}C in historical samples, year-classes prior to ~1990, must be corrected for the Suess Effect: historical changes to stable isotopes resulting from a multi-decadal enrichment of atmospheric CO_2. This was done according to the equation reported in Schloesser *et al*. (2010). Direct ages were estimated for samples collected during the 1997-2000 and 2011-2012 periods; for other samples, ages were estimated from CFL according to the growth model reported in Restrepo *et al*. (2010). For direct aging, otolith section thickness was reduced further to permit visualization of annuli for age determination. Images were taken with a digital camera paired to a stereo zoom microscope. Annuli were interpreted without reference to information on the specimen by a single experienced reader using Adobe Photoshop CS2 Version 9.0 to record images and annuli counts. Interpretation of Atlantic bluefin tuna age through direct counts of otolith annuli has been verified through bomb radiocarbon dating analysis (Neilson and Campana 2008).

Classification of the unknown sample mixtures to source populations was performed using a maximum likelihood estimation (MLE) method (aka finite mixture distribution; Prager and Shertzer 2005). The approach requires a baseline sample that represents all source populations (here two are assumed: Mediterranean Sea (MED) and Gulf of Mexico (GOMEX). The current baseline is relatively large (n=279), covers many year-classes (MED: 1998-2010; GOMEX: 1998-2004, 2006-2007), and shows consistent separation between the two populations regardless of year-class (Secor *et al*. 2011). The conditional maximum likelihood estimate procedure termed HISEA was employed (Millar 1990b;
http://www.stat.auckland.ac.nz/~millar/mixedstock/code.html).

3. Results

Otolith stable isotope stock composition analysis supported natal homing by Gulf of Mexico spawning fish over the past five decades. The oldest samples, archived by NMFS SEFSC and corresponding to estimated year-classes 1958-1968, resulted in an estimated ~100% natal homing, similar to the results of more recently

collected spawners from year-classes ranging 1979-1999 (**Table 1**). The most recent sample (2009-2010), exhibited slightly lower contribution rates from the Gulf of Mexico population (91.7% ±4.6% SD).

In contrast with the Gulf of Mexico samples, North American school juveniles have shown large changes in their stock composition. The small sample of historical purse seine-captured school size bluefin tuna (year-classes 1970-1975) showed 85% contribution by the western stock, the reverse of what has been observed for the most recent year-classes, 2005-2009 (**Table 1**; **Figure 2**). Interestingly, the intervening sample, year-classes 1991-1998, yielded an intermediate stock mixture rate (Gulf of Mexico population: 38.9%±6.3%).

4. Discussion

The results of this initial examination of historical samples conforms to expectations of (1) natal homing by the western stock, with nil to minimal straying from the Mediterranean population; and (2) an underlying influence of east and west stock productivity on mixing levels within North American fisheries that target juveniles. We emphasize however that these results are preliminary, subject to revision based on larger and more representative samples. Further, for most of the analyzed samples, ages were estimated based upon sizes so year-class ranges and Suess-corrections are only approximated. The NMFS SEFSC holds a large archive of otoliths, which could support a more robust analysis of historical mixing rates for year-classes spanning many decades. Analyses of these archived samples should receive priority for future work.

Preliminary analysis supports the view that the historical purse seine fishery was most heavily reliant on production from the western stock. During the period 1962-1972, this fishery harvested over 2 million small school juveniles (mean size 14.5 kg), with some annual harvests (1964, 1971) estimated to exceed 300,000 juveniles (**Figure 1**; Mather *et al*. 1995). The fishery may have taken many more individuals because fish > 4 years were discarded due to cannery market preference, and sets sometimes exceeded vessel capacity (Mather *et al*. 1995). To provide comparative context, the amount of juveniles harvested and discarded far exceeds typical modern recruitment levels for western stock bluefin tuna, which since 1980 has been estimated at ~100,000 per year (SCRS 2010). Still, the 2003 year-class, which has been attributed to the western stock was estimated as the fifth-largest in the time series (SCRS 2010).

A large number of western stock juveniles taken by historical purse seine fisheries coupled with high levels of natal homing may have led to recruitment overfishing, where strong year-classes were cropped to low levels. Moderately long-lived, highly fecund species like Atlantic bluefin tuna are periodic strategists (Winemiller and Rose 1992), which depend on strong year-classes that infrequently occur (Secor 2007). Mather *et al*. (1995) in their analysis of historical trends in size structure for school and medium size classes in North American fisheries noted strong year-classes occurring once every approximately ten years – 1938, 1950, 1958, 1965, and 1973. With the exception of the 2003 year-class, no strong year classes have been attributed to the western stock since 1973. However, analysis of samples collected in 2011-2012 from North Carolina (US) fisheries indicate that a substantial fraction of this year-class (about 50%) originated from the eastern stock (Secor *et al*. 2012).

In past and recent SCRS bluefin tuna assessments, VPA tuning indices (US East Coast Rod and Reel) have depended on the assumption that US angler category school bluefin tuna CPUE is a long-term index of western stock abundance. This assumption cannot be supported because (1) the index is influenced by eastern stock contributions and (2) the level of mixing underlying the index is not constant. Beyond information on stock composition and landings, reconstruction of past recruitments by the western stock requires consideration of changes in fishery selectivity and stock-specific life history differences. This directs efforts towards further integration of stock composition analysis into multi-stock age-structured simulation models (Link *et al*. 2011; Taylor *et al*. 2011; Kerr *et al*. 2012).

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6. Literature Cited

Carlsson, J., J. R. McDowell, P. Díaz-Jaimes, J. E. L. Carlsson, S. B. Boles, J. R. Goldo, and J. E. Graves. 2004. Microsatellite and mitochondrial DNA analyses of Atlantic bluefin tuna (*Thunnus thynnus thynnus*) population structure in the Mediterranean Sea. Mol. Ecol., 13: 3345–3356.

Dickhut, R.M., A.D. Deshpande, A. Cincinelli, M.A. Cochran, S. Corsolini, R.W. Brill, D.H. Secor, and J.E. Graves. 2009. North Atlantic bluefin tuna population dynamics delineated by organochlorine tracers. Environmental Science and Technology 43:8522-8527.

Fromentin, J. M., and J. E. Powers. 2005. Atlantic bluefin tuna: population dynamics, ecology, fisheries and management. Fish and Fisheries 6(4):281-306.

Kerr LA, SX. Cadrin and DH Secor. 2012. Evaluating population effects and management implications of mixing between Eastern and Western Atlantic bluefin tuna stocks. ICES CM 2012/ N:13.

Link, J. S., J. A. Nye, and J. A. Hare. (2011). Guidelines for incorporating fish distribution shifts into a fisheries management context. Fish and Fisheries 12, 461-469.

Mather, F.J., J.M. Mason, and A.C. Jones. 1995. Historical Document: Life history and fisheries of Atlantic bluefin tuna. NOAA Technical Memorandum NMFS-SEFSC – 370: 165 pp.

Millar, R. B. 1990a. Comparison of methods for estimating mixed stock fishery composition. Canadian Journal of Fisheries and Aquatic Sciences 47(11):2235-2241.

Millar, R. B. 1990b. Stock compostion program HISEA. http://www.stat.auckland.ac.nz/~millar/mixedstock/code.html

Neilson, J. D., and S. E. Campana. 2008. A validated description of age and growth of western Atlantic bluefin tuna (*Thunnus thynnus*). Canadian Journal of Fisheries and Aquatic Sciences 65(8):1523-1527.

Pella, J. and M. Masuda. 2005. Classical discriminant analysis, classification of individuals, and source population composition of mixtures, p. 517-552 *In* S.X. Cadrin, K.D. Friedland, and J.R. Waldman (ed.s) Stock Identification Methods: Applications in Fisheries Science. Elsevier Academic Press NY.

Porch, C. E. 2005. The sustainability of western Atlantic bluefin tuna: A warm-blooded fish in a hot-blooded fishery. Bulletin of Marine Science 76(2):363-384.

Prager, M.H. and K.W. Shertzer. 2005. An introduction to statistical algorithms useful in stock composition analysis, p.499-516 *In* S.X. Cadrin, K.D. Friedland, and J.R. Waldman (ed.s) Stock Identification Methods: Applications in Fisheries Science. Elsevier Academic Press NY.

Restrepo, V.R., G.A. Diaz, J.F. Walter, J. Neilson, S.E. Campana, D. Secor, and R.L. Wingate. 2010. An updated estimate of the growth curve of Western bluefin tuna. Aquatic Living Resources 23: 235-342.

Rooker, J.R., J.R. Alvarado-Bremer, B.A. Block, J.L. Cort, H. Dewar, G. De Metrio, R.T. Kraus, E.D. Prince, E. Rodriquez-Marin, D.H. Secor. 2007. Life history and stock structure of Atlantic bluefin tuna (*Thunnus thynnus*). Reviews in Fisheries Science 15:265-310.

Rooker, J.R., D.H. Secor, G.D. DeMetrio, R. Schloesser, B.A. Block, and J.D. Neilson. 2008. Natal homing and connectivity in Atlantic bluefin tuna populations. Science 322: 742-744.

Schloesser, R.W., J.D. Neilson, D.H. Secor, and J.R. Rooker. 2010. Natal origin of Atlantic bluefin tuna (*Thunnus thynnus*) from the Gulf of St. Lawrence based on otolith $\delta^{13}C$ and $\delta^{18}O$. Canadian Journal of Fisheries and Aquatic Sciences 67: 563-569.

Schloesser, R.W., J.R. Rooker, P. Louchuoarn, J.D. Neilson, and D.H. Secor. 2009. Inter-decadal variation in ambient oceanic $\delta^{13}C$ and $\delta^{18}O$ recorded in fish otoliths. Limnology and Oceanography 54(5): 1665-1668.

Secor, D.H., B. Gahagan, and J. Rooker. 2012. Atlantic bluefin tuna stock mixing within the U.S.North Carolina recreational fishery, 2011-2012. ICCAT SCRS/2012

Secor, D.H., B. Gahagan, and J.R. Rooker. (2011). Atlantic bluefin tuna population assignment based on otolith stable isotopes: the 2003 year-class within the U.S. North Carolina recreational fishery. International Commission for the Conservation of Atlantic Tunas SCRS/2011/169. Madrid.

Secor, D.H. 2007. The year-class phenomenon and the storage effect in marine fishes. J. Sea Res. 57: 91-103.

SCRS (Standing Committee on Research and Statistics, International Commission for the Conservation of Atlantic Tunas). 2010. Report of the 2010 Atlantic Bluefin Tuna Stock Assessment Session. 132 pp. http://www.iccat.es/en/assess.htm.

Taylor, N. G., M. K. McAllister, G. L. Lawson, T. Carruthers, and B. A. Block. 2011. Atlantic bluefin tuna: a novel multistock spatial model for assessing population biomass. Plos One 6, e27693.

Winemiller, K. O., and K. A. Rose. 1992. Patterns of life-history diversification in North American fishes: implications for population regulation. Canadian Journal of Fisheries and Aquatic Science 49:2196-2218.

Table 1. Natal population mixture rates for Atlantic bluefin tuna sampled in Gulf of Mexico (adults) and in US Shelf waters (school juveniles) samples during the period 1976-2012. MED=Mediterranean population; GOMEX=Gulf of Mexico population; MLE=maximum likelihood estimate of population composition; SD=standard deviation.

Year-classes	Year(s) sampled	Sample	N	Population	MLE(%)	MLE SD
1958-1968	1978	Gulf of Mexico Adults	60	MED	0.0	1.0
				GOMEX	100.0	
1979-1999	1999-2007	Gulf of Mexico Adults (Rooker *et al*. '08)	42	MED	3.0	3.9
				GOMEX	97.0	
1982-1999	2009-2010	Gulf of Mexico Adults	80	MED	8.3	4.6
				GOMEX	91.7	
1970-1975	1976-1977	North American School Juveniles	26	MED	15.2	10.5
				GOMEX	84.8	
1991-1998	1997-2000	North American School Juveniles (Rooker *et al*. '08)	120	MED	61.1	6.3
				GOMEX	38.9	
2005-2009	2011-2012	North American School Juveniles	86	MED	84.2	6.0
				GOMEX	15.8	

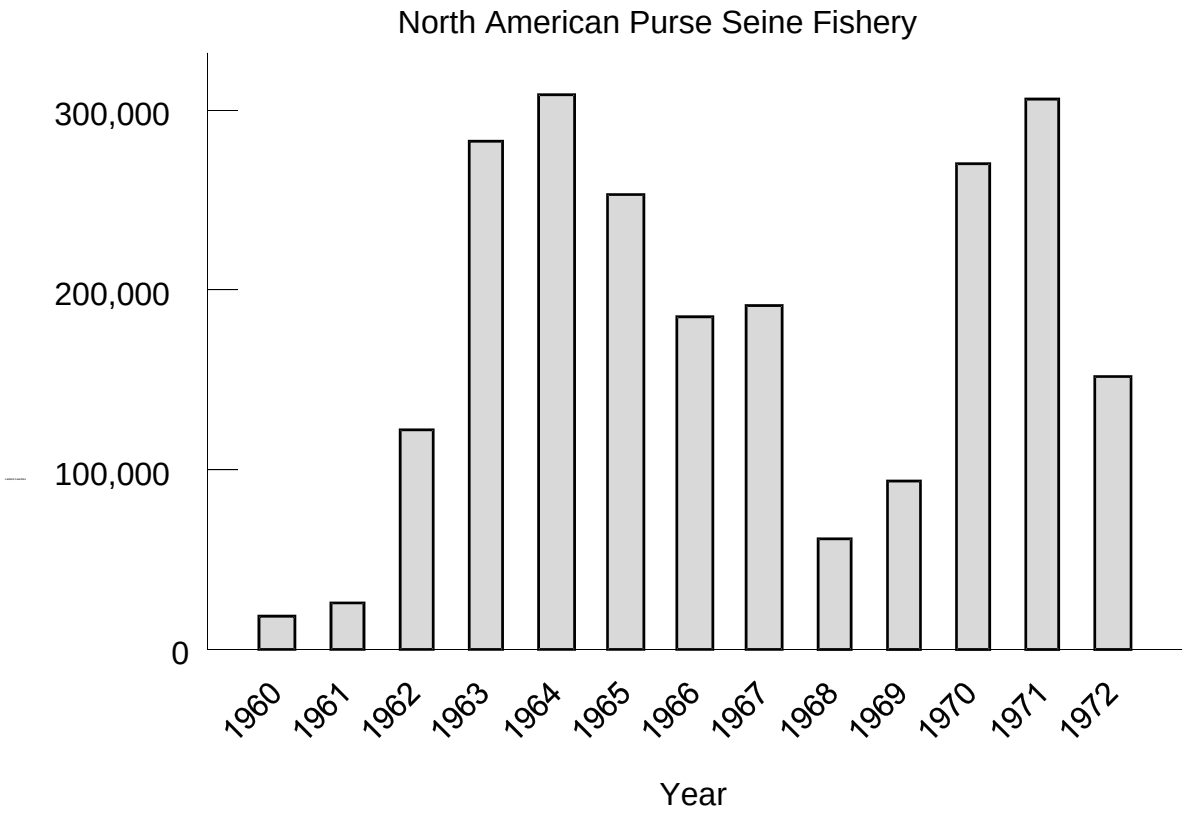

Figure 1. Estimated numbers of juveniles (age 1-4) landed by purse seine fisheries during the period 1960-1972. Data are from Mather *et al*. (1995), Figure 27. Mean individual weight for landed juveniles during this period was 14.5 kg. Data presented below is based on information given on figure axes by Mather *et al*. rather than units given in their legend, where an error in abundance units was noted.

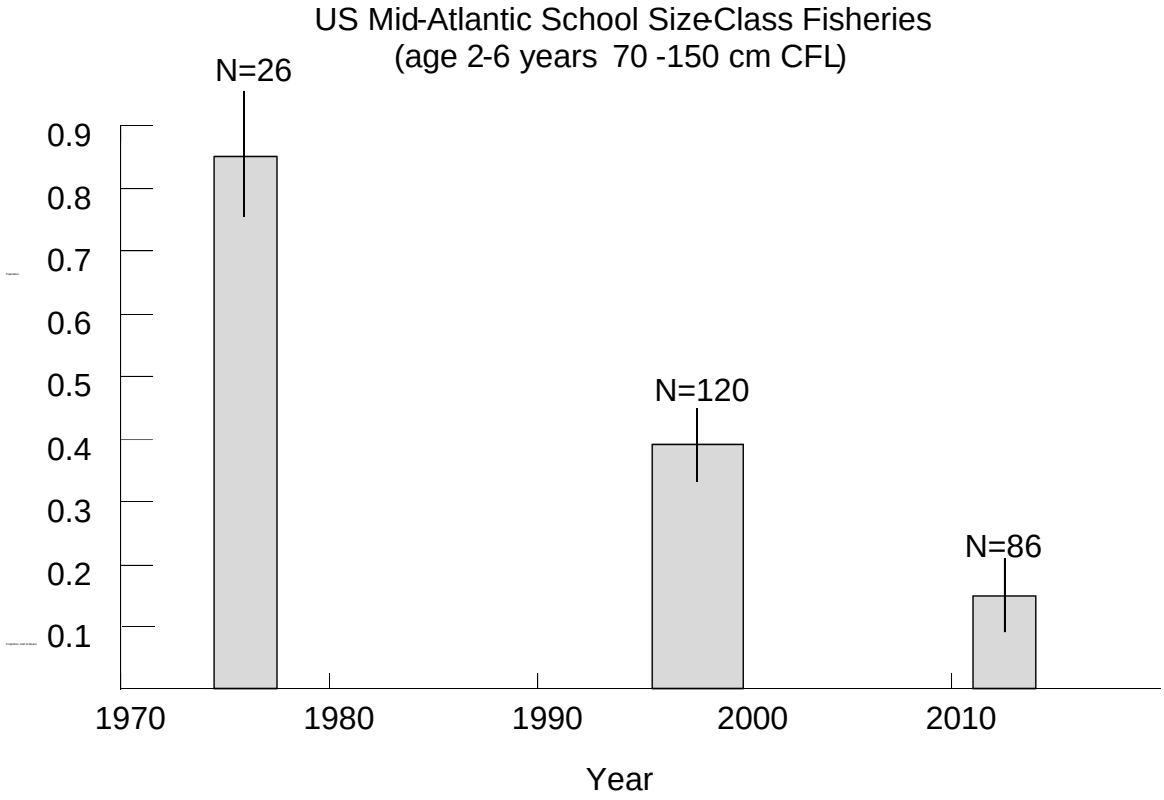

Figure 2. Population assignment for school size class Atlantic bluefin tuna captured either in commercial purse seines (1976-1977), or angling category US fisheries (1997-2000 and 2011-2012). Standard error bars are shown. See Table 1 for additional sample information.