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Polychlorinated biphenyls and organochlorine pesticides as intrinsic tracer tags of foraging grounds of bluefin tuna in the northwest Atlantic Ocean

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ABSTRACT

Researchers have utilized chemical fingerprints in the determination of habitat utilization and movements of the aquatic animals. In the present effort, we analyzed polychlorinated biphenyl (PCB) congeners and organochlorine pesticides in the samples of juvenile bluefin tuna caught offshore of Virginia, and in larger bluefin tuna from the Gulf of Maine and near Nova Scotia. For a given specimen, or a given location, PCB concentrations were highest, followed by DDTs, and chlordanes. Average contaminant concentrations from fish captured from the three locations were not significantly different; and PCBs, DDTs, and chlordanes correlated well with each other. Trans-nonachlor/PCB 153 ratios in bluefin tuna of eastern Atlantic (i.e., Mediterranean) origin are low compared to the corresponding ratios in fish in the western Atlantic. As the former migrate to the western Atlantic, these ratios gradually turnover due to the accumulation of biomass from forage contaminated with higher trans-nonachlor/PCB 153 ratio reflecting dissimilar use of chlordane pesticides on two sides of the Atlantic Ocean. The trans-nonachlor/PCB 153 ratio indicated that one juvenile bluefin tuna from offshore of Virginia and one large bluefin tuna from Gulf of Maine in the present study originated from foraging grounds in the Mediterranean Sea, and that they have made the trans-Atlantic migrations. The remaining individuals were determined to be either spawned in the Gulf of Mexico or the trans-nonachlor/PCB 153 ratio for the putative Mediterranean bluefin tuna was completely turned over to resemble the ratio characteristic to the western Atlantic. Based on the turnover time for trans-nonachlor/PCB 153 ratio previously determined, the residence time of juvenile bluefin tuna offshore Virginia was estimated to be at least 0.8 to 1.6 years. A discriminant function analysis (DFA) plot of total PCB normalized signatures of PCB congeners showed three separate clusters, which suggested that bluefin tuna from offshore Virginia, Gulf of Maine, and Nova Scotia could have had extended residences and foraging within the areas of capture to be able to sustain the stable signatures of PCB congeners. The DFA cluster results supported the concept of metapopulation theory of spatial ecology comprising discrete aggregates of local populations of bluefin tuna where the desired prey species are likely to be abundant. Despite their highly migratory trait and endothermic advantage of foraging in broader and colder habitats, the movements and mixing across the aggregation ranges related to feeding did not appear to be extensive. Advancement in the understanding of bluefin tuna population dynamics beyond the coarse concept of trans-Atlantic migrations to the metapopulation hypothesis provides a novel exploratory tool in the stock assessment and resource management. As the chemical tracer tags are fortified naturally and document the time- and space-integrated foraging history, they promise to serve as the low-cost alternatives to the high-cost electronic data recording tags employed for addressing the migratory movements of bluefin tuna. Between the different potential chemical tracer tags, a distinct advantage of PCB/pesticide analysis over the otolith micro-constituent analysis is that the muscle tissue of a given individual bluefin tuna can be sampled repeatedly for PCB/pesticide analysis over different spatial and temporal scales in a non-lethal manner.

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1. Introduction

North Atlantic bluefin tuna (*Thunnus thynnus*) is a prized species important to both the recreational and commercial fisheries. It is distributed from subtropical to subarctic regions across the North Atlantic (Mather et al., 1995; Fromentin and Powers, 2005). The species is subdivided into two units: a northwestern stock breeding in the Gulf of Mexico and an eastern stock breeding in the Mediterranean Sea (Carlsson et al., 2007; Boustany et al., 2007). Magnuson et al. (1994) estimated the population size of the latter to be at least an order of magnitude larger than the former. International Commission for the

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Conservation of Atlantic Tuna (ICCAT) regulates the bluefin tuna landings based on an assumption of a two stocks separated at the 45°W Meridian and negligible intermixing (Lutcavage et al., 1999; Rooker et al., 2007). Declines in the putative northwestern Atlantic population resulted in the reduction in the catch quota in the northwestern management unit, originally, without equivalent actions in the eastern management unit (Sissenwine et al., 1998). The northwestern Atlantic population is showing signs of recovery, and there has been progress in the recent years in controlling the exploitation rates of the eastern Atlantic management unit (ICCAT, 2014).

The results of tagging studies and the analyses of chemical markers in the otoliths and soft tissues indicate that bluefin tunas undergo extensive and complex migrations, including the trans-Atlantic movements; and up to 57% of the individuals comprising the eastern and northwestern Atlantic stocks may cross the ICCAT stock boundary line at some point in their lives (Lutcavage et al., 1999, 2001; Block et al., 2001, 2005; Rooker and Secor, 2004; Rooker et al., 2003; Rooker et al., 2008; Dickhut et al., 2009; Graves et al., 2015). Stable isotope data indicate that the occurrence of eastern bluefin tuna in the Mid-Atlantic Bight decreases with increasing size, and that larger bluefin tunas present in Gulf of Maine and Gulf of St. Lawrence in the northwestern Atlantic are almost entirely of northwestern origin (Rooker et al., 2008). However, if the eastward dispersive behaviors of adolescents from northwestern population across the 45°W management boundary occurs at rates observed for adolescents from eastern population, the smaller and less productive northwestern population will be disproportionately affected by higher fishing rates in the eastern management zone (Rooker et al., 2008). This, in turn, can negatively impact the stability and future commercial viability of this species.

Because of differential application practices of organochlorine pesticides in Europe and North America, the origin of a given bluefin tuna can be assigned to the eastern or northwestern origin by using the distinctive embedded ratios of certain PCB congeners and the organochlorine pesticides (Dickhut et al., 2009). Trans-nonachlor/PCB 153 ratios in bluefin tuna of eastern origin are low compared to the corresponding ratios in bluefin tuna of northwestern Atlantic origin. As the bluefin tuna of Mediterranean origin migrate to the northwestern Atlantic, these ratios gradually turnover due to their foraging in the northwestern Atlantic and the cumulative accumulation of biomass tagged with the higher trans-nonachlor/PCB 153 ratios. The origin of a given bluefin tuna can therefore be determined as Mediterranean if the trans-nonachlor/PCB 153 ratio is less than 0.164, and vice versa (Dickhut et al., 2009).

There are several hypotheses relevant to the bluefin tuna stock structure and movements. The prevailing "Overlap Model" focuses on the natal homing of the spawning stock, but with a high degree of overlap in the feeding areas on an annual and/or ontogenetic basis (Secor, 2001). Based on otolith chemistry, Rooker et al. (2008) reported that the giant bluefin tuna collected from Gulf of Maine and Gulf of St. Lawrence were 94.8% and 100% of northwestern origin, and Secor et al. (2014) reported that bluefin tuna spawning in the Gulf of Mexico exhibited 100% natal homing, regardless of the sampling period. Similarly, Rooker et al. (2014) reported that bluefin tuna collected at the entrance to the Strait of Gibraltar (eastern Atlantic Ocean) and from several regions within the Mediterranean Sea (Balearic Islands, Malta, and Sardinia) were 100% eastern Atlantic fish. These observations indicate that natal homing is well developed in both populations. The alternate "Diffusion Model" is based on an undefined degree of mixing in which the trans-Atlantic migrants become expatriates, joining the alternate population (Secor, 2001). In this approach, bluefin tuna spawned in one area can spawn in the other. The "Diffusion Model" appears to be of only minimal importance based on the near 100% natal homing behaviors observed in individuals from both populations. However, based on the spawning behavior of Pacific bluefin tuna in the ocean basin and in two marginal seas, another spawning region outside the Gulf of Mexico/Florida Straits and the Mediterranean Sea cannot be ruled out (Secor, 2001). Supportive of this idea, using popup satellite archival tags deployed on the adult Atlantic bluefin tuna off the coast of Nova Scotia and on the Georges Bank (northwestern Atlantic Ocean), Galuardi et al. (2010) found that during the assumed spawning period only 56% of the tagged fish occupied a known spawning area, while 44% were located in the distant oceanic regions. These observations are inconsistent with the notion of spawning site fidelity exclusively to the Gulf of Mexico. The authors also noted that the consideration of alternate spawning strategies and the recognition of a complex stock substructure may yield a more realistic view of the bluefin tuna population dynamics and could enhance the fisheries management rebuilding efforts.

The strong annual numerical index on a given side of the Atlantic Ocean, driven by the migratory behavior based recruitment differences, can result in an over-estimation of the past stock abundance, and perhaps erroneous assessments of future recovery (Secor, 2001). We therefore argue that the simple northwestern Atlantic or Mediterranean characterization of bluefin tuna would be far too coarse to elucidate the stock dynamics in ways needed for the development of effective management strategies (Kritzer and Sale, 2004). The primary goal of our study was to test the null hypothesis that no further fine-scale, geographical groupings of bluefin tuna exist beyond the simple northwestern Atlantic or Mediterranean designations. We therefore examined the signatures of select polychlorinated biphenyl (PCB) congeners and organochlorine pesticides in bluefin tuna caught in the northwestern Atlantic (juveniles captured offshore of Virginia, and larger individuals from Gulf of Maine and Nova Scotia). We first computed the ratios of PCB congeners and organochlorine pesticides in individual fish and compared them to the corresponding ratios reported by Dickhut et al. (2009) for young-of-the-year (YOY) bluefin tuna from Mediterranean Sea and offshore Virginia. We then assigned feeding areas of individual bluefin tuna based on the pesticide/PCB ratio guidelines (Dickhut et al., 2009). Lastly, we performed discriminant function analysis (DFA) of the total PCB normalized signatures of PCB congeners to either support or refute the null hypothesis on the concept of metapopulation behavior of north Atlantic bluefin tuna.

2. Materials and methods

Like many other non-polar organic compounds, PCBs and organochlorine pesticides are hydrophobic in nature, and they do tend to naturally bioaccumulate in the lipid-rich tissues. We therefore conceptually decided to analyze the lipid-rich liver samples of bluefin tuna, with the expectation that we will have the best success in detecting PCBs and pesticides if the bluefin tunas were indeed exposed to these chemical (for example, Stefanelli et al., 2002). However, as the study progressed, we received more muscle samples than the liver samples. We therefore adjusted our analytical protocols to include muscle as a target tissue in the subsequent analyses. Since we had planned to use the ratios of analytes and not the absolute concentrations, it was assumed that the tissue type will not introduce significant bias in the analyses. We assumed that the ratios of lipids and analytes, and the ratios among different analyte types in the muscle and liver tissue, would be approximately similar (Dickhut et al., 2009).

Samples of liver tissues of juvenile bluefin tuna were obtained from the fish landed by a local sport fishing fleet at Wachapreague on the Eastern Shore of Virginia (Fig. 1) in 2004. Actual capture sites and physical measurements were not available for these specimens. Based on the rod and reel sport fishing in the area (Turner et al., 1993), the sampled bluefin tuna were thought to be most likely from the 4.5–13.6 kg juvenile fish caught from approximately 30–50 km offshore. Gender could not be readily identified as the gonads of the juvenile bluefin tunas were not fully developed.

Samples of muscle tissues of larger bluefin tuna from the Gulf of Maine and Nova Scotia were obtained in 2006 either from specimens caught by purse seine or hook-and-line. These specimens were originally caught from June to October in 2004 and from June and July in 2005.