



# Trophic influences on mercury accumulation in top pelagic predators from offshore New England waters of the northwest Atlantic Ocean



Amy K. Teffer<sup>a,\*,1</sup>, Michelle D. Staudinger<sup>a,b,2</sup>, David L. Taylor<sup>c</sup>, Francis Juanes<sup>a,1</sup>

<sup>a</sup> University of Massachusetts, Department of Environmental Conservation, 160 Holdsworth Way, Amherst, MA 01003-9285, USA

<sup>b</sup> University of North Carolina Wilmington, Department of Biology and Marine Biology, Wilmington, NC 28403, USA

<sup>c</sup> Roger Williams University, Department of Marine Biology, One Old Ferry Road, Bristol, RI 02809, USA

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## ABSTRACT

Trophic pathways and size-based bioaccumulation rates of total mercury were evaluated among recreationally caught albacore tuna (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*), shortfin mako shark (*Isurus oxyrinchus*), thresher shark (*Alopias vulpinus*), and dolphinfish (*Coryphaena hippurus*) from offshore southern New England waters of the northwest Atlantic Ocean between 2008 and 2011. Mercury concentrations were highest in mako ( $2.65 \pm 1.16$  ppm) and thresher sharks ( $0.87 \pm 0.71$  ppm), and significantly lower in teleosts (albacore,  $0.45 \pm 0.14$  ppm; yellowfin,  $0.32 \pm 0.09$  ppm; dolphinfish,  $0.20 \pm 0.17$  ppm). The relationship between body size and mercury concentration was positive and linear for tunas, and positive and exponential for sharks and dolphinfish. Mercury increased exponentially with  $\delta^{15}\text{N}$  values, a proxy for trophic position, across all species. Results demonstrate mercury levels are positively related to size, diet and trophic position in sharks, tunas, and dolphinfish, and the majority of fishes exhibited concentrations greater than the US EPA recommended limit.

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## 1. Introduction

In contrast to the wealth of knowledge that exists regarding mercury bioaccumulation in freshwater ecosystems, trophic pathways and rates of accumulation are poorly understood in the marine environment (Doyon et al., 1998; Harris and Bodaly, 1998; Greenfield et al., 2001; Da Silva et al., 2005; Walters et al., 2010). The North Atlantic Ocean has been identified as a region of high dissolved mercury concentrations relative to the Pacific, Southern and Arctic Oceans, which has implications for enhanced bioavailability to marine food-webs in this region (Lamborg et al., 2014).

The burning of fossil fuels is a primary and continued source of mercury in the atmosphere (USGS, 2000; Varekamp et al., 2003).

\* Corresponding author.

E-mail addresses: [ateffer@uvic.ca](mailto:ateffer@uvic.ca) (A.K. Teffer), [mstaudinger@usgs.gov](mailto:mstaudinger@usgs.gov) (M.D. Staudinger), [dtaylor@rwu.edu](mailto:dtaylor@rwu.edu) (D.L. Taylor), [juanes@uvic.ca](mailto:juanes@uvic.ca) (F. Juanes).

<sup>1</sup> Present address: University of Victoria, Department of Biology, 3800 Finnerty Road, Victoria, BC V8P 5C2, Canada.

<sup>2</sup> Present address: DOI Northeast Climate Science Center, 134 Morrill Science Center, University of Massachusetts, Amherst, MA 01003-9297, USA.

Direct atmospheric deposition as well as runoff along the east coast of the United States further contribute to inorganic mercury loading in coastal and offshore waters of the northwest Atlantic (Van Arsdale et al., 2005; Driscoll et al., 2007; Krabbenhoft and Rickert, 2009; US EPA, 2010; Sackett et al., 2010). Microbial methylation of inorganic mercury occurs in coastal sediments and below the surface mixed layer of open ocean waters (Chen et al., 2008; Blum et al., 2013). Mercury is bioavailable in its methylated form and incorporated into the marine food chain by phytoplankton particulate uptake (Chen et al., 2009; Krabbenhoft and Rickert, 2009). Methylmercury moves between inshore and offshore food-webs through a 'trophic relay' (Kneib, 1997; Chen et al., 2008) and transfer to higher trophic levels is markedly efficient (Driscoll et al., 2007). Diet is the primary pathway for toxic mercury accumulation in both humans and fish; therefore, characterizing mercury sources and accumulation rates in food-webs targeted by fisheries is extremely important for human and ecosystem health assessments (Cabana et al., 1994; Hall et al., 1997; Lepak et al., 2009; Payne and Taylor, 2010). Elevated mercury burdens in humans and animals have been linked to endocrine, neural, and reproductive impairment (Porto et al., 2005; Scheulhammer et al., 2007; Crump and Trudeau, 2009; Tan et al., 2009; Veldhoen et al., 2013).

Mercury burdens generally increase with body size, age, and trophic position (Piraino and Taylor, 2009; Suk et al., 2009; Taylor et al., in press). However, rates of accumulation vary widely among species and systems due to differences in metabolism, habitat use, life histories and diets (Watras et al., 1998; Burger, 2009; Verdouw et al., 2011). For example, globally-distributed dolphinfish (*Coryphaena hippurus*) have been found to carry lower mercury concentrations at lower latitudes of the North Atlantic Ocean (e.g. Caribbean Sea, Gulf of Mexico; Cai et al., 2007; Adams, 2009) than those measured at higher latitudes of the Mid-Atlantic Bight (Burger and Gochfeld, 2011). Pelagic predator fishes can also exhibit variation in prey composition and size across geographic regions (Olson and Galván-Magaña, 2002) and with growth (Graham et al., 2007). These differences likely contribute to observed spatial and temporal variation in mercury accumulation rates, respectively.

Certain aspects of feeding ecology, such as the degree of piscivory and average prey size in regional diets, are potential indicators of predator mercury concentrations. Piscivorous predators have been shown to have higher concentrations of mercury in their tissues compared to those that feed on invertebrates and other lower trophic level prey (de Pinho et al., 2002; Adams, 2010). Prey size can also affect mercury bioaccumulation of predators, as larger prey are often older and/or feeding at higher trophic levels, thus carrying greater mercury burdens (Piraino and Taylor, 2009; Suk et al., 2009). Additionally, geographic variability in bioavailable mercury can influence mercury accumulation rates and tissue concentrations of migratory fishes across their range (Verdouw et al., 2011). Because tissue mercury concentrations measured at one time point or location represent cumulative uptake across a species' life span and geographic range, regional assessments of fish mercury content and feeding ecology are needed to identify the potential pathways of mercury transfer within marine food-webs. Information from multiple metrics of diet determination representing short- and long-term feeding habits (such as stomach contents and stable isotope analyses, respectively) can be used to more comprehensively characterize these pathways of mercury accumulation in highly migratory predator fishes.

In the northwest Atlantic Ocean, large pelagic fishes migrate seasonally to offshore waters of the southern New England region to feed upon abundant prey resources (Thompson, 1999; Natanson, 2002; MacNeil et al., 2005; ICCAT, 2010). Intense recreational and commercial fishing effort is focused on these pelagic predators during the summer and fall. In particular, dolphinfish, albacore (*Thunnus alalunga*) and yellowfin (*Thunnus albacares*) tunas, shortfin mako (*Isurus oxyrinchus*) and common thresher (*Alopias vulpinus*) sharks are targeted by recreational anglers for sport fishing tournaments where the primary goal is to catch the largest fish possible. Such practices raise human health concerns given the potentially high mercury concentrations of large fish and the high frequency of catch consumption by coastal communities of the northeast United States (Steinback et al., 2009).

As the impacts of climate change continue to grow, increasing ocean temperatures and acidification are impacting mercury cycling and methylation, potentially leading to altered bioaccumulation rates of mercury by marine biota (Deser and Blackmon, 1993; Levitus et al., 2000; Doney et al., 2009; Dijkstra et al., 2013). Climate change is also causing species to shift their geographical ranges, the timing of seasonal migrations, leading to altered trophic interactions (Collie et al., 2008; Nye et al., 2009; Fodrie et al., 2010). Therefore, baseline studies that provide information on trophic pathways and rates of contaminant bioaccumulation are increasingly needed to detect and track shifts as environmental conditions and ecological communities continue to change (Staudinger et al., 2013b). The trophic ecology and mercury

accumulation of top predators in offshore waters of southern New England have been poorly studied due in part to logistical difficulties in sampling and to the limited time period these fishes spend in this region. Mercury analysis of tuna and dolphinfish at this northern extent of their migratory range contributes further information relating to the cumulative nature of mercury accumulation by complementing previous studies focused in southern regions of the Atlantic Ocean, including the South Atlantic Bight and Gulf of Mexico (e.g. Adams, 2009; Senn et al., 2010; Petre et al., 2012).

To increase our understanding of the trophic pathways and mercury bioaccumulation in dolphinfish, albacore and yellowfin tunas, and mako and thresher sharks, total mercury was measured in the edible muscle tissues of these fishes. Interspecific differences in the relationships between mercury concentration, body size, diet, and feeding ecology were quantified. Results are discussed in the context of both human and ecosystem health, and are intended to assist fishers and the public in making informed decisions about the fish they catch and consume.

## 2. Materials and methods

### 2.1. Sample collection and processing

Dorsal muscle samples were collected from dolphinfish, tunas, and sharks landed dockside at recreational fishing tournaments on Cape Cod and the Islands of Massachusetts during summer and early fall (July, August and September) of 2008–2011. Tissue samples were removed, immediately placed on ice, and frozen until laboratory analyses were conducted. In addition, eight prey species were selected for mercury analysis based on their nutritional importance (percent weight) and population scale feeding habits (percent occurrence) (Teffer, 2012). Atlantic herring (*Clupea harengus*), round herring (*Etrumeus teres*), shortfin squid (*Illex illecebrosus*), longfin squid (*Loligo pealeii*), spiny dogfish (*Squalus acanthias*), Atlantic butterfish (*Pepilius triacanthus*), silver hake (*Merluccius bilinearis*) and bluefish (*Pomatomus saltatrix*) were collected from bottom trawl surveys conducted by the National Marine Fisheries Service (NMFS) during fall of 2008 and 2011. Predator weights were taken dockside (kg). Predator lengths were measured as curved fork length (CFL), prey fish as total length (TL), and squid as mantle length (ML). All body lengths were measured in centimeters (cm).

### 2.2. Mercury analysis

For all predator and prey specimens, a 1.0 g subsample of dorsal muscle tissue (dorsal mantle from squid) was excised and weighed ( $\pm 0.0001$  g), freeze-dried for 24 h in a Labconco freeze dry system, re-weighed to assess moisture content, and homogenized using mortar and pestle. All samples were analyzed for total mercury (ppm dry weight) using a Milestone DMA-80 Mercury Analyzer (Cizdziel et al., 2002). This method utilizes thermal decomposition, amalgamation, and atomic absorption spectrophotometry (EPA method 7473; US EPA, 1998), with an instrument detection limit of 0.01 ng mercury. Certified reference materials (CRMs) prepared by the National Research Council Canada, Institute of Environmental Chemistry (Ottawa, Canada) were used to calibrate the DMA-80 and included TORT-1 (lobster hepatopancreas) and DORM-2 (dogfish muscle) (US EPA, 1998). Calibration curves were highly linear (mean  $r^2 = 1.00$ ; range  $r^2 = 0.99–1.00$ ;  $P < 0.0001$ ), and the recovery of independently analyzed samples of DORM-2, DOLT-3 (dogfish liver), and NIST 2702 (marine sediment) CRMs ranged from 85.2% to 99.4% (mean = 93.7%). All samples were analyzed as duplicates, and an acceptance criterion of 10% was implemented.

Duplicate samples with <10% error were averaged for subsequent analysis (mean absolute difference between duplicates = 3.5%). Samples with >10% error were reanalyzed to achieve the acceptance criterion or were eliminated from further analysis. Blanks were run every ten samples to measure accuracy and drift of the mercury analyzer. The mean wet weight conversion value (dry weight/wet weight) for each species was used to convert dry weight mercury values to wet weight. For albacore tuna, only tissue taken in 2011 was used in the calculation of moisture content due to enhanced dehydration of frozen tissue taken from this species in years previous. Total mercury is here considered an acceptable measure of methylmercury for the purposes of this study, as methylmercury has been found to comprise the majority (>90%) of total mercury in fish tissue, especially at higher trophic levels (Storelli et al., 2002; Bank et al., 2007; Driscoll et al., 2007; US EPA, 2010). All mercury values were converted to wet weight using derived moisture content values (Tables 1 and 2) then log-transformed to meet assumptions for parametric statistical analyses.

Differences in weight and length among all predatory fishes were identified with one-way analysis of variance (ANOVA) models using species as a fixed factor and post hoc pairwise Tukey's Honest Significant Differences (Tukey HSD) tests. For predator fishes, differences in mercury concentrations and size-based accumulation rates were compared separately between elasmobranchs (sharks) and among teleosts (dolphinfish and tunas) due to disparity in the range of body sizes (covariate) and habitat use. Differences in mercury concentrations between elasmobranchs and among teleosts were identified with two-way ANOVA models with species as a fixed factor and weight or length as a covariate; for teleosts, post hoc pairwise two-way ANOVA models identified significant differences in mercury concentrations controlling for body size. We used an interaction term to identify significant differences in the rates of mercury accumulation with increasing predator weight or length (homogeneity of slopes) between elasmobranchs and among teleost species, with species as a fixed factor and weight or length as a random factor. A Bonferroni correction was used to account for multiple comparisons.

Linear and exponential least squares regressions were used to describe the relationships between total mercury and body size (weight and length) for each predator species. The regression model that best explained the relationship between mercury and body size for each predator species was chosen using residual sums of squares, coefficient of variation, and *P*-values (Sokal and Rohlf, 1995). Weight-specific mercury accumulation rates represent bioaccumulation relative to accumulated weight of each species. Length-specific mercury accumulation rates are indicative of bioaccumulation rates (e.g. Staudinger, 2011; Ordiano-Flores et al., 2011) and feeding ecology (e.g. relationship with gape restriction, ontogenetic shifts in diet), and serve as consumption guidelines for recreational anglers.

**Table 1**

Sample size, mean water content (percent  $\pm$  standard deviation; SD), total mercury (Hg) mean  $\pm$  SD content, curved fork length (CFL) mean  $\pm$  SD, and weight (kg) mean  $\pm$  SD of five pelagic predators. Percentage >0.3 ppm indicates the proportion of individuals with mercury burdens over the US EPA maximum recommended criterion. Results of pairwise comparisons (PW) of mercury, length and weight are designated by letters: predators that share a letter were not statistically different. For mercury, comparisons are made between sharks and among dolphinfish and tunas due to non-overlapping covariates (length and weight).

Species	<i>n</i>	Moisture %	Hg (ppm wet wt)				CFL (cm)			Weight (kg)	
			Mean $\pm$ SD	PW	Range	>0.3 ppm	Mean $\pm$ SD	PW	<i>n</i>	Mean $\pm$ SD	PW
Shortfin mako	32	0.73 $\pm$ 0.02	2.647 $\pm$ 1.156	A	0.755–4.933	100%	199.5 $\pm$ 23.0	A	22	82.6 $\pm$ 4.6	A
Common thresher	41	0.75 $\pm$ 0.01	0.875 $\pm$ 0.709	B	0.206–3.209	88%	205.6 $\pm$ 23.6	A	27	128.2 $\pm$ 6.3	B
Albacore tuna	15	0.72 $\pm$ 0.02 <sup>a</sup>	0.455 $\pm$ 0.144	C	0.294–0.683	87%	98.3 $\pm$ 6.2	B	11	18.1 $\pm$ 0.9	CD
Yellowfin tuna	47	0.72 $\pm$ 0.02	0.304 $\pm$ 0.087	D	0.044–0.503	62%	101.7 $\pm$ 14.8	B	24	20.4 $\pm$ 1.6	C
Dolphinfish	39	0.75 $\pm$ 0.02	0.205 $\pm$ 0.172	CD	0.021–0.648	28%	78.4 $\pm$ 15.9	C	32	4.7 $\pm$ 0.4	D

<sup>a</sup> Water content (%) of albacore tuna represents tissue taken only in 2011 (*n* = 4).

For prey species, differences in length and mercury concentrations were identified using two-way ANOVA models, with species as a fixed factor and length as a random factor; post hoc pairwise comparisons of mercury concentrations among prey were conducted using Tukey HSD tests. We evaluated prey length rather than weight due to the relative importance of prey length to predation (e.g. Ménard et al., 2006) and subsequent effects on predator mercury accumulation.

To assess the effect of feeding ecology on mercury content across predator species, mean predator mercury content was analyzed as a function of percent frequency of occurrence (%O) of fish prey and mean prey body length (all prey types) using least squares regression. Diet data were obtained from Teffer (2012), which examined a similar suite of predators collected during the same time period as the tissues used for mercury analysis. All statistical analyses were conducted in program R (R Development Core Team, 2012).

### 2.3. Stable isotope analysis

Stable nitrogen and carbon isotopic signatures were measured in tunas, sharks, and dolphinfish to gain information on interspecific differences in predator foraging ecology, trophic position, and habitat use. Subsamples of predator dorsal muscle tissues were dried in an oven at 60° for a minimum of 48 h, and then homogenized using a mortar and pestle. A normalization model that uses C:N ratios as a proxy for lipid content was used to estimate  $\delta^{13}\text{C}$  values and remove the potential effect of lipids on fish muscle tissues (McConnaughey and McRoy, 1979; Logan et al., 2008).

Tissues were flash-combusted (Costech ECS4010 elemental analyzer), and ratios of nitrogen ( $\delta^{15}\text{N}$ ) and carbon ( $\delta^{13}\text{C}$ ) stable isotopes were analyzed on a Thermo Delta V Plus continuous-flow isotope ratio mass spectrometer (CFIRMS) at the Center for Marine Science at the University of North Carolina, Wilmington. Raw  $\delta$  values were normalized using depleted and enriched glutamic acid reference materials USGS-40 and USGS-41. Sample precision was 0.2‰ and 0.1‰ for  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ , respectively.

Stable isotope abundances are expressed in  $\delta$  notation in per mille units (‰), according to the equation:

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000(\text{‰})$$

where *X* is  $^{13}\text{C}$  or  $^{15}\text{N}$  and *R* is the corresponding ratio  $^{13}\text{C}:^{12}\text{C}$  or  $^{15}\text{N}:^{14}\text{N}$ . The  $R_{\text{standard}}$  values were based on the Vienna PeeDee Belemnite (VPDB) for  $^{13}\text{C}$  and atmospheric  $\text{N}_2$  for  $^{15}\text{N}$ .

Least-squares linear and exponential regression models were used to determine the relationship between mercury concentration and  $\delta^{15}\text{N}$  values, which served as a proxy for trophic position, for individual predators and all predator species combined. Mercury concentrations were  $\log_{10}$  transformed prior to parametric analyses to meet the assumptions of normality and homogeneity of variance

**Table 2**

Sample size, mean water content (%)  $\pm$  standard deviation (SD), mean length  $\pm$  SD (cm) and total mercury (Hg) concentrations  $\pm$  SD (ppm wet weight) of prey collected from trawl surveys. Results of pairwise comparisons (PW) of length and mercury are designated by letters: species that share a letter were not statistically different.

Family	Common name	n	Water content (%)	TL (cm)	Hg (ppm wet wt)	TL PW	Hg PW
Squalidae	Spiny dogfish	14	0.76 $\pm$ 0.02	53.0 $\pm$ 5.3	0.088 $\pm$ 0.039	A	A
Pomatomidae	Bluefish	9	0.76 $\pm$ 0.02	17.0 $\pm$ 4.6	0.075 $\pm$ 0.028	B	A
Ommastrephidae	Shortfin squid	15	0.75 $\pm$ 0.01	17.4 $\pm$ 1.1	0.028 $\pm$ 0.005	B	B
Merluciidae	Silver hake	7	0.82 $\pm$ 0.03	27.7 $\pm$ 2.0	0.028 $\pm$ 0.010	C	BC
Clupeidae	Atlantic herring	10	0.75 $\pm$ 0.02	23.8 $\pm$ 1.4	0.024 $\pm$ 0.004	C	BC
Loliginidae	Longfin squid	10	0.76 $\pm$ 0.02	13.9 $\pm$ 4.8	0.023 $\pm$ 0.004	B	BCD
Clupeidae	Round herring	9	0.76 $\pm$ 0.01	12.9 $\pm$ 0.3	0.018 $\pm$ 0.003	B	CD
Stromateidae	Butterfish	10	0.77 $\pm$ 0.02	7.5 $\pm$ 1.3	0.016 $\pm$ 0.003	D	D

(Sokal and Rohlf, 1995). The model that best fit the data was selected based on residual sums of squares, coefficient of variation, and *P*-values (Sokal and Rohlf, 1995). An ANCOVA was used to compare changes in mercury content as a function of trophic position ( $\delta^{15}\text{N}$  values) among predators.

### 3. Results

#### 3.1. Mercury content of predators

The dorsal muscle tissues of 32 shortfin mako sharks, 41 thresher sharks, 15 albacore tuna, 47 yellowfin tuna, and 39 dolphinfish were evaluated for total mercury concentrations (Table 1). The greatest mercury concentrations were found in shortfin mako (2.647  $\pm$  1.156 ppm) and thresher sharks (0.875  $\pm$  0.709 ppm), followed by albacore tuna (0.455  $\pm$  0.144 ppm), yellowfin tuna (0.304  $\pm$  0.087 ppm) and dolphinfish (0.205  $\pm$  0.172 ppm), respectively.

The mercury content of shortfin mako was significantly higher than that of thresher sharks controlling for weight and length (Two-way ANOVA:  $F = 237.4$ ,  $df = 1$ ,  $P < 0.01$ ;  $F = 321.4$ ,  $df = 1$ ,  $P < 0.01$ , respectively). Common thresher and shortfin mako sharks were the largest predators sampled by length (thresher: 205.6  $\pm$  23.6 cm,  $n = 41$ ; mako: 199.5  $\pm$  23.0 cm,  $n = 32$ ) and weight (thresher: 128.2  $\pm$  6.3 kg,  $n = 27$ ; mako: 82.6  $\pm$  4.6 kg,  $n = 22$ ).

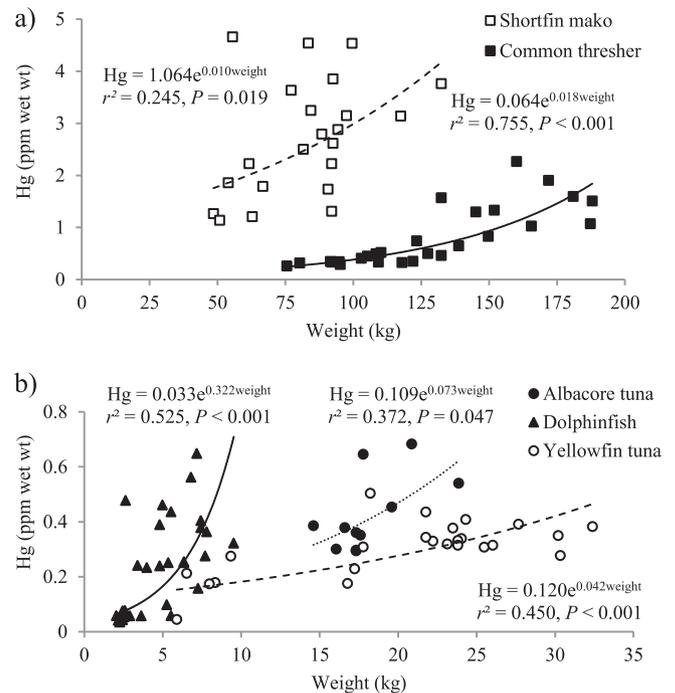
For sharks, the regression model that best described the relationship between predator weight and total mercury concentration was exponential ( $P$ -values  $< 0.05$ ) (Fig. 1). The regression model that best described the relationship between predator length and total mercury concentration was found to be exponential for both shortfin mako ( $r^2 = 0.435$ ,  $P < 0.01$ ) and thresher sharks ( $r^2 = 0.839$ ,  $P < 0.01$ ) (Fig. 2). We identified significant differences in size-specific accumulation rates (regression slopes) of sharks by length (Two-way ANOVA:  $F = 20.6$ ,  $df = 1$ ,  $P < 0.01$ ) but not by weight ( $F = 3.0$ ,  $df = 1$ ,  $P = 0.09$ ). Thresher and shortfin mako sharks showed relatively low rates of mercury accumulation per unit weight ( $\beta = 0.018$  and 0.010, respectively) and length ( $\beta = 0.029$  and 0.014, respectively). Consistently greater variability was apparent in the relationships of predator weight with mercury content than length-specific relationships (i.e. lower coefficients of variation in weight-mercury regressions).

For teleosts, significant differences in mercury concentrations were identified among dolphinfish and tunas controlling for weight and length (Two-way ANOVA:  $F = 3.3$ ,  $df = 2$ ,  $P = 0.04$ ;  $F = 8.4$ ,  $df = 2$ ,  $P < 0.01$ , respectively), primarily attributable to disparity between tunas. Controlling for weight and length, mercury content of albacore tuna was greater than that of yellowfin tuna (Two-way ANOVAs:  $P$ -values  $< 0.01$ ). Dolphinfish mercury content was lower than that of the tunas, but this difference was not statistically significant after Bonferroni correction ( $P$ -values  $> 0.02$ ), likely due to the low sample size for albacore and high variability in dolphinfish

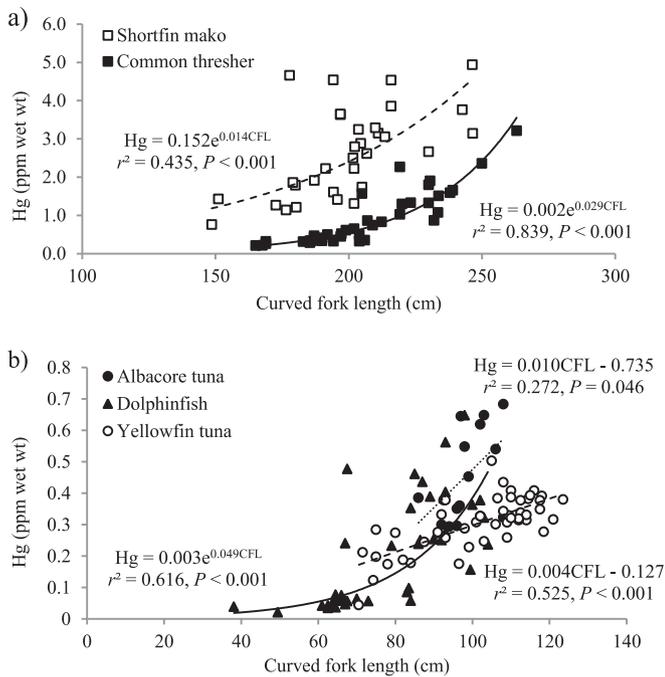
mercury concentrations. Predator length and weight differed significantly among dolphinfish and tunas ( $P < 0.01$ ) with dolphinfish as the smallest overall (78.4  $\pm$  15.9 cm,  $n = 39$ ; 4.7  $\pm$  0.4 kg,  $n = 32$ ).

For teleosts, significant differences were found between weight- and length-specific accumulation rates (i.e. regression slopes) (Two-way ANOVA:  $F = 3.3$ ,  $df = 2$ ,  $P = 0.04$ ;  $F = 8.4$ ,  $df = 2$ ,  $P < 0.01$ , respectively). The regression model that best described the relationship between predator weight and total mercury concentration was exponential ( $P$ -values  $< 0.05$ ). The slope of the relationship between predator weight and log-transformed mercury content was highest for dolphinfish ( $\beta = 0.322$ ,  $P$ -values  $< 0.01$ ), indicating the greatest increase in mercury content per unit weight of all predators examined. Albacore ( $\beta = 0.073$ ) and yellowfin tuna ( $\beta = 0.042$ ) followed dolphinfish for the next highest weight-specific mercury accumulation rates of all predators, though the relationship was marginally significant for albacore ( $P = 0.047$ ).

Among teleosts, the relationship between predator length and mercury concentration was best described by an exponential model for dolphinfish ( $r^2 = 0.616$ ,  $P < 0.01$ ) and a linear model for



**Fig. 1.** Least squares relationships between predator weight (kg) and total mercury (Hg) in a) shortfin mako (open squares, dashed line) and thresher sharks (closed squares, solid line) and b) albacore tuna (closed circles, dotted line), yellowfin tuna (open circles, dashed line), and dolphinfish (triangles, solid line) collected in the southern New England region.



**Fig. 2.** Least squares relationships between predator body size (curved fork length (CFL) measured in cm and total mercury (Hg) in a) shortfin mako (open squares, dashed line) and thresher sharks (closed squares, solid line) and b) albacore tuna (closed circles, dotted line), yellowfin tuna (open circles, dashed line), and dolphinfish (triangles, solid line) collected in the southern New England region.

yellowfin tuna ( $r^2 = 0.525$ ,  $P < 0.01$ ) (Fig. 2). The relationship between length and mercury concentration for albacore tuna was linear but marginally significant ( $r^2 = 0.272$ ,  $P = 0.046$ ), and likely due to the relatively low sample size and narrow range of body sizes sampled. The slope of the relationship between predator length and  $\log_{10}$ -transformed mercury content was highest for dolphinfish ( $\beta = 0.049$ ) and significantly greater than that of yellowfin (Two-way ANOVA:  $F = 20.3$ ,  $df = 1$ ,  $P < 0.01$ ), but not albacore tuna ( $F = 0.9$ ,  $df = 1$ ,  $P = 0.35$ ). Albacore tuna ( $\beta = 0.026$ ) and yellowfin tuna ( $\beta = 0.019$ ) followed dolphinfish for the next highest length-specific mercury accumulation rates.

### 3.2. Mercury content of prey

Of the eight prey species evaluated, mercury concentrations were highest in spiny dogfish ( $0.088 \pm 0.039$  ppm) and bluefish ( $0.075 \pm 0.028$  ppm) (Table 2). Northern shortfin squid

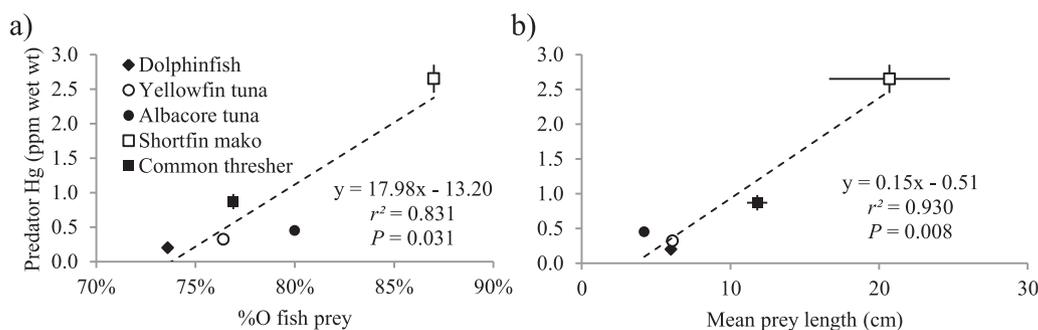
( $0.028 \pm 0.005$  ppm), silver hake ( $0.028 \pm 0.010$  ppm), Atlantic herring ( $0.024 \pm 0.004$  ppm), and longfin inshore squid ( $0.023 \pm 0.004$  ppm) exhibited intermediate mercury concentrations, while the lowest concentrations were found in round herring ( $0.018 \pm 0.003$  ppm) and butterfish ( $0.016 \pm 0.003$  ppm). Prey length varied significantly ( $F = 22.3$ ,  $df = 7$ ,  $P < 0.01$ ) among species (Table 2). Overall, the largest prey was spiny dogfish ( $53.2 \pm 5.2$  cm), and butterfish was the smallest ( $7.5 \pm 1.3$  cm). Silver hake and Atlantic herring were similarly sized ( $P > 0.05$ ) and larger than bluefish, shortfin and longfin squids, and round herring ( $P$ -values  $< 0.05$ ), which all had similar mean body sizes ( $P$ -values  $> 0.05$ ).

### 3.3. Mercury content and predator feeding ecology

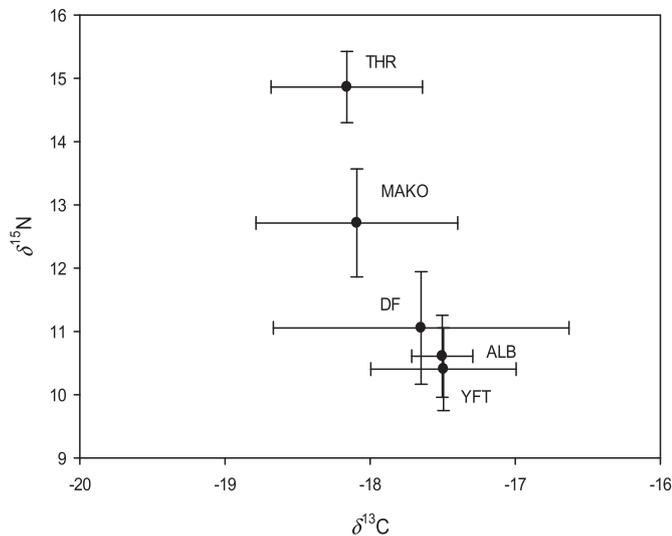
The diet of shortfin mako contained the highest amount of fish prey (%O = 87) and the largest prey (mean length =  $20.7 \pm 4.1$  cm). Albacore tuna and thresher sharks also showed relatively frequent occurrences of fish in their diets (80% and 77%, respectively), but smaller prey sizes ( $4.2 \pm 0.2$  and  $11.8 \pm 0.7$  cm, respectively). Yellowfin tuna (76%) and dolphinfish (74%) had the lowest occurrence of fish prey in their diets and relatively small-bodied prey ( $6.1 \pm 0.1$  cm and  $6.0 \pm 0.2$  cm, respectively). The relationship between the mean mercury concentration in the muscle tissue of dolphinfish, tunas, and sharks was positively correlated with the percent frequency of occurrence of fish prey ( $r^2 = 0.831$ ,  $P = 0.03$ ), and mean prey length ( $r^2 = 0.930$ ,  $P < 0.01$ ) in their diets (Fig. 3). These prey-based factors were more precise predictors of mean predator mercury content than mean predator weight ( $r^2 = 0.308$ ,  $P = 0.04$ ) or length ( $r^2 = 0.575$ ,  $P = 0.14$ ).

Stable nitrogen ( $\delta^{15}N$ ) isotopic values were higher in thresher ( $14.9 \pm 0.11\text{‰}$ ) and mako shark tissues ( $12.7 \pm 0.26\text{‰}$ ) compared to dolphinfish ( $11.1 \pm 0.31\text{‰}$ ) and tunas (albacore,  $10.6 \pm 0.19\text{‰}$ ; yellowfin,  $10.4 \pm 0.21\text{‰}$ ) signifying that sharks occupied higher trophic levels than the teleosts evaluated in this study (Fig. 4). Shark tissues were slightly more depleted in  $^{13}C$  compared to tunas and dolphinfish indicating they may forage in different pelagic habitats to some extent; however, carbon values spanned a relatively narrow range overall ( $0.7\text{‰}$ ). Dolphinfish exhibited the greatest variation in  $\delta^{13}C$  values of all predators examined signifying they forage over the greatest range of habitats of all predators examined (Table 3).

Trophic position (represented by  $\delta^{15}N$  values) had a significant and positive influence on mercury levels across all predators ( $F = 15.1$ ,  $P = 0.0003$ ) (Fig. 5). Mercury accumulation rates varied significantly among predator species as a function of  $\delta^{15}N$  values, with the greatest rates of increase found in sharks; an exponential model best described the relationship between mercury concentration and  $\delta^{15}N$  values in mako sharks ( $r^2 = 0.427$ ,  $F = 6.7$ ,  $P = 0.03$ )



**Fig. 3.** a) Mean mercury (Hg) concentration  $\pm$  standard error (SE) of dolphinfish, yellowfin tuna, albacore tuna, shortfin mako, and common thresher shark plotted as a function of percent frequency of occurrence (%O) of fish prey in total diets. b) Linear regression of mean  $\pm$  SE Hg concentration of dolphinfish, yellowfin tuna, albacore tuna, shortfin mako, and common thresher shark as a function of mean  $\pm$  SE prey length (all prey types combined). Diet data on prey occurrence and body size were adapted from Teffer (2012).



**Fig. 4.** Nitrogen ( $\delta^{15}\text{N}$ ) and carbon ( $\delta^{13}\text{C}$ ) isotope ratios (mean  $\text{‰} \pm \text{SD } \text{‰}$ ) in muscle tissues of albacore tuna (ALB), yellowfin tuna (YFT), dolphinfish (DF), shortfin mako shark (MAKO) and common thresher (THR) shark.

and a linear model for thresher sharks ( $r^2 = 0.433$ ,  $F = 18.4$ ,  $P < 0.01$ ). Likely because of the relatively narrow range of sizes and life histories sampled for dolphinfish and tunas, mercury accumulation was not found to vary significantly as a function of  $\delta^{15}\text{N}$  values within these species.

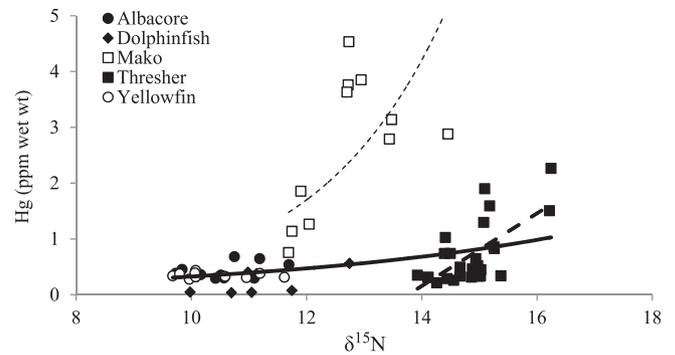
#### 4. Discussion

To the best of our knowledge, this is the first study to report contaminant levels for dolphinfish, tunas, and sharks at the northern extent of their range in the southern New England region of the northwest Atlantic Ocean. Total mercury concentrations of dolphinfish, tunas, and sharks harvested in offshore waters of southern New England were positively related to predator body size by weight and length, trophic level (approximated by  $\delta^{15}\text{N}$  values), the degree of piscivory and mean prey size in their respective diets. This information complements mercury evaluations previously conducted in more southern regions including the Gulf of Mexico, the eastern Atlantic, Pacific Ocean and the South Atlantic Bight of the northwest Atlantic Ocean (Besada et al., 2006; Kojadinovic et al., 2006; Cai et al., 2007; Kaneko and Ralston, 2007; Suk et al., 2009; Adams, 2009, 2010; Burger and Gochfeld, 2011; Ordiano-Flores et al., 2012). Mercury levels in southern New England were relatively high in all fishes, and exceeded the US EPA recommended threshold of 0.3 ppm (US EPA, 2010) in 100% of mako sharks and 63% of all other predators examined in this study. Our results suggest that anglers, particularly those participating in recreational fishing tournaments in the southern New England region, are at risk of adverse effects of mercury toxicity if they regularly consume these fishes.

**Table 3**

Sample size, mean and standard deviation (SD)  $\delta^{15}\text{N}$ , and  $\delta^{13}\text{C}$  values for pelagic predators.

Species	n	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$
		Mean $\pm$ SD	Mean $\pm$ SD
Dolphinfish	8	11.1 $\pm$ 0.31	-17.7 $\pm$ 0.36
Albacore tuna	10	10.6 $\pm$ 0.19	-17.5 $\pm$ 0.07
Yellowfin tuna	10	10.4 $\pm$ 0.21	-17.5 $\pm$ 0.16
Shortfin mako	11	12.7 $\pm$ 0.26	-18.1 $\pm$ 0.21
Common thresher	26	14.9 $\pm$ 0.11	-18.2 $\pm$ 0.10



**Fig. 5.** Total mercury (ppm wet weight) as a function of  $\delta^{15}\text{N}$  ( $\text{‰}$ ) for albacore tuna (closed circle), yellowfin tuna (open circle), dolphinfish (closed diamond), shortfin mako (open square) and common thresher (closed square) sharks. An exponential regression model is shown for all species combined (solid line), and individual species data for mako sharks (short dashed line). A linear model is shown for thresher sharks (long dashed line). Regression lines were not significant for tunas and dolphinfish.

#### 4.1. The influence of foraging ecology on predator mercury concentrations

##### 4.1.1. Teleosts

Diet is the primary pathway for mercury accumulation in fishes, and predators feeding at higher trophic levels (e.g., piscivores) generally accumulate greater contaminant levels than those feeding on lower trophic level prey (e.g., planktivores) (Campbell et al., 2006; Stacy and Lepak, 2012). The diets of albacore and yellowfin tunas contain large amounts of small prey including juvenile fishes and squids, and larval invertebrates such as crab megalops, (Teffer, 2012). The onset of piscivory and an increased depth of feeding have been demonstrated in Pacific yellowfin at 45 cm fork length (Graham et al., 2007). Although these shifts are likely reflected in mercury accumulation rates of yellowfin tuna in southern New England, all yellowfin evaluated here were larger than 45 cm. Therefore, evaluation of such an ontogenetic dietary shift relating to mercury burden was not possible. Albacore tuna show a higher degree of piscivory according to prey occurrence than yellowfin tuna in the southern New England region. Although this apparent piscivory helps explain the observed higher mercury levels of albacore, the percent contribution of fish to southern New England albacore diets by weight (10%) and number (11%) were found to be much lower than in dolphinfish and yellowfin tuna diets (%W = 43% and 30%; %N = 18% and 17%, respectively) (Teffer, 2012). The relatively high mercury content and consistent but potentially minor predation on teleosts point to age and metabolism as more relevant factors influencing mercury accumulation in southern New England albacore tuna.

Although albacore mercury concentrations were higher than those of yellowfin, the  $\delta^{13}\text{C}$  values measured in albacore and yellowfin tunas in this study were similar and did not show strong evidence that the two species were foraging in different habitats. In the Pacific and eastern Atlantic Oceans, albacore tuna diets contain relatively more mesopelagic prey than yellowfin tuna indicating they may forage at greater depths (Young et al., 2010; Goñi et al., 2011; Choy et al., 2009), which has been associated with increased mercury bioaccumulation in pelagic predators (Choy et al., 2009). In the Pacific, albacore also had greater mercury concentrations than yellowfin tuna and at comparable levels to the present study ( $0.50 \pm 0.24$  and  $0.30 \pm 0.18$  ppm, respectively; Kaneko and Ralston, 2007). Growth rates, metabolic costs and consumption rates differ between these two tuna species (Lessa and Duarte-Neto, 2004; Williams et al., 2012) and though not evaluated here, likely contribute to a potential interspecific

discrepancy in mercury concentrations between tunas (Trudel and Rasmussen, 2006). Although our data suggest that size-specific accumulation rates and average mercury concentrations are greater for the regional albacore tuna population compared to yellowfin tuna, low sample sizes for albacore tuna prevent inferences as to the primary drivers of this difference and further studies on this subject are needed.

Invertebrate prey, mainly shortfin squid, is the primary nutritional base of dolphinfish and yellowfin tuna in southern New England (Staudinger et al., 2013a; Teffer, 2012). Ommastrephid and Loliginid squids have been shown to concentrate moderate amounts of mercury in their tissues in the northwest and eastern Atlantic (Pierce et al., 2008; Staudinger, 2011; this study). Dolphinfish and yellowfin tuna also regularly consume small and juvenile prey associated with floating *Sargassum* communities (Casazza and Ross, 2008; Teffer, 2012; Staudinger et al., 2013a); however, large male dolphinfish exhibit different habitat use and foraging behaviors that may create sex-specific disparities in mercury levels (Manooch and Mason, 1983; Oxenford and Hunte, 1999; Rudershausen et al., 2010). Indeed,  $\delta^{13}\text{C}$  values measured in dolphinfish exhibited the greatest range of all predators indicating they are foraging over a wide range of habitats that likely include the Gulf Stream, as well as continental shelf and slope waters. Disparity in feeding behaviors, prey base and prey size among large-bodied dolphinfish may explain the high variation in mercury content of individuals greater than 70 cm CFL (Oxenford and Hunte, 1999; Olson and Galván-Magaña, 2002).

Although dolphinfish had the lowest mercury burdens of the predator species examined, the weight-specific accumulation rates of dolphinfish ranged between four- and 32-fold greater than that of other predators and its length-specific accumulation rate was also relatively high. These high size-based accumulation rates may be due to high daily ration and large mean prey size of dolphinfish relative to other predators examined (Olson and Galván-Magaña, 2002; Teffer, 2012). For many predatory fishes, fork length is positively correlated with mouth gape width and maximum prey size (Scharf et al., 2000; Salmon and Scholl, 2014). At large body sizes, dolphinfish have larger mouth gapes than tunas that allow them to consume larger prey, which may contribute to the greater mercury burdens seen here (Massuti et al., 1998; Olson and Galván-Magaña, 2002; Rudershausen et al., 2010; Young et al., 2010; Teffer, 2012). Mean prey size was highly correlated with mercury content across all predator species, suggesting prey size as a primary driver of mercury accumulation among all predators examined. However, this assumption is speculative until energy densities of prey, another factor affecting mercury accumulation of predators, is incorporated into a size-based analysis (Trudel and Rasmussen, 2006).

Our results show mercury concentrations in dolphinfish from the southern New England region were twice as high as those described by Adams (2009), and indicate higher accumulation rates, especially at large body sizes. Adams (2009) found that concentrations remain consistently low for dolphinfish across its geographic range relative to other predators; however, individuals from northern latitudes of the Atlantic were not included in this analysis. Slightly lower mercury levels have also been found in dolphinfish landed by anglers in the mid-Atlantic region ( $0.17 \pm 0.04$  ppm, Burger and Gochfeld, 2011) and from the Indian Ocean, Mozambique Channel ( $0.17 \pm 0.16$  ppm, Kojadinovic et al., 2006). This potential latitudinal trend is supported by relatively high mercury deposition and potentially enhanced bioavailability to marine food-webs in the North Atlantic Ocean (Lamborg et al., 2014).

#### 4.1.2. Sharks

The mercury content of shark muscle tissue was substantially higher than teleost concentrations examined in this study. Degree

of piscivory and prey body size in shark diets were strong predictors of shark mercury levels, which increased significantly with body size and  $\delta^{15}\text{N}$  values. As has been reported previously in the western Atlantic (Estrada et al., 2003; MacNeil et al., 2005), thresher shark tissues were enriched in  $^{15}\text{N}$  suggesting they occupy a higher trophic position than mako sharks. Body size is often a better predictor of an individual's trophic position within its community than species because of ontogenetic shifts in diet that occur over a life span (Jennings and Reynolds, 2007). Therefore trophic position may also change with age and sex depending on growth and behavior. Given their higher trophic position and larger body sizes, it was expected that thresher sharks would also exhibit higher mercury concentrations compared to mako sharks; however the opposite was true. Although mercury concentration is expected to increase with fish body size and age, this is not always true highlighting why conducting species and size-specific evaluations are important across communities and regions (Scott and Armstrong, 1972).

Because thresher and mako shark diets are so poorly known in the Atlantic, it is difficult to determine what factors are influencing these contradictory results (MacNeil et al., 2005; Suk et al., 2009). Compared to mako sharks, thresher sharks are thought to depend more on small bodied piscine prey such as butterfish and sand lance (*Ammodytes dubius*) (Bowman et al., 2000; Preti et al., 2001, 2004; MacNeil et al., 2005; Teffer, 2012), which have relatively low mercury levels (Staudinger, 2011; Taylor et al., 2014). In contrast, the primary prey of shortfin mako sharks during the summer in southern New England is adult bluefish (Estrada et al., 2003; MacNeil et al., 2005; Wood et al., 2009) and smaller elasmobranchs in some regions (Cliff et al., 1990). A recent study, showed that tissues of smooth dogfish (*Mustelus canis*) and spiny dogfish (*Squalus acanthias*) in the southern New England region accumulate relatively high mercury levels (Taylor et al., 2014), with spiny dogfish identified as prey to shortfin mako in southern New England (Teffer, 2012). Bluefish have been shown to accumulate high levels of mercury in their tissues relative to other coastal fish species in the mid-Atlantic and southern New England regions, even as juveniles (Burger, 2009; Staudinger, 2011; Szczebak and Taylor, 2011).

Given the average annual consumption rate of large bluefish by shortfin mako sharks (~500 kg/year, Wood et al., 2009; Stillwell and Kohler, 1982), an adult mako shark could consume greater than 200 mg of mercury per year. Indeed, the mercury concentrations of mako sharks reported here ranged from 0.76 to 4.93 ppm, which approaches concentrations known to cause adverse health effects in fish such as genotoxicity and reproductive impairment (Wiener et al., 2003; Porto et al., 2005; Scheulhammer et al., 2007; Crump and Trudeau, 2009). Such high mercury concentrations found in shortfin mako sharks in this study relative to other regions (Burger and Gochfeld, 2011; Kaneko and Ralston, 2007; Suk et al., 2009) are likely attributable to heavy predation on large bluefish (Wood et al., 2009) and high metabolic rates contributing to enhanced prey consumption (Carlson et al., 2004). Mako's greater percent of fish in their diets and larger prey sizes are likely influencing their overall mercury burdens more than predator body size alone. Other possible explanations of why makos exhibit higher mercury levels include differences in growth rates and efficiencies as well as the energetic densities of primary prey (Trudel and Rasmussen, 2006).

#### 4.2. Other factors influencing mercury accumulation of predatory fishes

In addition to dietary pathways, differences in age and growth rates contribute to variations in mercury bioaccumulation among species (Adams and Onorato, 2005; Verdouw et al., 2011).

Differences in life history characteristics likely influenced the considerable range of mercury concentrations found among sharks and teleosts examined in this study (Adams and Onorato, 2005; Piraino and Taylor, 2009; Verdouw et al., 2011). For example, Piraino and Taylor (2009) noted that long-lived tautog (*Tautoga onitis*) collected from Narragansett Bay, RI had greater mercury concentrations than striped bass (*Morone saxatilis*) of similar size. Growth efficiency is generally negatively correlated with mercury assimilation efficiency in fish (Dutton, 1997). Fish with fast growth rates may exhibit mercury dilution, wherein body mass increases so rapidly that mercury concentrations remain low (Doyon et al., 1998; Trudel and Rasmussen, 2006; Piraino and Taylor, 2009; Ward et al., 2010). However, there are exceptions (Trudel and Rasmussen, 2006) and high consumption rates generally associated with fast growth rates, as in dolphinfish (Olson and Galván-Magaña, 2002), may outpace growth dilution and result in elevated size-specific accumulation rates. Mercury content of prey and temperature will also influence how growth affects mercury accumulation of predators (Dijkstra et al., 2013).

Age is an important factor not directly addressed in the present study. The shortfin mako and thresher sharks evaluated here were similar in body size, but likely ranged widely in age both within and between species (Natanson, 2002; Natanson et al., 2006). Similar to other large shark species, shortfin mako and common thresher sharks are slow-growing and live considerably longer than the teleost fishes evaluated in this study (Natanson, 2002; Natanson et al., 2006). Conversely, dolphinfish are fast growing (Schwenke and Buckel, 2008) and have a relatively short life span of generally less than 2 years (Oxenford, 1999; Adams, 2009), maintaining relatively low population-level mercury concentrations despite high size-based accumulation rates. Albacore tuna in addition to their more piscivorous feeding habits, are longer lived and slower growing than yellowfin tuna (Lessa and Duarte-Neto, 2004; ICCAT, 2010; Williams et al., 2012). Similarity of  $\delta^{13}\text{C}$  values measured in sampled albacore and yellowfin tunas suggest similar regional feeding habits. However, albacore is more temperately distributed than the more tropical yellowfin tuna and dolphinfish, which have more southern migration routes (ICCAT, 2010). Further study is needed to identify whether enhanced bioavailability of mercury in northern Atlantic food-webs (Lamborg et al., 2014) is contributing to increased exposure of more temperate species, suggested by differences in mercury concentration between albacore and yellowfin tunas.

Tunas, sharks and dolphinfish are highly migratory predators feeding continuously as they travel along the east coast of the United States or between offshore to inshore habitats (Oxenford, 1999; Farrell, 2009; MacNeil et al., 2005; ICCAT, 2010). The amount of bioavailable mercury varies widely across geographic regions, contributing to intraspecific differences in mercury concentrations collected from different localities (Chen et al., 2008, 2009). Because mercury accumulation is an additive process attributable to an organism's diet over its entire life span, mercury burdens of the species evaluated here reflect foraging habits on greater spatial and temporal scales than are accrued on their summer feeding grounds in the southern New England region. Future work should incorporate mercury deposition and methylation rate estimates for regional comparisons.

Stable isotopes provide additional insight into trophic and habitat influences on mercury accumulation, but should be viewed with caution. All of the predators evaluated in this study are highly migratory therefore even though  $\delta^{13}\text{C}$  values were relatively narrow across all species they may still represent different and complex combinations of environmental baselines (Chouvelon et al., 2012). Tunas and dolphinfish are known to be primarily associated with Gulf Stream waters along the US Atlantic coast; however,

habitat use and behavior at the northern (and potentially expanding) edge of their range is not known. Mako and thresher sharks move between Gulf Stream and shallower, inshore waters to forage on the continental shelf (Kohler et al., 2002), and the high frequency of bluefish in mako shark diets is consistent with inshore feeding habits. In addition, tagging studies have found that bigeye thresher sharks (*Alopias superciliosus*) make diel vertical migrations into waters below the thermocline, and also occupy a combination of pelagic and neritic coastal waters (Weng and Block, 2004).  $\delta^{15}\text{N}$  values may also reflect different sources of primary production from different habitats and seasons. Compound-specific isotope techniques would be useful to better understand habitat use across predators and differences in the trophic-transfer of mercury (Popp et al., 2007).

#### 4.3. Human health and management implications

The vast majority of recreationally caught marine fish in coastal regions are harvested for human consumption (Burger, 2009; Steinback et al., 2009), though relatively few anglers and consumers are aware of the associated health risks (Steinback et al., 2009). Seventy percent of all predatory fishes sampled in this study exhibited mercury concentrations greater than the US EPA recommended threshold of 0.3 ppm (US EPA, 2010). Shortfin mako and the largest thresher sharks exhibited mercury concentrations associated with detrimental effects to the health of both humans and fish (Crump and Trudeau, 2009). Although mako and thresher sharks are often discarded after being measured at tournament weigh stations, some anglers do value and consume shark "steaks", and shark meat is served at local restaurants and was previously donated to food banks (Teffer, personal communication). Given the extremely high mercury concentrations measured in sharks in this study, anglers should be made aware of the health risks of consuming these species even in small amounts.

Dolphinfish landings in the southern New England region have increased exponentially over the past decade (NOAA, 2014). This species of sport fish may be a good choice for many anglers who regularly consume their catch (Adams, 2009). The majority (70%) of dolphinfish had mercury concentrations below the US EPA recommended 0.3 ppm limit, likely owing to age and growth characteristics (Oxenford, 1999; Oxenford and Hunte, 1999). Tunas and dolphinfish reached or exceeded the US EPA threshold of 0.3 ppm at approximately 70 cm in body length. The considerable variation in mercury concentrations in dolphinfish and tunas above 70 cm introduces challenges for assigning consumption guidelines for larger fish. However, it would be conservative for pregnant women and young children to avoid consumption of sharks completely and limit the consumption of dolphinfish and tunas greater than 70 cm. It should be noted that additional factors, such as the counteractive effects of selenium on mercury toxicity, were not evaluated by this study but may be important variables relating to human mercury accumulation from fish consumption (Ralston, 2008; Raymond and Ralston, 2009).

## 5. Conclusions

There is considerable species- and size-specific variation in mercury content among cartilaginous and teleost fishes (Burger, 2009; Verdouw et al., 2011; Staudinger, 2011; Taylor et al., 2014). Therefore, improved understanding of which species exhibit the highest mercury burdens, descriptions of how mercury changes with fish growth as well as the dietary pathways that produce high contaminant levels are crucial to minimizing human health risks associated with fish consumption. The northwest Atlantic, particularly southern New England, is a region of intense seasonal fishing

pressure with relatively few studies describing the feeding ecology or contaminant levels of its top predators.

Fish is a lean source of Omega-3 fatty acids, beneficial for heart health and an overall balanced diet (US FDA, 2009); the associated health benefits in addition to the risks should be well understood and widely conveyed. Given the trends described by the present study, implementation of slot limits (e.g. maximum of 70 cm for tunas and dolphinfish) on upper trophic level fishes as opposed to just minimum size limits may mitigate potential health risks associated with mercury bioaccumulation (Burger, 2009; Staudinger, 2011). Informed consumption of fishery resources requires proper resource management, monitoring, and public outreach and education. These actions are reasonable, attainable, and necessary to understanding and mitigating risks associated with mercury accumulation from regional fish consumption.

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