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PREDICTING POTENTIAL ATLANTIC SPAWNING GROUNDS OF WESTERN ATLANTIC BLUEFIN TUNA BASED ON ELECTRONIC TAGGING RESULTS, 2002-2011

Molly E. Lutcavage[1], Benjamin Galuardi[1,2] and Tim C. H. Lam[1]

SUMMARY

From 2002-2011, dispersal patterns of Atlantic bluefin tuna (ABFT) released from New England and Canadian foraging grounds (n=126 , estimated sizes 150-185 cm curved fork length, CFL) with PSATS showed that most of the individuals retaining tags until the following April-June (20/36) did not enter the Gulf of Mexico (GOM), their presumed spawning ground. Spatial and environmental information returned by the tags suggest that some ABFT spawn elsewhere, possibly in late winter or spring, near the Gulf Stream margin, the Bahamas, and Caribbean Sea. Most of the fish utilizing the GOM during the observed period (all $\geq$ 185 cm CFL) did so between February and March, and remained there for several months. None of the smaller (i.e., 150 - <185cm CFL) tagged individuals entered the Gulf of Mexico, but were at times located in oceanographic conditions similar to known spawning areas (e.g., SST from 22-26^{o}C, recirculation zones). Dispersal patterns exhibited by mature ABFT are consistent with life history models predicting that smaller/younger fish should reproduce in areas closer to foraging grounds than larger individuals. Confirmation of reproductive activity in the Atlantic, while difficult to accomplish, is key to obtaining an accurate assessment of spawning stock biomass for western ABFT.

RÉSUMÉ

De 2002 à 2011, des schémas de dispersion de thons rouges de l'Atlantique (ABFT) remis à l'eau à partir des zones d'alimentation de la Nouvelle-Angleterre et du Canada (n=126 , tailles estimées 150-185 cm longueur courbée à la fourche, CFL) et porteurs de marques-archives pop-up reliées par satellite (PSAT) ont fait apparaître que la plupart des spécimens qui avaient retenu les marques jusqu'aux mois d'avril-juin (20/36) suivants n'étaient pas entrés dans le golfe du Mexique, leur zone de frai présumée. Les informations spatiales et environnementales obtenues par les marques suggèrent que certains ABFT fraient ailleurs, éventuellement à la fin de l'hiver ou au printemps, en bordure du Gulf Stream, près des Bahamas et de la mer des Caraïbes. La plupart des poissons qui ont utilisé le golfe du Mexique pendant la période d'observation (tous $\geq$ 185 cm CFL) l'ont fait entre février et mars et y sont demeurés pendant plusieurs mois. Aucun des plus petits spécimens marqués (c'est-à-dire 150 - <185cm CFL) n'a pénétré dans le golfe du Mexique, mais ils ont parfois été localisés dans des conditions océanographiques similaires aux zones de frai connues (p. ex. SST de 22-26^{o}C, zones de recirculation). Les schémas de dispersion affichés par les ABFT matures concordent avec les modèles du cycle vital qui prédisent que les poissons plus petits/plus jeunes devraient se reproduire dans des zones plus proches des zones d'alimentation que les spécimens plus grands. Il est primordial de recevoir la confirmation d'une activité reproductrice dans l'Atlantique, malgré la difficulté de la tâche, si l'on veut obtenir une évaluation exacte de la biomasse du stock reproducteur pour l'ABFT de l'Ouest.

RESUMEN

Desde 2002 a 2011, los patrones de dispersión del atún rojo del Atlántico (ABFT) liberados desde las zonas de alimentación de Nueva Inglaterra y Canadá (n=126, tallas estimadas de 150-185 longitud curvada a la horquilla, CFL) con PSATS mostraron que la mayoría de los ejemplares que conservaba las marcas no entraba en el golfo de México (GOM), su supuesta zona de desove, hasta el siguiente abril-junio (20/36). La información medioambiental y espacial obtenida de las marcas sugiere que algunos atunes rojos del Atlántico desovan en otro sitio, probablemente a finales del invierno o en primavera, cerca del borde de la Corriente del golfo, Bahamas y el Caribe. La mayoría de los peces que utiliza el GOM durante el periodo observado (todos $\geq$ 185

[1] Large Pelagics Research Center, Dept. of Environmental Conservation, UMass Amherst, Gloucester Marine Station, PO Box 3188, Gloucester MA, 01931, USA, mlutcavage@eco.umass.edu, timlam@eco.umass.edu, galuardi@eco.umass.edu
[2] Graduate School of Marine Science, UMass Dartmouth, MA, USA.

cm CFL) lo hace entre febrero y marzo, y permanece allí varios meses. Ninguno de los ejemplares marcados más pequeños (es decir, 150 - <185cm CFL) entró en el golfo de México, pero a veces se ubicaban en sitios con condiciones oceanográficas similares a zonas de desove conocidas (por ejemplo, SST entre 22 y 26ºC, zonas de recirculación). Los patrones de dispersión que presenta el atún rojo del Atlántico maduro son coherentes con modelos del ciclo vital que predicen que los peces más pequeños/más jóvenes deberían reproducirse en áreas más cercanas a las zonas de alimentación que los ejemplares más grandes. La confirmación de la actividad reproductiva en el Atlántico, aunque es difícil de lograr, es clave para obtener una evaluación precisa de la biomasa del stock reproductor para el atún rojo del Atlántico occidental.

KEYWORDS

Atlantic bluefin tuna, spawning grounds, reproductive behavior, tagging

1. Introduction

In current stock assessments, western Atlantic bluefin tuna (ABFT) are presumed to spawn in the Gulf of Mexico and Straits of Florida in April – June, and to exhibit spawning site fidelity to those locations. However, the dispersal patterns of adult ABFT released with electronic tags from NW Atlantic foraging grounds in the US and Canada consistently showed that only some individuals retaining tags through the presumed spawning period entered those areas (Lutcavage *et al.* 1999; Block *et al* 2005; Galuardi *et al.* 2010). Based on their dispersal patterns, large size and good somatic condition, we initially proposed that some fish might be spawning elsewhere in the Atlantic (Lutcavage *et al.* 1999), as suggested by historic studies (Wilson, 1965; Baglin, 1976; Mather *et al.* 1995). Results from annual electronic tagging campaigns in New England (US), Southwest Nova Scotia and the Gulf of St. Lawrence (Canada) consistently show multiple dispersal patterns from feeding grounds with annual return to foraging areas, as well as differences in migration patterns among size classes, release location and season (e.g., Sibert *et al.* 2006).

In an early biological review, Westman and Neville (1942) noted that the spawning locality of ABFT "is as yet a mystery". By the 1950's, scientists confirmed that ABFT reproduced in the Straits of Florida and Gulf of Mexico (e.g., Rivas 1954; Shingu *et al.* 1980; Mather *et al.* 1995), yet Mather (1962) noted " The indications are that the bluefin spawn over wide areas and a considerable period of time in the western Atlantic. The giants evidently spawn in the southern areas in April and May, while the medium-sized ones apparently spawn north of the Gulf Stream somewhat later." Observations that there might be additional spawning grounds off the Gulf Stream margin, Windward Passage, Bahamas, and Brazil (Farrington, 1939; Wilson, 1965; Richards, 1976, Mather *et al.* 1995; Tekeuchi *et al.* 2008), and that medium-sized ABFT spawn in the Atlantic, have been largely ignored until recently. Recent larval cruises conducted off the Yucatan Straits and habitat modeling (Muhling *et al.* 2010; 2011) also support the historic view that reproduction occurs not only in the GOM but also in Atlantic regions, in habitat suitable for larval development.

The current ABFT biological paradigm for stock assessment assumes that ABFT exhibit spawning site fidelity to the Gulf of Mexico, supported by recent biomarker results, and a lack of evidence to the contrary (Teo *et al.* 2007; Rooker *et al.* 2008). However, consistent results from electronic tagging of ABFT released from NW Atlantic foraging grounds since 1997 continue to question these assumptions. One hypothesis is that adult ABFT that don't enter the GOM or Straits of Florida are not sexually mature (Boustany *et al.* 2008), or omit spawning that year. However, endocrine and histological studies confirm sexual maturity in ABFT < 185 cm CFL and as small as 134 cm CFL (Knapp *et al.* 2013). Most, if not all of the individuals released in adult ABFT tagging studies would be considered sexually mature. It's reasonable to expect that most adult ABFT in good somatic condition that don't enter the GOM are spawning elsewhere, in a watermass suitable for larval development, as initially stated by Mather (1962; 1995 historic document) and others (Wilson, 1965; Baglin, 1976). Current electronic tags lack biological sensors that could detect or confirm spawning (Galuardi *et al.* 2010). Nonetheless, under the assumption that mature, ABFT in good condition will spawn each year (Goldstein *et al.* 2007; Chapman *et al.* 2011), we examined dispersal routes and oceanographic associations of electronically tagged ABFT in order to identify locations of potential Atlantic spawning areas. Here, we utilize our PSAT tagging dataset to hypothesize and define spatial and temporal parameters of potential spawning habitat.

2. Methods

All our PSAT tagging campaigns (2002-2011) were conducted from commercial or recreational fishing vessels using methods described in detail elsewhere (Lutcavage *et al*. 1999; Wilson *et al*. 2005; Galuardi *et al*. 2010). All were popup archival satellite tags (PSATS), models Microwave Telemetry Inc. (MTI), PTT-100 or X Tags PSATs or Wildlife Computers (WC) MK10 PSATs, tethered via monofilament to a nylon dart inserted into the fish at the base of the origin of the second dorsal fin. Most tag missions were set to 10-12 months. Fishing was conducted either by rod and reel, purse seine, or long line fishing. Fish condition was assessed, and fish that were undamaged were tagged while they remained in the water. Fish weight was estimated by the captain and senior crew members in 25 lb (~ 12 kg) increments. The PSAT tags recorded temperature and depth and sunrise/sunset times (MTI tags) or light measurement (WC). All fish were determined to be in good health. We used a state-space Kalman filters to estimate position based on time of sunrise, sunset, and sea surface temperature (SST) and depth (Nielsen and Sibert 2007; Lam *et al*. 2008, Royer and Lutcavage 2009). To assess the presence of potential spawning areas, we extracted maximum daily temperature recorded at each location. We divided our sample of tagged fish into groups equal of larger than 185 cm CFL and 150 - 185 cm CFL. Here, we used the smaller sized group to include fish below the US commercial minimum size limit (185 cm CFL) shown to exhibit signs of maturity (Knapp *et al*. 2013).

3. Results and Discussion

The pooled dispersal routes of ABFT released from foraging grounds off New England and Canada are shown in relation to season (Dec-Jan, Feb-March, and April-June) and estimated size classes (**Figure 1**). The July-November period is not shown, as most fish retaining PSATs for nearly a year returned to their release locations. The red location symbols indicate sea surface temperatures between 22-26 ^{o} C, typical of known spawning areas. From the total of 126 tracks we also summarize dispersal patterns in relation to Atlantic (**Figure 1**) and Gulf of Mexico regions. In **Figure 1**, panels A, B, C indicate dispersal patterns of fish that entered the GOM during the tracking period. Panels D, E, F represent bluefin tuna that did not enter the GOM over the observed period. Panels C, F, I represent locations of tagged individuals during the presumed spawning period in the GOM (April-June). A few large ABFT entered the Gulf in winter (panel A), in fact as early as late October (not shown); though most of the tagged fish entered during Feb- March (**Table 1**). Comprehensive tag records indicate that ABFT may be present in the GOM over eight months of the year. It is notable that over 50% of ABFT > 185 cm CFL in our sample did not enter the GOM while monitored.

Large ABFT (> 185 cm CFL) that did not enter the GOM (Panels D,E,F) dispersed mostly in the NW Atlantic, west of the 45 ^{o} W ICCAT stock management line, but several traveled to Azores- Canaries frontal regions in springtime, then to the Bahamas/ Antilles area before returning to foraging grounds via the Gulf Stream margin. Track locations associated with warm water, i.e., SST's >22 ^{o}C, appeared to have the broadest geographic extent from Dec-March. The Dec-June distribution of "medium" size fish (estimated 150-185 cm CFL, panels G, H, I) remained entirely in the NW Atlantic and were associated with the Gulf Stream and South Atlantic Bight, and Caribbean Sea. This size class in the western Atlantic includes sexually mature individuals (Knapp *et al*. 2013), and in fact, the minimum size included here (150 cm CFL) is a conservative lower size limit, since maturity was detected in fish as small as 134 cm CFL (Knapp *et al*. 2013). In the Eastern Atlantic, fish of this size would be considered sexually mature (Corriero *et al*. 2005). Although only twelve records were obtained for April-June, none entered the GOM nor showed signs of heading east toward the Mediterranean Sea, and most returned to release areas. If a portion of these individuals are spawning, it is likely to be in locations indicated in red (SST's $\geq$22 ^{o} C) in dispersal tracks (**Figura 1**, panels G,H,I).

Based on results returned by electronic tags and evaluation of somatic, trophic, and reproductive condition of fish that we and others have examined on their feeding grounds in the NW Atlantic (Chase, 2002; Golet *et al*. 2007; Goldstein *et al*. 2007; Logan *et al*. in prep), our hypotheses include the following: 1). large, sexually mature fish in good condition spawn annually, as predicted by life history models (Chapman *et al*. 2011), 2) in the GOM, contingents of large ABFT spawn not only in springtime and in known areas (Richards, 1976; Shingo *et al*. 1980) but may also spawn in winter in the southern GOM and adjacent seas, when conditions are appropriate, 3). contingents of large ABFT also spawn in the Atlantic. 4). spawning patterns of ABFT exhibit size dependence, similar to Mediterranean patterns (Heinisch *et al*.2008) and smaller individuals may spawn in diverse areas of the NW Atlantic, Gulf Stream margin, and Caribbean/Antilles region, where and when conditions are appropriate for larval development, and may do so in winter and spring, as noted by previous workers (Wilson, 1965; Mather, 1962; Baglin, 1976). Bluefin tuna that become residents of the GOM in autumn and winter are undoubtedly feeding there, since electronic tag records indicate deep and repetitive diving (e.g., Teo *et al*. 2007; Galuardi *et al*. 2010).

Bluefin tuna are asynchronous spawners, and appear to spawn over a 2-4 week period (Corriero *et al*. 2003). Evidence for spawning includes hydrated oocytes, post ovulatory follicles, and of course, larvae, but detecting spawning itself is difficult. Eggs remain hydrated for only 24 h or so, and post ovulatory follicles are reabsorbed within 48h (Schaefer, 1998). Nonetheless, evidence for spawning in areas close to feeding grounds is growing (Goldstein *et al*. 2007; Knapp *et al*. 2013), and we've sampled commercially landed ABFT in the northern Bahamas (May) the New England (June-July) whose histological appearance indicated that the females appeared to be within 2-4 weeks of spawning (pre and post, respectively). Additional evidence includes recent surveys that found ABFT larvae in the Yucatan Straits and adjacent areas (Muhling *et al*. 2011; J. Franks, personal comm.). Biophysical modeling outputs match larval development habitat characteristics in these areas (Muhling *et al*. 2010).

Earlier studies (e.g., Wilson, 1965; Mather, 1962) had no *a priori* knowledge of explicit dispersal and spawning behavior of bluefin tuna, nor their reproductive schedules and profiles, yet came to the conclusions supported by electronic tagging studies and conclusive evaluation of sexual maturity (Knapp *et al*. 2013). Since the larval survey in the Gulf of Mexico and adjacent areas is the only fishery independent index of abundance used for the western stock (Ingram *et al*. 2010), it plays a central role in assessment. If our PSAT tagging results roughly indicate the portion of western ABFT spawning in the Atlantic each year, spawning stock biomass would not be adequately reflected in the current western stock assessment. Based on our combined findings of a younger age/size of sexual maturity (Knapp *et al*. 2013) and prediction of additional spawning areas, it will be important to confirm and define the areal and temporal extent of spawning of western ABFT. We recommend that this can be accomplished via the following: 1). expanded reproductive sampling, especially of small/younger size classes, as well as in offshore regions, 2) more extensive larval sampling, utilizing biophysical modeling (e.g., Lehodey *et al*. 2003; Muhling *et al*. 2010) and state of the art sampling methods, 3). Integration of behavioral information from electronic tagging and maturity analysis with early life history parameters to identify potential spawning habitats.

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Table 1. Number of Atlantic bluefin tuna > 185 cm entering the Gulf of Mexico during the specified period.

Months	*N*
Dec-Jan	6
Feb-Mar	12
Apr-Jun	3
Total	21

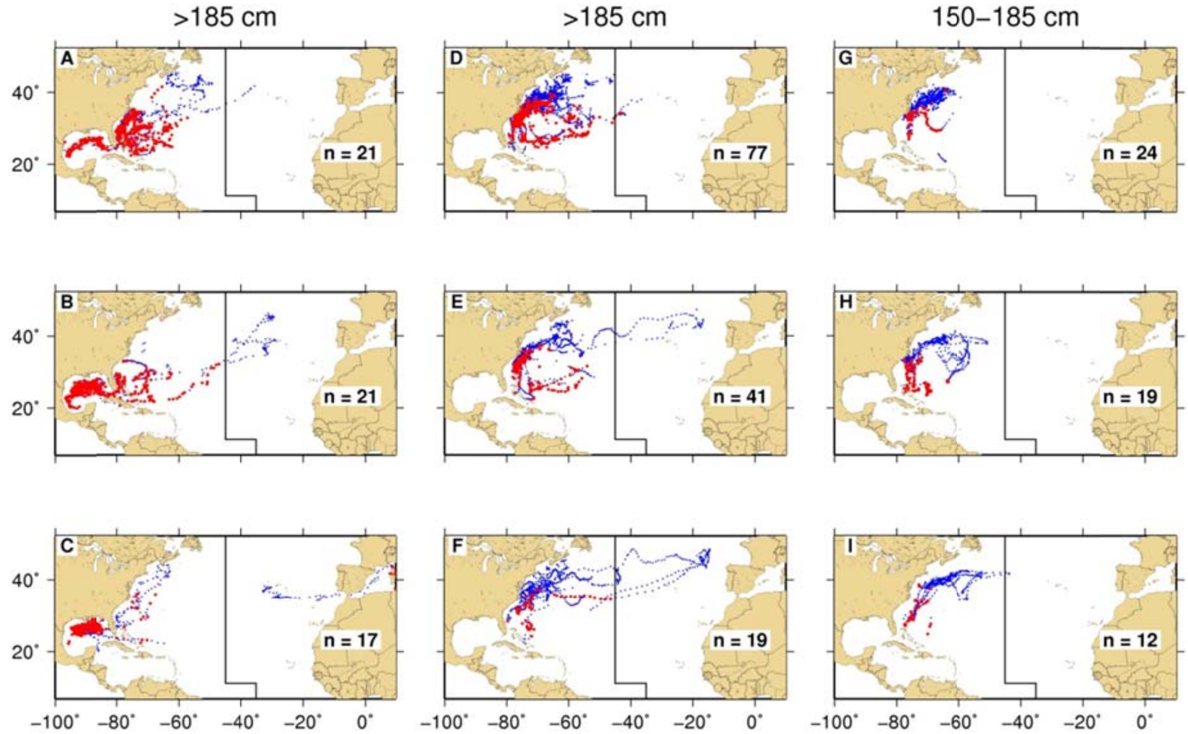

Figure 1. Daily positions of Atlantic bluefin tuna from electronic tagging in the northwest Atlantic between 2002 and 2011 (n = 126) for the months of December and January (panels A, D and G), February-March (panels B, E and H) and April-June (panels C, F and I), representing the putative spawning period for the western Atlantic. Panels A-C represent fish >185cm CFL at time of tagging which utilized the Gulf of Mexico. Panels D-F are fish >185cm (~73 inches, the commercial size limit) at time of tagging which did not enter the Gulf of Mexico. Panels G-I represent fish 150-185cm at time of tagging. Red points indicate ambient maximum temperatures (SST) between 22-26°C.