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SYNOPSIS OF REGIONAL MIXING LEVELS FOR ATLANTIC BLUEFIN TUNA ESTIMATED FROM OTOLITH STABLE ISOTOPE ANALYSIS, 2007-2014

David H. Secor[1]

SUMMARY

Over the past ten years, several international groups have estimated stock mixing levels for Atlantic bluefin tuna from otolith stable isotope analysis. Mixing levels for important management regions are summarized from recent SCRS reports and publications for the period 2007-2014. Lack of mixing between the two principal stocks for Gulf of Mexico, Gulf of St. Lawrence, Eastern Atlantic, and Mediterranean samples is consistent with stock mixing patterns for samples collected 1990-2002. In contrast, recent analyses show diminished contributions by the Mediterranean population to US mid-Atlantic aggregations of juveniles and evidence of small but significant contributions by this population to Canadian fisheries, likely the result of increased selection for smaller sized fish in the Canadian Maritimes. A gap in our current understanding on mixing and western stock sustainability is lack of information for Gulf of Maine commercial category bluefin tuna. Mixing levels in the US Mid-Atlantic, Canadian Maritimes, and North Central Atlantic show non-stationary dynamics, meriting additional sampling and analysis for these regions in the coming years.

RÉSUMÉ

Au cours des dix dernières années, plusieurs groupes internationaux ont estimé les niveaux de mélange entre les stocks de thon rouge de l'Atlantique à partir de l'analyse des teneurs en isotopes stables des otolithes. Les niveaux de mélange des principales régions de gestion sont extraits des récents rapports du SCRS et des publications pour la période 2007-2014. L'absence de mélange entre les deux principaux stocks concernant des échantillons du golfe du Mexique, du golfe du St Laurent, de l'Atlantique Est et de la Méditerranée, coïncide avec les schémas de mélange de stock des échantillons collectés entre 1990 et 2002. En revanche, des analyses récentes font état d'une réduction des contributions de la population méditerranéenne aux concentrations de juvéniles du centre-atlantique américain ainsi que de contributions limitées, mais significatives, de cette population aux pêcheries canadiennes, ce qui s'explique probablement par une sélection accrue de poissons de plus petite taille dans les pêcheries maritimes canadiennes. Une lacune dans l'état actuel des connaissances sur le mélange et la durabilité du stock occidental concerne un manque d'information concernant la catégorie commerciale du thon rouge du golfe du Maine. Des niveaux de mélange dans le centre-atlantique américain, la zone maritime canadienne et le centre de l'Atlantique Nord sont le reflet de dynamiques non stationnaires, justifiant un échantillonnage et des analyses plus poussés pour ces régions au cours des prochaines années.

RESUMEN

En los últimos diez años, varios grupos internacionales han estimado niveles de mezcla del stock para el atún rojo del Atlántico a partir de análisis de isótopos estables de otolitos. Se resumen los niveles de mezcla para importantes regiones de ordenación a partir de informes recientes del SCRS y publicaciones para el periodo 2007-2014. La falta de mezcla entre los dos principales stocks para las muestras del golfo de México, del golfo de San Lorenzo, del Atlántico este y del Mediterráneo es coherente con los patrones de mezcla del stock de las muestras recopiladas entre 1990-2002. Por el contrario, análisis recientes muestran contribuciones menores de la población del Mediterráneo a las concentraciones de juveniles del Atlántico central estadounidense y pruebas de pequeñas pero importantes contribuciones de esta población a las pesquerías canadienses, probablemente resultado de una mayor selección de peces de talla más pequeña en las pesquerías marítimas canadienses. Una laguna en

[1] Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, P.O. Box 38, Solomons, Maryland 20688 U.S. secor@umces.edu

nuestros conocimientos actuales de la mezcla y de la sostenibilidad del stock occidental es la falta de información sobre el atún rojo de categoría comercial del golfo de Maine. Los niveles de mezcla en el Atlántico central estadounidense, las pesquerías marítimas de Canadá y el Atlántico norte central muestran una dinámica no estacionaria, que merece un muestreo y análisis adicionales en estas regiones en años próximos.

KEYWORDS

Otolith Stable Isotopes, Stock composition, Natal homing, Tuna fisheries, Thunnus thynnus

1. Introduction

Otolith stable isotope composition analysis is now being used to assign population structure for Atlantic bluefin tuna fisheries and aggregations throughout the species range. Mixing in Atlantic bluefin tuna fisheries depends on (1) the degree of transoceanic migrations by Mediterranean (eastern stock) and Gulf of Mexico-origin (western stock) fish and (2) the relative recruitment (production) between these two stocks (Porch *et al.* 2000; Secor 2002; Taylor *et al.* 2011). A current concept of mixing based on otolith stable isotope composition analysis (Rooker *et al.* 2008) supports the following premises:

- Natal homing for adults returning to either the Mediterranean Sea or Gulf of Mexico to spawn.
- Substantial trans-Atlantic migration during the juvenile (sub-adult) period. Because the eastern stock is ~10 fold more productive than the western stock, this migration results in high levels of eastern stock mixing (subsidy) in those US fisheries that target juveniles. In comparison, contributions by western origin juveniles to European and North African fisheries are manifest as very low mixing levels, which are difficult to detect.
- During the adult period, individuals of both populations re-assort themselves so that they remain within the sub-ocean basin of their origin (i.e., east or west of 45º W).

This concept is very broad and merits scrutiny in terms of more representative sampling, changes in the relative productivity and trans-oceanic migrations for the two principal stocks, and population structure imparted by sub-populations, contingents, and possible unknown spawning areas (Secor in press). In this synopsis, I summarize recent mixing levels, present a discussion on whether the above concept of mixing still holds, and prioritize research needed to further evaluate the role of mixing on sustainability of Atlantic bluefin tuna.

2. Methods

This is a literature review of recent primary literature and SCRS reports on Atlantic bluefin tuna stock mixing estimated from otolith stable isotope composition analysis. This approach was jointly developed by JR Rooker and DH Secor, who subsequently trained scientists from the European Union, Canada, and the US. Thus, the compiled studies represent consistent methodologies for otolith processing, stable isotope analysis, and stock classification estimation. Otoliths were prepared according to Schloesser *et al.* (2010) and analyzed for $\delta^{18}O$ and $\delta^{13}C$ from core regions. Classification of the unknown sample mixtures to source populations was performed using a maximum likelihood estimation (MLE) method (HISEA: Millar 1990) and a juvenile baseline (age =1 year; N=265) drawn from eastern and western nurseries for the period 1998-2011 (Rooker *et al.* 2014).

3. Results

Between 2007 and 2013, otoliths of 1841 Atlantic bluefin tuna were analyzed from fisheries and aggregations in the Gulf of Mexico, US Atlantic, Canadian Maritimes, Gulf of St. Lawrence, the Central North Atlantic Ocean, Eastern Atlantic Ocean approaches to the Mediterranean Sea, and the Mediterranean Sea (**Table 1**). This represents a substantial albeit minor fraction of the total otoliths that have been collected for this purpose, which numbers ~6000 (Pallares *et al.* 2013). Curved and straight fork lengths ranged widely within and among samples and were inconsistently reported as either ranges or means ± standard deviations (**Table 1**). Therefore, mixing levels are reported here on a regional basis, unstratified for length, sex, and other attributes associated with mixing. Sample sizes ranged between 9 (Balearic Islands) and 333 (North Carolina). In general, sample sizes supported 5 to 10% error on mixing levels of $p \geq 0.10$ (where p=proportion of the minority population) (**Table 2**). Below p=0.1, lower levels of error are needed to differential p from nil, requiring much larger sample sizes.

Recent mixing levels in North America indicate ~100% contribution of the western stock to spawning aggregations in the Gulf of Mexico, US recreational and commercial fisheries (excluding the North Carolina winter fishery), and the targeted fishery on giant bluefin tuna in the Gulf of St. Lawrence (**Figure 1**). Moderate levels of mixing (eastern stock) were observed in the North Carolina winter fishery (24%) and the Canadian Maritimes (15%). A small sample from the inshore St. Margarets Bay also showed a small amount of mixing (11%). Mediterranean and Eastern Atlantic samples were nearly exclusively of eastern-stock origin. The exception was an estimated 6% and 1% contribution of the western stock to the Morocco and Cyprus samples. Error associated with the stock classification procedure (**Table 1**) and sampling error (**Table 2**), indicate that these low rates cannot be distinguished from nil. The Central North Atlantic sample showed substantial mixing, with a majority contribution (79%) from the eastern stock.

4. Discussion

Recent otolith stable isotope results conform to certain aspects of the general concept of stock mixing in Atlantic bluefin tuna – natal homing in spawning areas, ~100% western stock contribution in the Gulf of St. Lawrence, ~100% eastern stock composition in the Mediterranean and Eastern Atlantic, and mixing in juvenile aggregations along the US east coast. On the other hand several results point to mixing levels that have changed over the last two decades. Although the NC winter fishery sample showed moderate levels of mixing (24% eastern stock contribution), US recreational fisheries for small juveniles (mean CFL=115±26 cm CFL) showed 100% contribution by the western stock. The lack of mixing for this group is in strong contrast to previous results, which indicated mixing levels approaching 50% for juveniles in this size range (Rooker *et al.* 2008).

The Canadian Maritimes region, which had not been previously analyzed, showed minor but significant contributions by the Eastern stock. Past research indicates a propensity for smaller size classes of North American bluefin tuna to show increased eastern stock contributions. Higher contributions by the eastern stock in the Canadian Maritimes sample in comparison to the Gulf of St. Lawrence sample may have been due to the inclusion of juveniles and smaller adults in this sample. Inferences on mixing levels in the St. Margaret's Bay cannot yet be supported due to a low sample size.

The North Central Atlantic sample was mixed, dominated by the eastern stock. Past telemetry research support contributions of both stocks to this region (Lutcavage 2000; Block *et al.* 2005; Walli *et al.* 2009). Interestingly, Rooker *et al.* (2014) reported a gradient in mixing, where the western stock's contribution was 56% west of the 45° W management boundary, but only 15% east of the 45° W meridian. For the entire sample, mixing levels varied substantially between 2010 (western stock=36%) and 2011 (western stock=9%), indicating non-stationary dynamics or sampling error.

Mixing levels were apparently reduced for juveniles sampled in US waters, compared to those sampled in the 1990s. Explanations for this decline in eastern stock contribution include (1) lack of adequate sampling; (2) increased relative production by the western stock; and (3) decreased trans-oceanic migration by the eastern stock. Mixing levels will be influenced by classification error, sampling rate, and representativeness of the sample. The latter issue is particularly important when covariates such as size, sex, season, and year come into play. The influence of these variables is suggested by recent analyses, but remains poorly studied. Improved stratified sampling designs will better inform how these variables influence mixing and allow for improved estimation of mixing. Strong recruitments in the western stock might cause mixing levels to decline (Secor *et al.* in press), but recent strong year-classes have been noted for both western and eastern stocks (Anon. 2013). There is currently no compelling data to indicate whether decreased mixing in US juvenile samples is the result of changes in the relative production or migration rates between the two principal stocks. Absent this information, simulation modeling may suggest scenarios of asymmetric production between the stocks, which are consistent with recent mixing levels (Kerr *et al.* 2012).

Additional otolith composition analyses are needed to fill out the picture on stock mixing of Atlantic bluefin tuna. Many otolith samples have been collected and await processing, statistical analyses, and reporting of results. The Gulf of Maine in particular merits attention. This region has been intensively sampled for otoliths for five years (2010-2014) resulting in >2000 samples (W. Golet, Univ. Maine, pers. comm.). These remain unanalyzed despite the central role this region plays to US commercial fisheries and the growth of Atlantic bluefin tuna. Beyond analyses of existing samples, priority should be placed to increase sampling rates for regions where mixing occurs or where mixing shows temporal dynamics. These regions include the US mid-Atlantic and New England, Canadian Maritimes, and the North Central Atlantic Ocean.

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Table 1. Stock mixing levels for Atlantic bluefin tuna sampled in regions throughout the Western, Central, and Eastern North Atlantic Ocean and the Mediterranean Sea. East references Mediterranean population; West references Gulf of Mexico population; CFL=curved fork length (cm), range; SFL=straight fork length (cm), mean± SD; SD=standard deviation.

			Predicted Origin		
Region	**CFL**	**N**	**%East**	**%West**	**%SD**
Western Atlantic					
Gulf of Mexico (2007-2011)[1]	180-288	169	0	100	0
US Recreational Fishery (2010-2011)[2]	60-210	247	0	100	0
US Comm. Fishery (2010-2011)[2]	150-275	74	0	100	0
North Carolina (2011-2013)[3]	115-267	333	24	76	4.1
Gulf of St. Lawrence (2011-2012)[4]	186-313	191	0	100	0.2
Canadian Maritimes (2011-2012)[4]	127-300	151	15	85	5.4
St. Margarets Bay (2011-2012)[4]	175-277	17	11	89	11.6
Central Atlantic	**SFL**				
Central Atlantic (2010-2011)[5]	184.8±13.1 ('10)	108	79	21	6.5
	188.2±13.1 ('11)	94			
Eastern Atlantic	**SFL**				
Portugal (2011)[5]	212.3±19.4	93	100	0	0
Strait of Gibraltar (2010-2011)[5]	156.8±41.9 ('10)	16	100	0	0
	166.0±38.6 ('11)	81			
Morocco[5] (2011-2012)[5]	210.8±37.2 ('11)	32	94	6	4.7
	118.9±21.1 ('12)	49			
Mediterranean	**SFL**				
Balaeric Islands (2011)[5]	141.9 ± 81.5	9	100	0	0
Malta (2011)[5]	167.1±72.5	82	100	0	0
Sardinia (2011)[5]	97.2±59.8	20	100	0	0
Cyprus (2011)[5]	135.5±65.8	48	99	1	2.9

[1]Secor *et al.* 2014b
[2]Secor *et al.* 2013
[3]Secor *et al.* in press
[4]Busawon *et al.* 2014
[5]Rooker *et al.* 2014

Table 2. Sample size (N) requirements for levels of mixing (p, q) and error (E) 0.05 and 0.10. Error on p, the minority stock proportion, is estimated for a 95% confidence interval. For the normal probability distribution of p, sample size is estimated as $N=4/E^2\ (p\ q)$ (Secor and Houde 1995). Shaded cells indicate violations to the normal approximation of the binomial distribution.

Error=0.05 Mixing Level p, q	N	Error=0.10 Mixing Level p, q	N
0.05, 0.95	76	0.05, 0.95	19
0.10, 0.90	144	0.10, 0.90	36
0.15, 0.85	204	0.15, 0.85	51
0.20, 0.80	256	0.20, 0.80	64
0.25, 0.75	300	0.25, 0.75	75
0.30, 0.70	336	0.30, 0.70	84
0.35, 0.65	364	0.35, 0.65	91
0.40, 0.60	384	0.40, 0.60	96
0.45, 0.55	396	0.45, 0.55	99
0.50, 0.50	400	0.50, 0.50	100

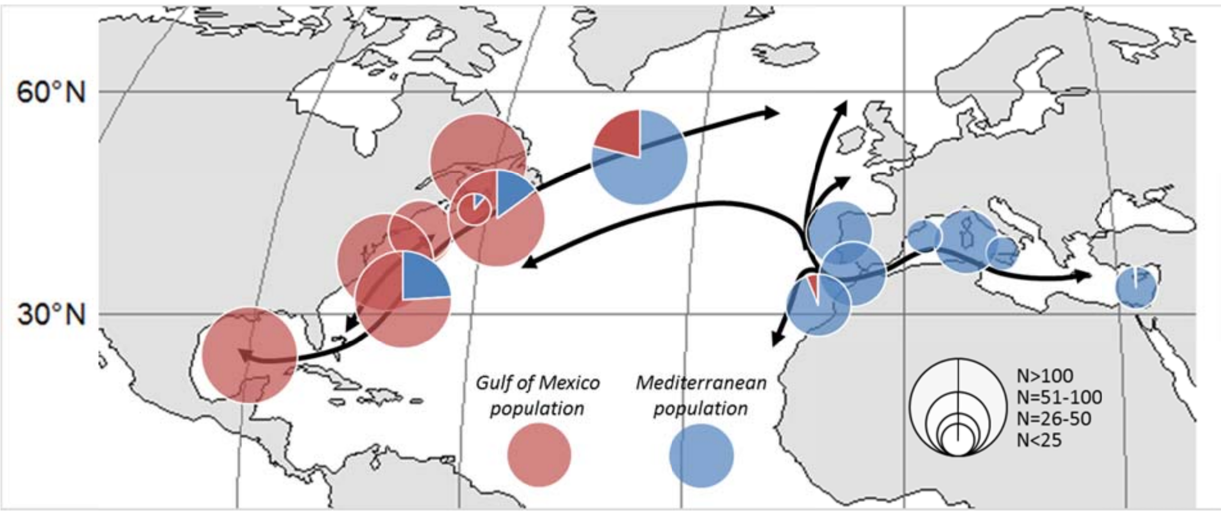

Figure 1. Mixing levels of Atlantic bluefin tuna estimated through otolith stable isotope analysis, 2007-2014. Pie charts are scaled according to sample size. Generalized migration routes are from Fromentin *et al.* 2014.