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Mercury Bioaccumulation In Three Popular Subsistence And Recreational Estuarine Fishes From Southeastern U.S.A.

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Mercury bioaccumulation in three popular subsistence and recreational estuarine fishes from southeastern U.S.A.

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ABSTRACT

A rising concern in recent years has occurred over the presence of methylmercury in seafood, particularly fishes, and its impact on human health. However, fish also provide many health benefits, including improved cardiovascular health and neurodevelopment. Because fishes are the main source of methylmercury exposure to humans, and are such an integral part of the human diet, understanding the risks versus the benefits of fish consumption is imperative in allowing the public to make healthy, educated choices. One way that state and federal governments attempt to do this is through issuing fish consumption advisories. Unfortunately, these advisories do not always reflect mercury concentrations at the local level, and do not always focus on fish species that are commonly caught and consumed by local fishers. The objectives of this study were to examine the mercury concentrations of three commonly caught and consumed estuarine fishes (Southern Kingfish, Croaker, and Weakfish) in South Carolina in order to provide localized information for fish consumption advisories. The mean mercury levels for the three species were consistent with those reported in similar studies, as well as the trend of increasing levels of mercury with an increase in age, size, and weight. The mean mercury levels of all three species were low and all fell below the posted state and national levels of concern for mercury consumption in fishes. These findings support the idea that the health benefits of consuming certain species of commonly caught inshore species outweigh the potential concern from mercury

contamination. Hopefully, increased research into similar, smaller inshore fish species such as the ones in this study can provide policy-makers with more localized data to educate affected human populations.

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CHAPTER 1

INTRODUCTION

Mercury (Hg) is a naturally occurring metal in the environment, but can enter aquatic systems through anthropogenic activities (Mason et al. 1999, Lindberg et al. 2007). Over the last century, Hg has increased in its levels due to corresponding increases in industrial growth and pollution (Fitzgerald et al. 1998, Schuster et al. 2002, Lindberg et al. 2007, Driscoll et al. 2013). Mercury is an important environmental contaminant because of its global distribution and the negative health impacts it can have on humans and other biota (Friedmann et al. 1996, Basu et al. 2005, del Carmen Alvarez et al. 2006, Myers et al. 2009). Mercury is present in inorganic and organic forms, and the organic form, methylmercury (meHg), is particularly toxic, persists in animal tissue, and can bioaccumulate in aquatic foodwebs (Baeyens et al. 2003, Staudinger 2011, Thera and Rumbold 2014). In coastal ecosystems, Hg methylation is largely controlled by bacterial activity and the bioavailability of inorganic Hg, which is dependent on sediment and porewater concentrations of organic carbon and sulfide (Gilmour et al. 1992, Branfireun et al. 1999, Harmon et al. 2007). Mercury accumulates in tissues of fishes mainly as MeHg, which often comprises more than 90% of the total Hg (THg) in fish muscle of carnivorous and omnivorous species (Bloom 1992, Bank et al. 2007). Human exposure to Hg is mainly through consuming mercury-contaminated fishes (Trudel and Rasmussen 1997, Clarkson and Strain 2003). MeHg functions as a neurotoxic agent that can affect the development of the nervous system and poses a risk to the developing fetus (Marsh et al. 1987, Stern 1993, Grandjean et al. 1997). Reduced seafood consumption due to advisories addressing the concern of meMg exposure in the US may cause more harm than good, as the risks of low-level mercury exposure from seafood may not outweigh its nutritional benefits. Fishes are excellent sources of nutrients including protein, low-saturated fat, and many micronutrients, which are important for cardiovascular health. They are also a rich source of polyunsaturated fatty acids, which are also important for cardiovascular health and essential for the development of the brain and retina (Mozaffarian et al. 2003, Domingo et al. 2006, Domingo 2007, Nesheim and Yaktine 2007). Additionally, oceanic fish are relatively rich in selenium, necessary for seleno-enzyme functions, and selenium may offer some protection against mercury toxicity (Burger and Gochfeld 2011).

Advisories issued by federal authorities have evolved over the last several years. For species with the highest Hg concentrations (Hg>1.0 ppm; e.g., shark and swordfish), the US FDA originally advised women who were pregnant, nursing, or of childbearing age and children to limit consumption to once a month, and everyone else to one 7 oz. serving a week. For fish found with concentrations averaging 0.5 ppm, consumers were advised to limit consumption to two servings per week (US FDA 1995). In 2004, the US Environmental Protection Agency (US EPA) and the US FDA released their first joint federal fish consumption advisory for Hg in fish and shellfish, which was updated in 2014. Currently, the US EPA has a screening level of 0.3 ppm wet weight, suggesting seafood found below this concentration is safe for human consumption. The US FDA revised their advice, suggesting to avoid eating fish with Hg concentrations above the action level of 1.0 ppm (United States Environmental Protection Agency 2001, 2006, 2007, United States Food and Drug Administration and United States Environmental Protection Agency 2009)

Balancing the health benefits against the potential risks of mercury through seafood consumption is the main dilemma faced by state and federal agencies for constructing fish consumption advisories, and why local, site-specific data on mercury concentrations is important for providing information to the public. Recent research on subsistence fishing in coastal South Carolina demonstrated the culture and perceived nutritional benefits of consuming community-caught fish (Ellis et al. 2014), further documenting the importance of quantifying region-specific mercury-levels for the targeted species. The objective of this study was to investigate and describe mercury concentration patterns in the muscle tissue of three commonly consumed estuarine fishes in the southeastern U.S.A.

CHAPTER 2

METHODS

2.1 Study area and species descriptions

Estuarine systems connect terrestrial, freshwater, and open ocean ecosystems, therefore the availability of Hg within estuaries is impacted by these other systems. Wetlands are major contributors within estuaries to the transformation of inorganic Hg in meHg, by sulfur- and iron-reducing bacteria and methanogens (Wood et al. 1968, Kerin et al. 2006, Kim et al. 2008). The underlying mechanisms influencing Hg methylation rates among ecosystems remain poorly understood, but several studies have shown that dissolved organic carbon, water pH, and the abundance of sulfur-reducing bacteria all contribute to the methylation process (Gilmour and Henry 1991, Miskimmin 1991, Gilmour et al. 1992, French et al. 1999). South Carolina estuaries are characterized by turbid waters contained in a vast matrix of tidal creeks running through extensive wetlands and *Spartina alterniflora*-dominated salt marshes. This results in large amounts vascular plant material throughout the system decomposing aerobically and anaerobically. The anaerobic processes are controlled by bacteria and contribute to the biogeochemical cycling of an array of nutrients and pollutants within the estuaries (Dame et al. 2000).

Atlantic croaker *Micropogonias undulatus* (Sciaenidae) occurs in abundance in estuarine waters and is common along the coast from Cape Cod to Florida in the Atlantic and the entire Gulf coast to Campeche, Mexico (Kobylinski and Sheridan 1979, Lankford et al. 1999, Shervette and Gelwick 2008). It is a heavily targeted species in commercial and recreational fishing and likely plays an important role in estuarine trophic dynamics (Nemerson and Able 2003, Simonsen and Cowan 2013). Croaker exhibits a number of dietary shifts during its lifetime, and has been recorded as prey at the community level for a number of larger aquatic species (Gannon and Waples 2004, Nemerson and Able 2004, Nye et al. 2011, Drymon et al. 2012). Atlantic Croaker reaches a maximum age of 8 yrs (Barbieri et al. 1994). It is a gonochoristic species with a protracted spawning season from October to March, often peaking in November, with croakers along the South Carolina coast spawning entirely in the ocean as far out as 30 mi offshore (Bearden 1964, Morse 1980, Barbieri et al. 1994).

Southern Kingfish (also known as Whiting) *Menticirrhus americanus* (Sciaenidae) is a demersal species that occurs in shallow waters along the Atlantic coast of the U.S. and the Gulf of Mexico. It is a benthic feeding species in the Drum Family that primarily consumes invertebrates (Woodland et al. 2011, Willis et al. 2015). Southern Kingfish reaches a maximum age of 6 yrs in South Carolina, is gonochoristic, and typically spawns in nearshore coastal waters during spring-summer, utilizing tides and currents to carry larvae into estuarine habitats where they thrive and grow (Smith and Wenner 1985). Southern Kingfish is a common inhabitant of South Carolina estuaries. It is absent in the coldest months of the year, which may indicate that it moves south or slightly offshore to warmer, deeper waters (Hildebrand and Cable 1934).

Weakfish *Cynoscion regalis* (Sciaenidae) is commonly found along the Atlantic coast of the United States from southern Florida to Massachusetts Bay, occasionally straying into the Eastern Gulf of Mexico (Crawford et al. 1989, Mercer 1989). It is a relatively abundant species of the estuarine and nearshore waters of the Atlantic coast, and is considered a valuable recreational resource (Hildebrand and Cable 1934, Wilk 1979). Estuarine areas are important feeding and spawning grounds for adult weakfish, and provide nursery areas for the young (Massmann 1963, Merriner 1976, Nemerson and Able 2004, Montie et al. 2015, Turnure et al. 2015). The movement of adult weakfish indicates an aggregation in sounds, bays, and estuaries during the warmer months followed by a migration offshore as water temperatures decline in the fall (Hildebrand and Cable 1934). Weakfish reaches a maximum age of 12 yrs (Lowerre-Barbieri et al. 1995), and is a gonochoristic species that spawns from May-October (Welsh and Breder 1923).

2.2 Fish sample collection and lab processing

Fish samples for this study were obtained from three sources: 1) coast-wide routine fish population monitoring efforts by South Carolina Department of Natural Resources (SCDNR); 2) recreational fishing charters out of Edisto, SC, that fished in nearshore waters (less than 3 km from shore); and 3) donated from anglers at popular pier fishing sites near Edisto Beach. Fish samples were collected from January 2013 through May 2014. All samples were placed on ice after capture and then frozen until further processing.

For processing, samples were thawed then weighed to the nearest g and measured for standard length (SL), fork length (FL; when applicable), and total length (TL) to the nearest mm. Muscle tissue for mercury analysis was obtain by filleting the left anterior part of the body, excluding ribs, then collecting 2-3 g of tissue from the internal portion of the fillet. Special care was taken to avoid puncturing fish entrails and stainless steel cutlery was used to obtain the tissue samples and sterilized between tissue collection from each sample using 70-90% alcohol. Sex for each fish was determined by macroscopic examination of gonads. Then sagittal otoliths were removed from the fish for determination of fish age. Age estimation followed standardized procedures used in Smylie et al. (2016a). Briefly, one sagittal otolith from each fish sample was embedded in epoxy resin then thinly sectioned through the core transversely with a low-speed saw using a diamond-edge blade. Otolith sections were mounted on glass slides and examined using a dissecting microscope with transmitted light by two independent readers.

Mercury concentrations were determined using a DMA-80 Direct Mercury Analyzer within a 0.3 g (wet weight) subsample of muscle tissue. The DMA-80 determines total mercury (THg). Three blanks, one 0.03 g (dry weight) dogfish liver (DOLT-4) Standard Reference Material (SRM) sample, one 0.03 g (dry weight) oyster (1566b) SRM sample, and two more blanks were run prior to each set of muscle tissues samples and after every 10 muscle tissue samples. Approximately 10% of muscle fillet samples were run in duplicate. Calibration curves for the sample runs had r^2 values exceeding 0.99. All reported data were within the range of calibrated values. Recovery of the SRMs ranged from 82–114% with a mean of 99% ± 7.8 SD. Mean detection limit, based on three times the standard deviation of blanks, was 0.0098 ppm of Hg wet weight. Differences between duplicate measurements of tissue from the same fish sample ranged from 87–108% with a mean of 98% ± 10.2 SD. Because MeHg is the predominant form of mercury stored in fish muscle tissues (Rüdel et al. 2010), THg was measured as a proxy for MeHg and hereafter is referred to as Hg.

More fish samples were collected than could be analyzed for Hg. We utilized a randomized stratified sampling design that factored in fish sex and age in order to obtain a subsample of individuals for Hg analysis. All statistics were performed using ln-transformed Hg concentrations. For each species, linear regression analysis was used to independently examine the relationships between fish age-Hg concentration, fish length-Hg concentration, and fish weight-Hg concentration. For Kingfish, females and males were analyzed separately. We could not analyze females and males separately in the other two species, because too few Croaker males were collected and only 2-year-old males Weakfish were collected.

CHAPTER 3

RESULTS

A total of 371 fish samples were processed for this study. Of those, 28 Southern Kingfish, 32 Weakfish, and 26 Croaker were analyzed for Hg (Table 1). The mean size for all Kingfish collected in this study was 266 mm TL and the mean size for just those analyzed for Hg was 264 mm TL. Kingfish samples tested for Hg ranged in size from 193-366 mm TL and age from 0-4 years. The mean size of all Croaker collected in this study was 170 mm TL and the mean size for Croaker analyzed for Hg was 171 mm TL. Croaker samples tested for Hg ranged in size from 136-200 mm TL and age from 1-5 years. The mean size of all Weakfish collected in this study was 263 mm TL and the mean size for those analyzed for Hg was also 263 mm TL. Weakfish ranged in size from 148-357 mm TL and age from 0-3 years. Kingfish attained a larger maximum length and weight compared to the other two species and Croaker had the highest maximum age compared to the other two species (Table 1).

Overall, Hg concentrations were low in the three species, with only one Kingfish and one Weakfish sample exceeding 0.30 ppm wet weight (Figures 1-3). Croaker had the lowest mean Hg concentration (0.05 ppm; Table 1). Hg concentration increased significantly with size, weight, and age of Southern Kingfish (Figure 1, Table 2). In Croaker, Hg concentration increased significantly with size, weight, and age (Figure 2; Table 2) with age and Hg concentration exhibiting the highest R^2 value. For Weakfish, Hg significantly correlated with age, size, and weight (Figure 3; Table 2) with age also exhibiting the highest R^2 value. Relative to each other, Hg bioaccumulated at a faster rate in Weakfish, attaining a concentration of 0.34 ppm by age 3, compared to a maximum of 0.27 ppm in Kingfish and 0.07 in Croaker at age 3 (Figures 1-3).

Table 3.1. Summary of size, weight, age, and mercury levels for all analyzed species

Species	Total Number of Samples (# for Hg)	Size Range (Mean) TL mm	Weight Range (Mean) g	Age Range (Mean) Yrs	Hg Range (Mean) ppm
Kingfish	287 (28)	All: 193-366 (265) F: 211-366 (269) M: 193-305 (235)	All: 48-599 (204) F: 89-599 (212) M: 48-280 (137)	All: 0-4 (1.7) F: 0-3 (1.6) M: 0-4 (1.8)	All: 0.03-0.35 (0.14) F: 0.03-0.27 (0.14) M: 0.03-0.35 (0.15)
Croaker	49 (26)	All: 136-244 (171) F: 136-200 (167) M: 173-244 (209)	All: 20-164 (58) F: 20-128 (54) M: 60-164 (114)	All: 1-5 (1.5) F: 1-2 (1.2) M: 1-5 (2.8)	All: 0.01-0.23 (0.05) F: 0.02-0.10 (0.04) M: 0.01-0.23 (0.10)
Weakfish	34 (32)	All: 148-357 (263) F: 148-357 (263) M: 254-303 (278)	All: 28-373 (192) F: 28-373 (199) M: 153-249 (191)	All: 0-3 (1.4) F: 0-3 (1.2) M: 2 (2.0)	All: 0.04-0.33 (0.14) F: 0.04-033 (0.13) M: 0.17-0.23 (0.19)

Table 3.2. Summary of regression analyses explaining variation in mercury levels in all species

Species	**Sex**	**Size (R^2)**	**Weight (R^2)**	**Age (R^2)**
Kingfish	Male	0.481	0.406	0.890
	Female	0.644	0.634	0.784
Croaker		0.618	0.535	0.857
Weakfish		0.710	0.646	0.861

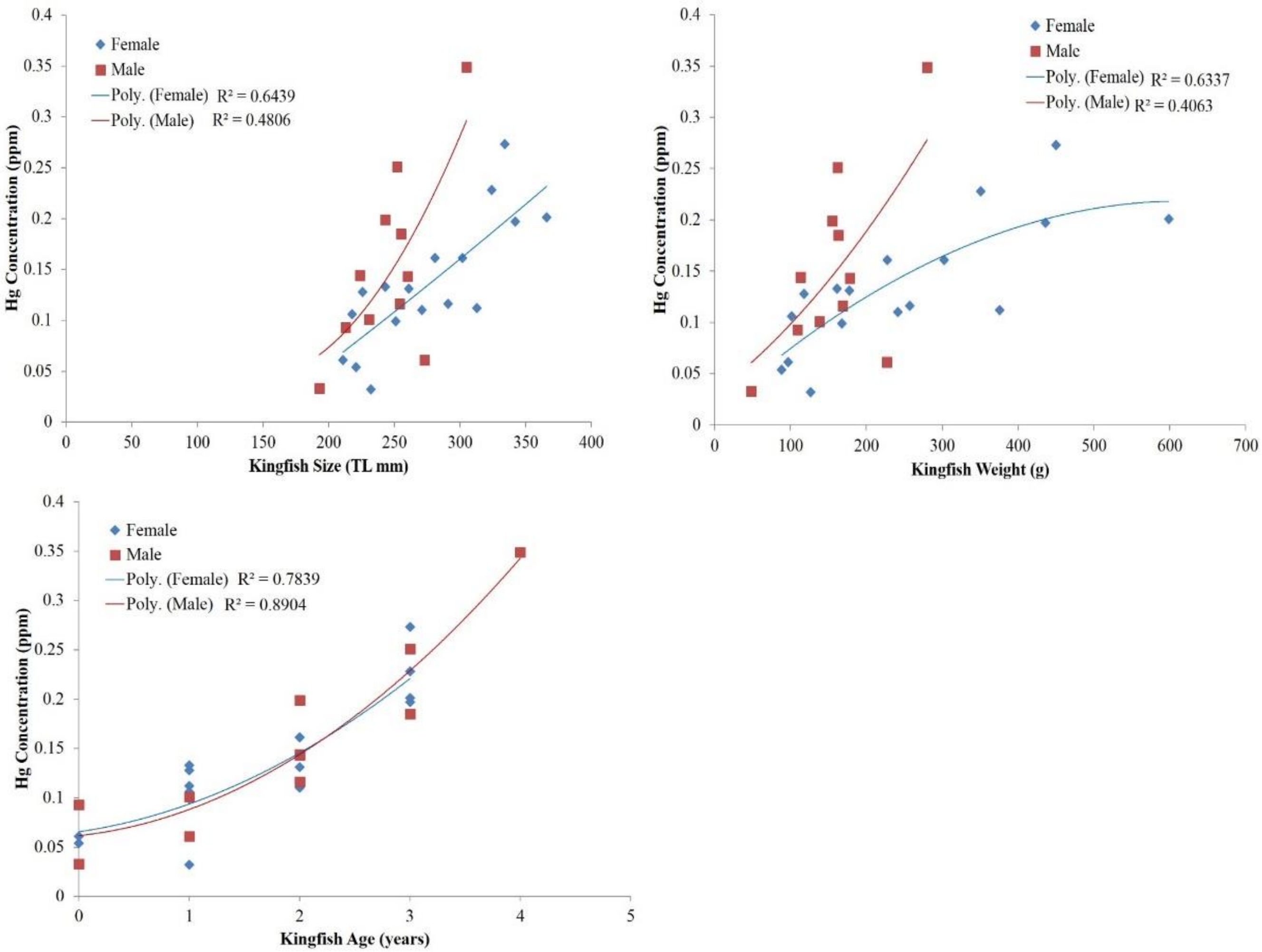

Figure 3.1. Results for Kingfish regression analyses with size vs Hg (top), weight vs Hg (middle), and age vs Hg (bottom).

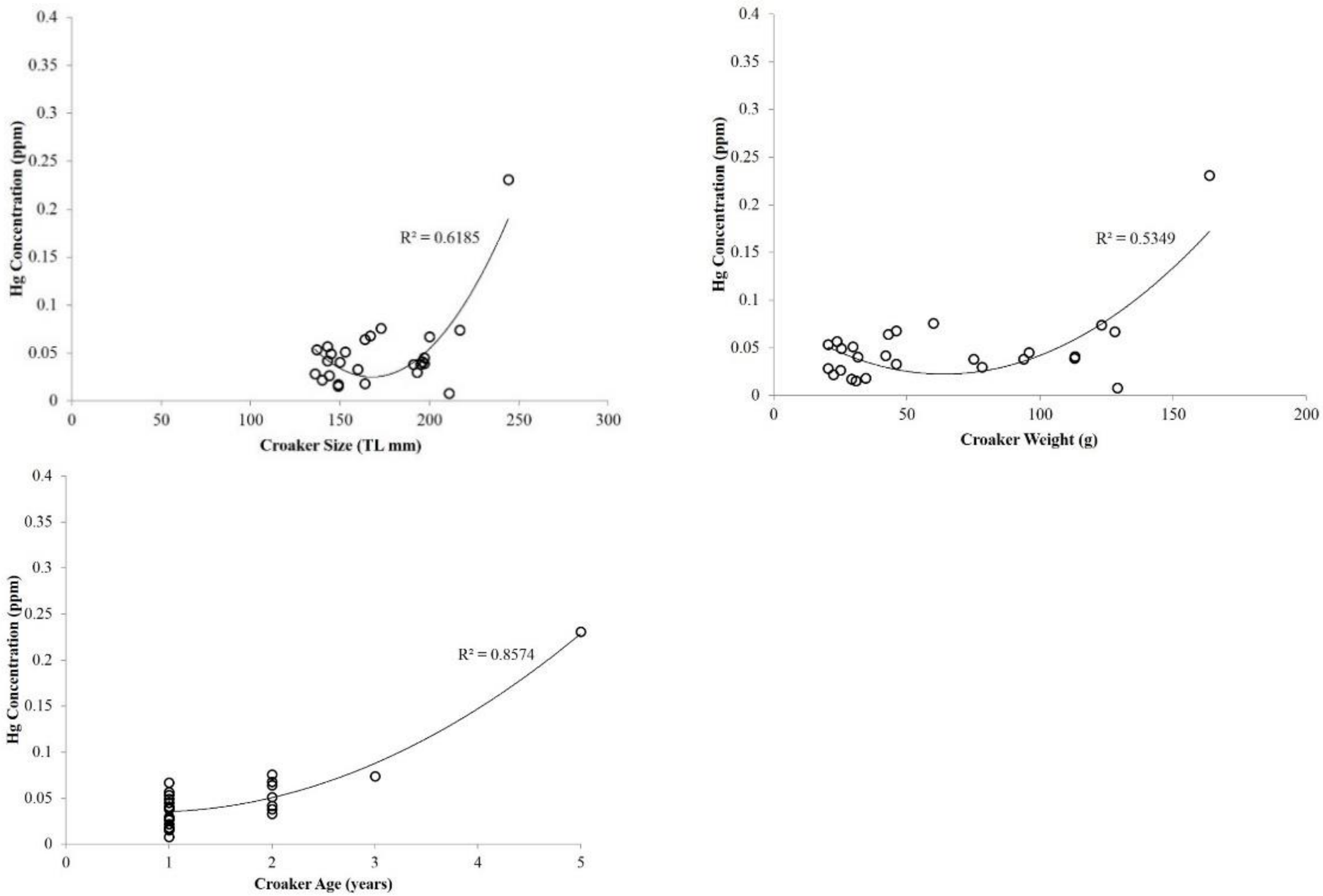

Figure 3.2. Results for Croaker regression analyses with size vs Hg (top), weight vs Hg (middle), and age vs Hg (bottom).

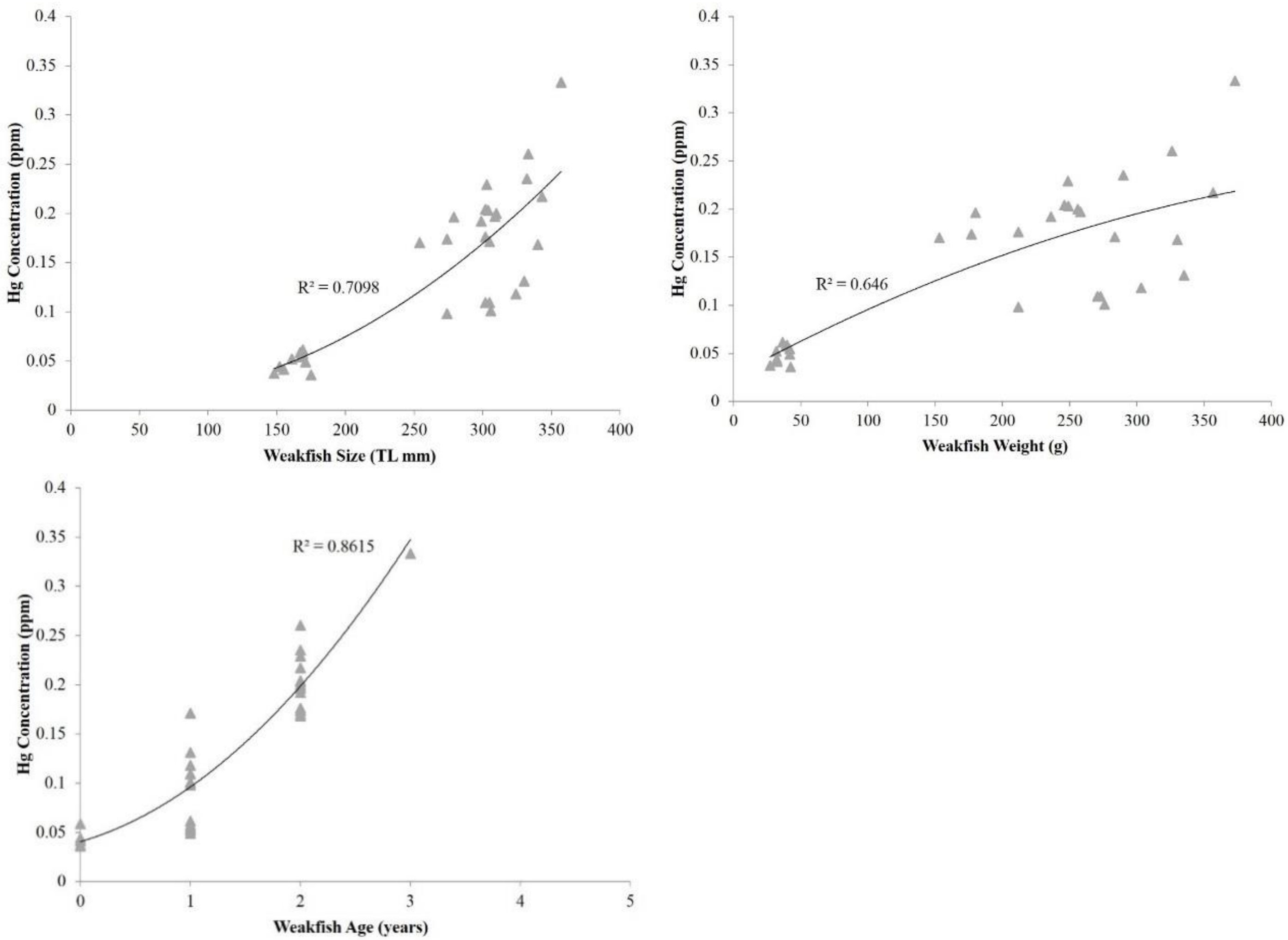

Figure 3.3. Results for Weakfish regression analyses with size vs Hg (top), weight vs Hg (middle), and age vs Hg (bottom).

CHAPTER 4

DISCUSSION

Continued concerns over the increasing levels of mercury in aquatic environments has led to an increase in research and monitoring efforts in recent years. The intent of this study was to contribute to these efforts by concentrating on less researched, but important areas of mercury exposure to provide useful information to consumers and for fish consumption advisories. Many recent advisories on marine fish consumption have focused on larger species from offshore ecosystems and have not provided much information on species that may be low in mercury and provide little risk (Burger and Gochfeld 2011). This is the first study to focus on the relationship of fish age, size, and Hg bioaccumulation in these three drum species, identified as some of the most commonly caught fishes by inshore anglers, including members of the local Gullah/Geechee community (Ellis 2013). Recent research on fishing and fish consumption in the Gullah/Geechee community of coastal SC found that many community members considered locally-caught fish an important part of their diet (Ellis 2013, Ellis et al. 2014).

4.1 Comparisons with other studies on *Cynoscion*, *Menticirrhus*, and *Micropogonias*

Relative to the amount of published studies on Hg bioaccumulation in fishes, few have directly quantified fish age and then examined how Hg concentrations change with age. Instead, studies have focused on fish size as a proxy for time. This complicates the comparison of Hg bioaccumulation among different species, because species vary in maximum sizes, maximum ages, and growth rates   . This also complicates within species comparisons among studies, because growth rates can vary among populations. Two other studies reported Hg concentrations in Southern Kingfish, one from New Jersey (Burger and Gochfeld 2011) and the other from Florida (Adams et al. 2003), but neither of those studies quantified fish age for this species (Table 3).

The New Jersey study analyzed 23 Southern Kingfish samples caught 2003-2008 from sites along the New Jersey shore (Burger and Gochfeld 2011). The size range of fish samples was within the SC samples sizes, but the mean fish size was larger (Table 3) which may explain why the mean Hg concentration was also higher (0.17 versus 0.14 ppm), but still relatively low overall. The Florida study collected 76 Southern Kingfish that were analyzed for Hg from six coastal areas around Florida from 1989-2001 (Adams et al. 2003). Mean size and mean Hg were both greater in the Florida study (Table 3). The other two studies also included samples from an additional Kingfish species, Northern Kingfish *Me. saxatalis* (Table 3) which had similar Hg levels between the two studies and similar to the Southern Kingfish concentrations (Adams et al. 2003, Burger and Gochfeld 2011).

Kingfish from South Carolina reach a maximum age of six years (Smith and Wenner 1985). A large study of Southern Kingfish biology reported on the south Atlantic Bight population. A total of 9359 samples were collected and the mean size and size range were 230 mm TL and 180-360 mm TL (Smith and Wenner 1985). Ninety percent of the fish sampled were 2 years old or younger. Our study collected a similar size range of Kingfish and the mean age of our samples was 1.7 years. Mean Hg was low in our samples and if they are reflective of the overall population, and based on the trends in age from both studies, then consumption of this species provides an overall low risk to Hg exposure.

Croaker has been analyzed for Hg in a few studies beyond the current one (Table 3). Samples from New Jersey (Burger and Gochfeld 2011) and Florida (Adams et al. 2003, Tremain and Schaefer 2015) all resulted in low levels of Hg for this species (Table 3). A similar trend occurred for Weakfish sampled in New Jersey (Burger and Gochfeld 2011), Florida (Adams et al. 2003), and an additional South Carolina study (Glover et al. 2010). None of these other studies reported on ages in the sampled populations so we cannot compare bioaccumulation rates for any of the species, but the overall trends based on lengths and Hg concentrations indicate that Hg is relatively low for these commonly targeted inshore species.

A closely related species to Weakfish that also occurs in coast SC waters is Speckled Seatrout *Cynoscion nebulosus*. Three studies from FL and SC (Table 3) have provided an in-depth examination of Hg concentrations in Speckled Seatrout (Adams et al. 2003, Adams et al. 2010, Glover et al. 2010). The SC study analyzed a total of 91 fish and reported a mean fish size and a mean Hg concentration of 381 mm TL and 0.11 ppm, respectively, and a maximum Hg concentration of 0.54 ppm (Glover et al. 2010). That same SC study reported similar results for Weakfish (Table 3), which provides additional evidence that the individual fish most likely to be caught by anglers from coastal sciaenid species in the genera *Cynoscion*, *Menticirrhus,* and *Micropogonias* have relatively low Hg levels. By contrast, a study from FL reported a mean Hg concentration of 0.41 ppm for Speckled Seatrout caught during 1989 – 2001 from nine coastal areas distributed throughout the FL coastline (Adams et al. 2003). However, the mean and maximum (680 mm SL) sizes of their samples were much greater than the SC samples (Table 3) which may partially explain the elevated Hg concentrations. In addition, six of the nine FL coastal areas sampled were along the west coast of FL which is important because several studies have reported elevated Hg levels for fish populations from the Gulf of Mexico when compared within the same species to populations from the east coast of the U.S. (Adams and Onorato 2005, Adams and McMichael 2007).

A more recent study from FL examined Hg concentrations in Speckled Seatrout collected from the Indian River Lagoon system, located on the Atlantic-side (Adams and Paperno 2012). That study did not report the sizes for their Speckled Seatrout samples, but did indicate that their samples ranged in age from 0-2 yr, which was similar to the age range of Weakfish samples we analyzed for Hg (Table 3). Adams and Paperno (2012) reported mean Hg concentrations from specific sampling locations that ranged from 0.18-0.33, and those means were closer to what our study found for Weakfish. Similar to our summation of generally low Hg levels for Kingfish, Croaker, and Weakfish from SC, Adams and Paperno (2012) concluded that overall Hg concentrations in Speckled Seatrout were low for the areas they sampled.

4.2 Comparisons with species from different aquatic ecosystems

Several studies have documented aquatic ecosystem/habitat-level trends in fish tissue Hg concentrations, such as differences between and among freshwater, estuarine, and offshore fishes (Gilmour and Riedel 2000, Adams and Onorato 2005, Glover et al.

2010, Smylie et al. 2016b), and differences between marine fishes feeding in benthic and pelagic habitats (Sinkus 2016). In general, fishes in estuaries appear to have lower Hg concentrations when compared to freshwater systems (Gilmour and Riedel 2000, Glover et al. 2010, Smylie et al. 2016b) and offshore systems (Adams and Onorato 2005, Glover et al. 2010). A few studies that have utilized similar methods to the current study enable direct comparisons of Hg bioaccumulation (change in mean Hg concentration with age) in our study's three species, two popular freshwater foodfish species, and two popular offshore recreationally- and commercially-targeted marine species (Figure 4).

Freshwater fish species commonly targeted by local SC anglers exhibit a wide range of patterns in Hg bioaccumulation (Glover et al. 2010). Bluegill *Lepomis macrochirus* is a freshwater species in the Centrarchidae family that feed on a combination of benthic invertebrates and zooplankton (Osenberg et al. 1988). Bluegill that were collected from the Broad River in SC (which ultimately empties into Charleston Harbor), exhibited a similar pattern of bioaccumulation and mean concentrations-at-age compared to Kingfish and Weakfish from the current study (Figure 4). However, compared to Croaker, Bluegill had higher mean concentrations-at-age, but had a similar rate of increase over time (V. Shervette, unpublished data). Flathead Catfish *Pylodictis olivaris*, a popular foodfish species caught by local anglers in SC, feeds mainly on other fishes (Pine et al. 2005) and lives up to 16 years as documented in a Georgia study (Grabowski et al. 2004). Mean Hg concentrations-at-age for Flathead Catfish caught from the Edisto River system were much higher than levels found in the estuarine species (V. Shervette, unpublished data).

A recent study on Hg bioaccumulation in offshore reef fish species of the southeastern U.S. reported on the relationship between Hg concentrations and fish age (Sinkus 2016). Gag Grouper *Mycteroperca microlepis* is a long-lived, slow-growing benthic species in the Serranidae family and feeds mainly on other benthic fishes and invertebrates (Harris and Collins 2000, Tremain and Adams 2012). Greater Amberjack *Seriola dumerili* is a moderately long-lived, faster-growing species from the Carangidae family that in the Atlantic reaches a maximum age of 15 years and a maximum size of 1355 mm FL (Manooch and Potts 1997). Sinkus (2016) reported mean values for Hg and age for all samples collected within a species and for legal-sized individuals within a species. Compared to Kingfish, Weakfish, and Croaker, the two offshore species, Gag and Amberjack, had higher mean ages for legal-size fish (Gag: 4.6 yr; Amberjack: 6.5 yr) and corresponding higher mean Hg concentrations (Gag: 0.28 ppm; Amberjack: 0.52 ppm). Croaker and Kingfish do not have recreational size limits in SC waters, but Weakfish has a minimum size limit of 305 mm TL (12 in TL; www.scdnr.gov/regs). Mean age and Hg concentration for legal-size Weakfish collected in the current study were 1.8 yr and 0.19 ppm, respectively, which are still lower than Gag and Amberjack samples. However, the actual rates of Hg bioaccumulation for Gag and Amberjack and the mean Hg concentrations-at-age for overlapping ages among the species do not appear to differ compared to the three estuarine species from the current study (Figure 4).

4.3 Mercury and fish health

Aquatic contaminants pose risks to the fish themselves and to things that consume them. A few studies have examined the physiological effects of acute and chronic Hg-exposure for a very small number of fish species (Wobeser 1975, McKim et al. 1976, Friedmann et al. 1996, Depew et al. 2012). For example, one study examined the effect of chronic dietary mercury exposure on Atlantic Salmon *Salmo salar* and found that Hg can negatively impact coordination, appetite, and swimming activity (Bernstssen et al. 2003). Another study examined the relationship between Hg exposure and a series of biochemical markers in Walleye *Sander vitreus* and Perch *Perca flavescens* and suggested that Hg may have adverse effects on physiology and cellular metabolism (Larose et al. 2008). Other studies have attempted to establish Hg threshold levels for biological effects by combining the findings of primary literature investigations (Beckvar et al. 2005, Depew et al. 2012). However, the application of such Hg threshold levels to studies like the current one is questionable since the threshold effect values are based on research from only a few fish species, mostly from freshwater system, and are not provided as muscle tissue Hg concentration values, but rather as whole-body fish Hg concentrations (Beckvar et al. 2005) or in terms of dietary intake (Depew et al. 2012). Despite the limitations, some studies do apply a whole-body or muscle tissue Hg concentration threshold value to estimate ecological risk (Sandheinrich et al. 2011, Wiener et al. 2012).

Atlantic Croaker is one of the few marine fishes that has been the focal species of a study relating Hg exposure and negative health impacts (del Carmen Alvarez et al. 2006). The study evaluated the behavioral performance of larval Atlantic Croaker at different stages that were the direct offspring of female adults fed Hg-contaminated food. The study found that maternally transferred Hg caused concentration-dependent effects on larvae survival skills (del Carmen Alvarez et al. 2006). However, that study did not report whole-body or muscle tissue Hg-concentrations for the adult Croaker.

A recent study on Hg bioaccumulation in estuarine populations of Longnose Gar *Lepisosteus osseus* examined the relationship between Hg concentrations in muscle tissue to reproductive output and fish growth (Smylie et al. 2016b). Fish health appeared to be unaffected by Hg at concentrations reported in that study (less than 1.3 ppm wet weight). The highest Hg concentration found in the current study was 0.35 ppm from one Kingfish. Obvious negative impacts to individual fish health from chronic Hg exposure are unlikely for Kingfish, Croaker, and Weakfish from SC coastal waters as indicated by the overall low levels of Hg found in the muscle tissue of these species.

4.4 Risk to humans

Fishes collected from estuaries and nearshore, coastal waters in this research and an additional SC study (Glover et al. 2010) contained some of the lowest reported Hg levels in fish muscle tissue compared to adjacent aquatic ecosystems and compared to studies on the same or closely-related species from other coastal regions of the US. The health risks for humans related to consuming fish depends on the amount of Hg in the edible portion of a fish and how much and how often a person consumes those species of fish. In order to protect the public from chronic over-exposure to Hg, the USEPA established a consumption advisory Hg screening level of 0.3 ppm (United States Environmental Protection Agency 2007, United States Food and Drug Administration and United States Environmental Protection Agency 2009). An advisory is issued for a fish species or group when the majority of samples from that species or group exceeds the 0.3 ppm screening level. Kingfish, Croaker, and Weakfish collected from SC coastal waters in this study rarely exceeded a Hg concentration of 0.3 ppm and the mean Hg concentrations documented for each species were well below the screening level.

Fishes are excellent sources of nutrients including protein, low-saturated fat, and many micronutrients, which are important for cardiovascular health. They are also a rich source of polyunsaturated fatty acids, which are also important for cardiovascular health and essential for the development of the brain and retina (Mozaffarian et al. 2003, Domingo et al. 2006, Domingo 2007, Nesheim and Yaktine 2007). Coastal communities in SC that rely on estuarine fishes, such as Kingfish, Croaker, and Weakfish, as a major source of protein do not appear to be at high risk for over-exposure to Hg since these species are low in Hg. Efforts to monitor Hg levels in fish populations targeted by local communities should be continued and expanded into the future to ensure the overall safety of eating our local fishes.

Table 4.1. Comparison of Hg studies on Kingfish, Croaker, and Weakfish species.

Species	Location and N	Hg mean (range)	Size mean (range)	Age mean (range)	Source
Me. americanus	Coastal SC; N = 28	0.14 (0.03-0.35 ppm)	264 (193-366 mm TL)	1.7 (0-4 yrs)	Current Study
	New Jersey; N = 23	0.17 (max: 0.36 ppm)	280 (230-330 mm TL)	Not Reported	Burger and Gochfeld 2011
	Six coastal areas FL; N = 76	0.21[1] (0.02-0.78 ppm)	248[1] (121-348 mm SL)	Not Reported	Adams et al 2003
Me. saxatalis	New Jersey; N = 72	0.15 (max: 1.24 ppm)	280 (220-400 mm TL)	Not Reported	Burger and Gochfeld 2011
	Two coastal areas FL; N = 3	0.25[1] (0.15-0.48 ppm)	269[1] (221-300 mm SL)	Not Reported	Adams et al 2003
Mi. undulatus	Coastal SC; N = 26	0.05 (0.01-0.23)	170 (136-244 mm TL)	1.5 (1-5 yrs)	Current Study
	New Jersey; N = 72	0.12 (max: 0.31 ppm)	310 (220-380 mm TL)	Not Reported	Burger and Gochfeld 2011
	Eastern FL; N = 65	0.03 (0.01-0.07 ppm)	167 (128-286 mm TL)	Not Reported	Tremain and Schaefer 2015
	Four coastal areas FL; N = 47	0.06[1] (0.02-0.18 ppm)	219[1] (89-385 mm SL)	Not Reported	Adams et al 2003
C. regalis	Coastal SC; N = 32	0.14 (0.04-0.33 ppm)	263 (148-357 mm TL)	1.4 (0-3 yrs)	Current Study
	Coastal SC; N = 68	0.12 (max: 0.54 ppm)	382 mm TL	Not Reported	Glover et al. 2010
	New Jersey; N = 60	0.15 (max: 0.50 ppm)	440 (300-810 mm TL)	Not Reported	Burger and Gochfeld 2011
	Three coastal areas FL; N = 174	0.18[1,2] (0.02-0.78 ppm)	219[1,2] (116-415 mm SL)	Not Reported	Adams et al 2003
C. nebulosus	Coastal SC; N = 91	0.11 (max: 0.54 ppm)	381 mm TL	Not Reported	Glover et al. 2010
	Nine coastal areas FL; N = 786	0.41[1] (0.02-2.50 ppm)	363[1] (143-680 mm SL)	Not Reported	Adams et al 2003
	Eastern FL; N = 123	Means of sample areas range: 0.18-.033	Not Reported	(0-2 yrs)	Adams and Paperno 2012

[1] Calculated from mean Hg values provided for each sample location [2]This study reported on the *C. regalis/arenarius* complex

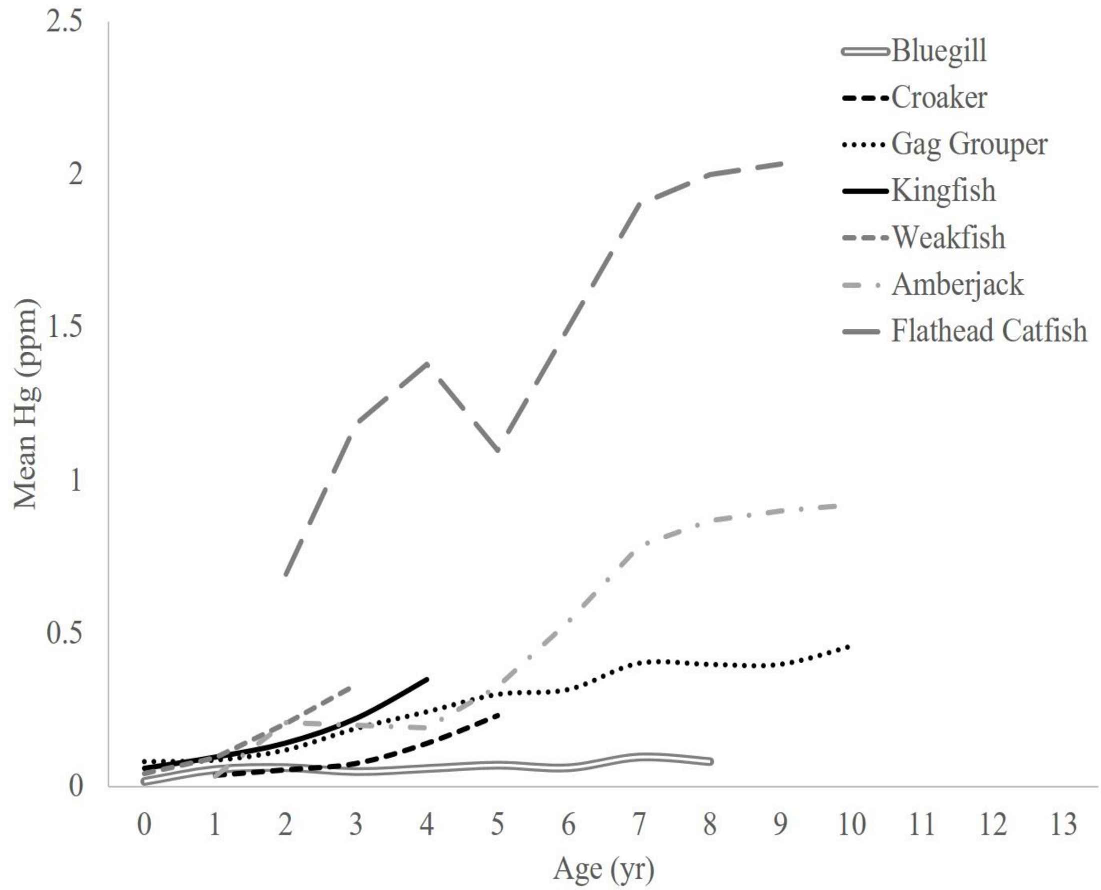

Figure 4.1. Comparison of the change in Hg concentrations with age among the three estuarine species in this study (Kingfish, Croaker, and Weakfish), two freshwater species from a complimentary study in SC (Bluegill and Flathead Catfish), and two offshore marine species (Gag Grouper and Amberjack). The lines represent the connections between the mean Hg concentration-at-age for each species. Hg concentrations for the freshwater species are from V. Shervette, unpublished data and for the offshore species are from Sinkus (2016).

LITERATURE CITED

Adams, D. H., and R. H. McMichael. 2007. Mercury in king mackerel, Scomberomorus cavalla, and Spanish mackerel, S. maculatus, from waters of the south-eastern USA: regional and historical trends. Marine and freshwater research **58**:187-193.

Adams, D. H., R. H. McMichael, and G. E. Henderson. 2003. Mercury Levels in Marine and Estuarine Fishes of Florida 1989–2001. revised.

Adams, D. H., and G. V. Onorato. 2005. Mercury concentrations in red drum, *Sciaenops ocellatus*, from estuarine and offshore waters of Florida. Marine Pollution Bulletin **50**:291-300.

Adams, D. H., and R. Paperno. 2012. Stable isotopes and mercury in a model estuarine fish: multibasin comparisons with water quality, community structure, and available prey base. Science of the Total Environment **414**:445-455.

Adams, D. H., C. Sonne, N. Basu, R. Dietz, D.-H. Nam, P. S. Leifsson, and A. L. Jensen. 2010. Mercury contamination in spotted seatrout, Cynoscion nebulosus: an assessment of liver, kidney, blood, and nervous system health. Science of the Total Environment **408**:5808-5816.

Baeyens, W., M. Leermakers, T. Papina, A. Saprykin, N. Brion, J. Noyen, M. De Gieter, M. Elskens, and L. Goeyens. 2003. Bioconcentration and biomagnification of mercury and methylmercury in North Sea and Scheldt estuary fish. Archives of Environmental Contamination and Toxicology **45**:498-508.

Bank, M. S., E. Chesney, J. P. Shine, A. Maage, and D. B. Senn. 2007. Mercury bioaccumulation and trophic transfer in sympatric snapper species from the Gulf of Mexico. Ecological Applications **17**:2100-2110.

Barbieri, L. R., M. E. Chittenden, and S. K. Lowerrebarbieri. 1994. Maturity, Spawning, and Ovarian Cycle of Atlantic Croaker, Micropogonias-Undulatus, in the Chesapeake Bay and Adjacent Coastal Waters. Fishery Bulletin **92**:671-685.

Basu, N., A. Scheuhammer, N. Grochowina, K. Klenavic, D. Evans, M. O'Brien, and H. M. Chan. 2005. Effects of mercury on neurochemical receptors in wild river otters (Lontra canadensis). Environmental Science & Technology **39**:3585-3591.

Bearden, C. M. 1964. Distribution and Abundance of Atlantic Croaker, Micropogon Undulatus, in South Carolina. Bears Bluff Laboratories.

Beckvar, N., T. M. Dillon, and L. B. Read. 2005. Approaches for linking whole-body fish tissue residues of mercury or DDT to biological effects thresholds. Environmental Toxicology and Chemistry **24**:2094-2105.

Bernstssen, M., A. Aatland, and R. Handyc. 2003. Chronic dietary mercury exposure causes oxidative stress, brain lesions, and altered behaviour in Atlantic salmon (*Salmo salar*) parr. Aquatic Toxicology **65**:55-72.

Bloom, N. S. 1992. On the chemical form of mercury in edible fish and marine invertebrate tissue. Canadian Journal of Fisheries and Aquatic Science **49**:1010-1017.

Branfireun, B. A., N. T. Roulet, C. A. Kelly, and J. W. M. Rudd. 1999. In situ sulphate stimulation of mercury methylation in a boreal peatland: Toward a link between acid rain and methylmercury contamination in remote environments. Global Biogeochemical Cycles **13**:743-750.

Burger, J., and M. Gochfeld. 2011. Mercury and selenium levels in 19 species of saltwater fish from New Jersey as a function of species, size, and season. Science of the Total Environment **409**:1418-1429.

Clarkson, T. W., and J. J. Strain. 2003. Nutritional factors may modify the toxic action of methyl mercury in fish-eating populations. Journal of Nutrition **133**:1539s-1543s.

Crawford, M. K., C. B. Grimes, and N. E. Buroker. 1989. Stock Identification of Weakfish, *Cynoscion regalis*, in the Middle Atlantic Region. Fishery Bulletin **87**:205-211.

Dame, R., M. Alber, D. Allen, M. Mallin, C. Montague, A. Lewitus, A. Chalmers, R. Gardner, C. Gilman, B. Kjerfve, J. Pinckney, and N. Smith. 2000. Estuaries of the south Atlantic coast of North America: Their geographical signatures. Estuaries **23**:793-819.

del Carmen Alvarez, M., C. A. Murphy, K. A. Rose, I. D. McCarthy, and L. A. Fuiman. 2006. Maternal body burdens of methylmercury impair survival skills of offspring in Atlantic croaker (Micropogonias undulatus). Aquatic Toxicology **80**:329-337.

Depew, D. C., N. Basu, N. M. Burgess, L. M. Campbell, E. W. Devlin, P. E. Drevnick, C. R. Hammerschmidt, C. A. Murphy, M. B. Sandheinrich, and J. G. Wiener. 2012. Toxicity of dietary methylmercury to fish: Derivation of ecologically meaningful threshold concentrations. Environmental Toxicology and Chemistry **31**:1536-1547.

Domingo, J. L. 2007. Omega-3 fatty acids and the benefits of fish consumption: Is all that glitters gold? Environment International:6.

Domingo, J. L., A. Bocio, G. Falcó, and J. M. Llobet. 2006. Benefits and risks of fish consumption Part I. A quantitative analysis of the intake of omega-3 fatty acids and chemical contaminants. Toxicology:8.

Driscoll, C. T., R. P. Mason, H. M. Chan, D. J. Jacob, and N. Pirrone. 2013. Mercury as a global pollutant: sources, pathways, and effects. Environmental Science & Technology **47**:4967-4983.

Drymon, J. M., S. P. Powers, and R. H. Carmichael. 2012. Trophic plasticity in the Atlantic sharpnose shark (Rhizoprionodon terraenovae) from the north central Gulf of Mexico. Environmental Biology of Fishes **95**:21-35.

Ellis, J. H. 2013. Fishing and Fish Consumption Patterns in the Gullah/Geechee Sea Island Population. Dissertation. University of South Carolina.

Ellis, J. H., D. B. Friedman, R. Puett, G. I. Scott, and D. E. Porter. 2014. A Qualitative Exploration of Fishing and Fish Consumption in the Gullah/Geechee Culture. Journal of Community Health **39**:1161-1170.

Fitzgerald, W. F., D. R. Engstrom, R. P. Mason, and E. A. Nater. 1998. The case for atmospheric mercury contamination in remote areas. Environmental Science & Technology **32**:1-7.

French, K. J., D. A. Scruton, M. R. Anderson, and D. C. Schneider. 1999. Influence of physical and chemical characteristics on mercury in aquatic sediments. Water Air and Soil Pollution **110**:347-362.

Friedmann, A. S., M. C. Watzin, T. Brinck-Johnsen, and J. C. Leiter. 1996. Low levels of dietary methylmercury inhibit growth and gonadal development in juvenile walleye (*Stizostedion vitreum*). Aquatic Toxicology **35**:265-278.

Gannon, D. P., and D. M. Waples. 2004. Diets of coastal bottlenose dolphins from the US mid-Atlantic coast differ by habitat. Marine Mammal Science **20**:527-545.

Gilmour, C., and G. Riedel. 2000. A survey of size-specific mercury concentrations in game fish from Maryland fresh and estuarine waters. Archives of Environmental Contamination and Toxicology **39**:53-59.

Gilmour, C. C., and E. A. Henry. 1991. Mercury Methylation in Aquatic Systems Affected by Acid Deposition. Environmental Pollution **71**:131-169.

Gilmour, C. C., E. A. Henry, and R. Mitchell. 1992. Sulfate Stimulation of Mercury Methylation in Fresh-Water Sediments. Environmental Science & Technology **26**:2281-2287.

Glover, J., M. Domino, K. Altman, J. Dillman, W. Castleberry, J. Eidson, and M. Mattocks. 2010. Mercury in South Carolina Fishes, USA. Ecotoxicology **19**:781-795.

Grabowski, T. B., J. J. Isely, and R. R. Weller. 2004. Age and growth of flathead catfish, *Pylodictus olivaris* Rafinesque, in the Altamaha River system, Georgia. Journal of Freshwater Ecology **19**:411-417.

Grandjean, P., P. Weihe, R. F. White, F. Debes, S. Araki, K. Yokoyama, K. Murata, N. Sorensen, R. Dahl, and P. J. Jorgensen. 1997. Cognitive deficit in 7-year-old children with prenatal exposure to methylmercury. Neurotoxicology and Teratology **19**:417-428.

Harmon, S. M., J. King, J. Gladden, and L. Newman. 2007. Using sulfate-amended sediment slurry batch reactors to evaluate mercury methylation. Archives of Environmental Contamination and Toxicology **52**:326-331.

Harris, P. J., and M. R. Collins. 2000. Age, growth and age at maturity of gag, *Mycteroperca microlepis*, from the southeastern United States during 1994-1995. Bulletin of Marine Science **66**:105-117.

Hildebrand, S. F., and L. E. Cable. 1934. Reproduction and development of whitings or kingfishes, drums, spot, croaker, and weakfishes or sea trouts, family Sciaenidae, of the Atlantic coast of the United States. US Government Printing Office.

Kerin, E. J., C. C. Gilmour, E. Roden, M. T. Suzuki, J. D. Coates, and R. P. Mason. 2006. Mercury methylation by dissimilatory iron-reducing bacteria. Applied and environmental microbiology **72**:7919-7921.

Kim, E., R. P. Mason, and C. M. Bergeron. 2008. A modeling study on methylmercury bioaccumulation and its controlling factors. Ecological Modelling **218**:267-289.

Kobylinski, G. J., and P. F. Sheridan. 1979. Distribution, Abundance, Feeding and Long-Term Fluctuations of Spot, Leiostomus-Xanthurus, and Croaker, Micropogonias-Undulatus, in Apalachicola Bay, Florida, 1972-1977. Contributions in Marine Science **22**:149-161.

Lankford, T. E., T. E. Targett, and P. M. Gaffney. 1999. Mitochondrial DNA analysis of population structure in the Atlantic croaker, Micropogonias undulatus (Perciformes : Sciaenidae). Fishery Bulletin **97**:884-890.

Larose, C., R. Canuel, M. Lucotte, and R. T. Di Giulio. 2008. Toxicological effects of methylmercury on walleye (*Sander vitreus*) and perch (*Perca flavescens*) from lakes of the boreal forest. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology **147**:139-149.

Lindberg, S., R. Bullock, R. Ebinghaus, D. Engstrom, X. Feng, W. Fitzgerald, N. Pirrone, E. Prestbo, and C. Seigneur. 2007. A synthesis of progress and uncertainties in attributing the sources of mercury in deposition. AMBIO: A Journal of the Human Environment **36**:19-33.

Lowerre-Barbieri, S. K., M. E. Chittenden, and L. R. Barbieri. 1995. Age and Growth of Weakfish, *Cynoscion regalis*, in the Chesapeake Bay-Region with a Discussion of Historical Changes in Maximum Size. Fishery Bulletin **93**:643-656.

Manooch, C. S. I., and J. C. Potts. 1997. Age, growth, and mortality of greater amberjack, *Seriola dumerili*, from the US Gulf of Mexico headboat fishery. Bulletin of Marine Science **61**:671-683.

Marsh, D. O., T. W. Clarkson, C. Cox, G. J. Myers, L. Amin-Zaki, and S. Al-Tikriti. 1987. Fetal methylmercury poisoning. Relationship between concentration in single strands of maternal hair and child effects. Archives of Neurology:6.

Mason, R. P., N. M. Lawson, A. L. Lawrence, J. J. Leaner, J. G. Lee, and G.-R. Sheu. 1999. Mercury in the Chesapeake Bay. Marine Chemistry **65**:77-96.

Massmann, W. H. 1963. Age and size composition of weakfish, Cynoscion regalis, from pound nets in Chesapeake Bay, Virginia 1954–1958. Chesapeake Science **4**:43-51.

McKim, J., G. Olson, G. W. Holcombe, and E. Hunt. 1976. Long-term effects of methylmercuric chloride on three generations of brook trout (*Salvelinus* *fontinalis*): toxicity, accumulation, distribution, and elimination. Journal of the Fisheries Board of Canada **33**:2726-2739.

Mercer, L. P. 1989. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (mid-Atlantic): weakfish. DTIC Document.

Merriner, J. V. 1976. Aspects of the reproductive biology of the weakfish, Cynoscion regalis (Sciaenidae). North Carolina. Fish. Bull **74**:18-26.

Miskimmin, B. M. 1991. Effect of Natural Levels of Dissolved Organic-Carbon (Doc) on Methyl Mercury Formation and Sediment Water Partitioning. Bulletin of Environmental Contamination and Toxicology **47**:743-750.

Montie, E. W., S. Vega, and M. Powell. 2015. Seasonal and Spatial Patterns of Fish Sound Production in the May River, South Carolina. Transactions of the American Fisheries Society **144**:705-716.

Morse, W. W. 1980. Maturity, Spawning, and Fecundity of Atlantic Croaker, Micropogonias-Undulatus,Occurring North of Cape-Hatteras, North-Carolina. Fishery Bulletin **78**:190-195.

Mozaffarian, D., R. N. Lemaitre, L. H. Kuller, G. L. Burke, R. P. Tracy, and D. S. Siscovick. 2003. Cardiac benefits of fish consumption may depend on the type of fish meal consumed: the Cardiovascular Health Study. Circulation **107**:1372.

Myers, G. J., S. W. Thurston, A. T. Pearson, P. W. Davidson, C. Cox, C. F. Shamlaye, E. Cernichiari, and T. W. Clarkson. 2009. Postnatal exposure to methyl mercury from fish consumption: A review and new data from the Seychelles Child Development Study. Neurotoxicology **30**:338-349.

Nemerson, D. M., and K. W. Able. 2003. Spatial and temporal patterns in the distribution and feeding habits of Morone saxatilis in marsh creeks of Delaware Bay, USA. Fisheries Management and Ecology **10**:337-348.

Nemerson, D. M., and K. W. Able. 2004. Spatial patterns in diet and distribution of juveniles of four fish species in Delaware Bay marsh creeks: factors influencing fish abundance. Marine Ecology Progress Series **276**:249-262.

Nesheim, M. C., and A. L. Yaktine. 2007. Seafood Choices: Balancing Benefits and Risks. Washington, D.C.

Nye, J. A., D. A. Loewensteiner, and T. J. Miller. 2011. Annual, Seasonal, and Regional Variability in Diet of Atlantic Croaker (Micropogonias undulatus) in Chesapeake Bay. Estuaries and Coasts **34**:691-700.

Osenberg, C. W., E. E. Werner, G. G. Mittelbach, and D. J. Hall. 1988. Growth patterns in bluegill (*Lepomis macrochirus*) and pumpkinseed *(L. gibbosus*) sunfish: environmental variation and the importance of ontogenetic niche shifts. Canadian Journal of Fisheries and Aquatic Sciences **45**:17-26.

Pine, W. E. I., T. J. Kwak, D. S. Waters, and J. A. Rice. 2005. Diet selectivity of introduced flathead catfish in coastal rivers. Transactions of the American Fisheries Society **134**:901-909.

Sandheinrich, M. B., S. P. Bhavsar, R. Bodaly, P. E. Drevnick, and E. A. Paul. 2011. Ecological risk of methylmercury to piscivorous fish of the Great Lakes region. Ecotoxicology **20**:1577-1587.

Schuster, P. F., D. P. Krabbenhoft, D. L. Naftz, L. D. Cecil, M. L. Olson, J. F. Dewild, D. D. Susong, J. R. Green, and M. L. Abbott. 2002. Atmospheric mercury deposition during the last 270 years: a glacial ice core record of natural and anthropogenic sources. Environmental Science & Technology **36**:2303-2310.

Shervette, V. R., and F. Gelwick. 2008. Seasonal and spatial variations in fish and macroinvertebrate communities of oyster and adjacent habitats in a Mississippi estuary. Estuaries and Coasts **31**:584-596.

Simonsen, K. A., and J. H. Cowan. 2013. Effects of an Inshore Artificial Reef on the Trophic Dynamics of Three Species of Estuarine Fish. Bulletin of Marine Science **89**:657-676.

Sinkus, W. N. 2016. Mercury bioaccumulation in offshore reef species from waters of the southeastern US. Thesis. College of Charleston.

Smith, J. W., and C. A. Wenner. 1985. Biology of the Southern Kingfish in the South Atlantic Bight. Transactions of the American Fisheries Society **114**:356-366.

Smylie, M., V. Shervette, and C. McDonough. 2016a. Age, Growth, and Reproduction in Two Coastal Populations of Longnose Gars. Transactions of the American Fisheries Society **145**:120-135.

Smylie, M. S., C. J. McDonough, L. A. Reed, and V. R. Shervette. 2016b. Mercury bioaccumulation in an estuarine predator: Biotic factors, abiotic factors, and assessments of fish health. Environmental Pollution **214**:169-176.

Staudinger, M. D. 2011. Species- and size-specific variability of mercury concentrations in four commercially important finfish and their prey from the northwest Atlantic. Marine Pollution Bulletin **62**:734-740.

Stern, A. H. 1993. Reevaluation of the Reference Dose for Methylmercury and Assessment of Current Exposure Levels. Risk Analysis **13**:355-364.

Thera, J. C., and D. G. Rumbold. 2014. Biomagnification of Mercury through a Subtropical Coastal Food Web Off Southwest Florida. Environmental Toxicology and Chemistry **33**:65-73.

Tremain, D. M., and D. H. Adams. 2012. Mercury in groupers and sea basses from the Gulf of Mexico: Relationships with size, age, and feeding ecology. Transactions of the American Fisheries Society **141**:1274-1286.

Tremain, D. M., and A. M. Schaefer. 2015. Mercury concentrations in the prey of apex piscivores from a large subtropical estuary. Marine Pollution Bulletin **95**:433-444.

Trudel, M., and J. B. Rasmussen. 1997. Modeling the elimination of mercury by fish. Environmental Science & Technology **31**:1716-1722.

Turnure, J. T., K. W. Able, and T. M. Grothues. 2015. Patterns of intra-estuarine movement of adult weakfish (Cynoscion regalis): evidence of site affinity at seasonal and diel scales. Fishery Bulletin **113**:167-179.

United States Environmental Protection Agency. 2001. Methylmercury.

United States Environmental Protection Agency. 2006. Mercury Study report to Congress.

United States Environmental Protection Agency. 2007. National Listing of Fish Advisories: Technical Fact Sheet.

United States Food and Drug Administration, and United States Environmental Protection Agency. 2009. Consumption Advice.

Welsh, W. W., and C. M. Breder. 1923. Contributions to life histories of Sciaenidae of the eastern United States coast. US Government Printing Office.

Wiener, J. G., M. B. Sandheinrich, S. P. Bhavsar, J. R. Bohr, D. C. Evers, B. A. Monson, and C. S. Schrank. 2012. Toxicological significance of mercury in yellow perch in the Laurentian Great Lakes region. Environ Pollut **161**:350-357.

Wilk, S. J. 1979. Biological and fisheries data on weakfish, Cynoscion regalis (Bloch and Schneider). NOAA Technical Serial Report **21**.

Willis, C. M., J. Richardson, T. Smart, J. Cowan, and P. Biondo. 2015. Diet composition, feeding strategy, and diet overlap of 3 sciaenids along the southeastern United States. Fishery Bulletin **113**:290-301.

Wobeser, G. 1975. Prolonged oral administration of methyl mercury chloride to rainbow trout (*Salmo gairdneri)* fingerlings. Journal of the Fisheries Board of Canada **32**:2015-2023.

Wood, J. M., F. S. Kennedy, and C. G. Rosen. 1968. Synthesis of Methyl-Mercury Compounds by Extracts of a Methanogenic Bacterium. Nature **220**:173-&.

Woodland, R. J., D. H. Secor, and M. E. Wedge. 2011. Trophic Resource Overlap Between Small Elasmobranchs and Sympatric Teleosts in Mid-Atlantic Bight Nearshore Habitats. Estuaries and Coasts **34**:391-404.