ARTICLE IN PRESS

Marine Environmental Research xxx (2013) 1–12

Contents lists available at SciVerse ScienceDirect

Marine Environmental Research

journal homepage: www.elsevier.com/locate/marenvrev

Effects of trophic ecology and habitat use on maternal transfer of contaminants in four species of young of the year lamniform sharks☆

Kady Lyons [a,*], Aaron Carlisle [b], Antonella Preti [c], Christopher Mull [d], Mary Blasius [a], John O'Sullivan [e], Chuck Winkler [f], Christopher G. Lowe [a]

[a] California State University Long Beach, Long Beach, CA, USA
[b] Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA
[c] National Marine Fisheries Service, Southwest Fisheries Science Center, La Jolla, CA, USA
[d] Simon Fraser University, Burnaby, BC, Canada
[e] Monterey Bay Aquarium, Monterey, CA, USA
[f] Southern California Marine Institute, Terminal Island, CA, USA

ARTICLE INFO

Article history:
Received 24 February 2013
Received in revised form
14 May 2013
Accepted 15 May 2013

Keywords:
Maternal offloading
Elasmobranch
Trophic ecology
Bioaccumulation
Organochlorine
Metals

ABSTRACT

Organic contaminant and total mercury concentrations were compared in four species of lamniform sharks over several age classes to examine bioaccumulation patterns and gain insights into trophic ecology. Contaminants found in young of the year (YOY) sharks were assumed to be derived from maternal sources and used as a proxy to investigate factors that influence maternal offloading processes. YOY white (*Carcharodon carcharias*) and mako (*Isurus oxyrinchus*) sharks had comparable and significantly higher concentrations of PCBs, DDTs, pesticides, and mercury than YOY thresher (*Alopias vulpinus*) or salmon (*Lamna ditropis*) sharks. A significant positive relationship was found between YOY contaminant loads and maternal trophic position, suggesting that trophic ecology is one factor that plays an important role in maternal offloading. Differences in organic contaminant signatures and contaminant concentration magnitudes among species corroborated what is known about species habitat use and may be used to provide insights into the feeding ecology of these animals.

1. Introduction

Legacy organic contaminants such as DDTs and PCBs continue to pose problems for aquatic biota despite cessation of their production and use in the United States (Rapaport and Eisenreich, 1988; Turusov et al., 2002). Due to their physical properties these contaminants can persist in the environment for many decades and bioaccumulate through the food chain, reaching very high concentrations in upper trophic level marine predators, such as dolphins (Fair et al., 2010), pinnipeds (Blasius and Goodmanlowe, 2008), and sharks (Mull et al., 2012). While production and disposal of many of these compounds have been banned or heavily regulated for over 50 years, their long persistence remains an issue for maintaining and restoring healthy aquatic communities as these contaminants continue to reenter and recycle through food webs (Evans et al., 1991; Calamari et al., 2000).

Inorganic mercury, on the other hand, is continually released into the environment through both anthropogenic and natural processes such as the burning of fossil fuels or volcanic emissions, respectively (Hylander and Meili, 2003; Nriagu and Becker, 2003). The conversion of inorganic mercury into an organic form allows this heavy metal to bioaccumulate through food webs similar to organic contaminants (Mason et al., 1995). However, mercury does not predictably concentrate in specific tissue types as do organic contaminants, which accumulate in lipid storage organs such as liver and blubber (Roos et al., 2010; Yordy et al., 2010). In marine mammals, up to 95% of total organic contaminant loads may fractionate into blubber compared to blood, liver, and muscle (Schantz et al., 1993; Aguilar and Borrell, 1994; Hickie et al., 1999). In fishes, especially elasmobranchs, the liver is used as the main organ of energy storage, and the highest wet weight concentrations of organic contaminants have been found here compared to muscle

Abbreviations: PCBs, polychlorinated biphenyls; DDT, dichlorodiphenyltrichloroethane; 4,4′-DDE, dichlorodiphenyl dichloroethane; ANOSIM, analysis of similarity; SIMPER, similarity percentage analysis.

* Corresponding author.
E-mail address: kady.lyons@sbcglobal.net (K. Lyons).

0141-1136/$ – see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.marenvres.2013.05.009

(Storelli et al., 2003; Schlenk et al., 2005; Gelsleichter and Walker, 2010; Mull et al., 2012). On the other hand, higher concentrations of mercury have been documented in the muscles of some fish species rather than in tissues with highest lipid content (Mason et al., 1995; Endo et al., 2008; Suk et al., 2009), suggesting mercury partitioning is influenced by other factors besides the hydrophobic properties driving organic contaminant tissue-specific accumulation, such as mercury's affinity for disulfide bridges.

While DDT, PCBs, and mercury can now be found throughout the world's oceans, marine areas adjacent to heavily populated or industrialized areas tend to have significantly higher levels of these contaminants (Brown et al., 1998; Klasing et al., 2009). In particular, high levels remain near historic dumping sites or in marine areas receiving large inputs of urban or agricultural runoff (Hu et al., 2010; Webster et al., 2011). In southern and central California high levels of organic contaminants, particularly DDT, remain in sediments which lead the U.S. Environmental Protection Agency (EPA), a governmental body responsible for assessing and monitoring environmental health and remediation, to designate areas within these regions as Superfund sites (Eganhouse et al., 2000; Tomaszewski et al., 2007). For example, it was estimated that 11 tons of PCBs and 110 tons of DDT still remain in sediment on the Palos Verdes Shelf Superfund site in southern California (Eganhouse et al., 2000; Lee et al., 2002). The high levels of DDT have given animals utilizing these and surrounding areas a unique "California" contaminant signature, where the relative proportion of DDTs to PCBs is higher compared to that in biota from other distant locations that are further offshore or north or south (Brown et al., 1998; Krahn et al., 2007). Conversely, animals with higher proportions of chlordane pesticides compared to PCBs are reflective of an "Alaskan" signature (Krahn et al., 2007). Therefore, relative concentrations of these contaminants can be used as an indicator of regional habitat use.

While animals may acquire these contaminants through diet, other processes such as maternal offloading may represent another important pathway of contaminant accumulation, especially during the early life stages. Maternal offloading is the process whereby females passively transfer contaminants when lipids are mobilized from fat stores for yolk or milk production (Addison and Brodie, 1987; Russell et al., 1998). However, various factors related to feeding, such as trophic position (Fair et al., 2010; Ross et al., 2000) and reproductive history (i.e. number of previous birthing events; Aguilar and Borrell, 1994; Borrell et al., 1995) have been shown to influence the amount of contaminants females may transfer to offspring in marine mammals. For instance, females tend to offload the highest amount of contaminants to offspring during their first reproductive event and fewer contaminants to subsequent litters (Borrell et al., 1995). While these processes have been well studied in marine mammals, maternal offloading is less understood in other upper trophic level marine predators, such as elasmobranchs, though it has been shown to occur (Butler and Schutzmann, 1979; Mull et al., 2013; Lyons and Lowe, submitted for publication).

Since marine mammals invest a substantial amount of resources into their offspring, females can offload a large portion of their contaminants. Therefore, the contaminant concentrations of pups and calves are typically reflective of their mothers' accumulated loads, but will change during juvenile stages due to growth dilution and dietary accumulation (Wells et al., 1994; Ross et al., 2000; Metcalfe et al., 2004). This phenomenon may also occur for elasmobranch species, where reproductive energetic investment is also large (Carrier et al., 2004). The high levels of organic contaminants measured in young of the year (YOY) white sharks were primarily attributed to maternal offloading, as many of these young sharks could not acquire these levels through their own feeding (Mull et al., 2012, 2013). Through an opportunistic sampling of a late-term pregnancy thresher shark, Lyons and Lowe (submitted for publication) demonstrated maternal offloading to occur in elasmobranchs since *in utero* embryos had measurable concentrations of organic contaminants and mercury in their liver and muscle tissues as well as in their yolky stomach contents, which consisted of consumed ovulated eggs. Therefore, contaminants in newborn offspring likely reflect their mother's accumulated contaminant burdens and the contaminant signatures (i.e., both total loads and congener profiles) measured in young animals may be used to explore adult female trophic ecology and factors that may influence maternal offloading processes in elasmobranchs.

Southern California is a known nursery area for three species of lamniform sharks (white shark *Carcharodon carcharias*, Weng et al., 2007a; shortfin mako *Isurus oxyrinchus*, Holts and Bedford, 1989; and thresher *Alopias vulpinus*, Cartamil et al., 2010a) and purportedly for a fourth (salmon shark *Lamna ditropis*; Goldman and Musick, 2006). While these species share similar physiological and reproductive characteristics (e.g., regional endothermy and oophagus reproduction; Gilmore, 1993; Carlson et al., 2004) they differ in their habitat use and trophic ecology, both among species and across age classes, which may influence the levels and types of contaminants these species accumulate. Therefore, the purpose of our study was to investigate potential factors that may affect maternal offloading processes in elasmobranch species by examining the roles that maternal trophic position, habitat use, and age at maturity have on contaminant concentrations measured in YOY sharks of four closely related species. In addition, we also aim to address how these factors may influence species bioaccumulation at different age classes.

2. Methods

2.1. Sample collection

For each species, samples of liver and white muscle tissue were collected from each individual when available. Thus, sample sizes represent the number of unique individuals examined. When possible, liver samples were taken from the tip of the left liver lobe and muscle samples from the dorsal musculature anterior to the dorsal fin. Size criteria used to define age classes are reported in Table i (Supplemental; Cailliet et al., 1985, Francis and Duffy, 2005, Ribot-Carballal et al., 2005; Goldman & Musick 2006; Smith et al. 2008). Sharks were considered juveniles if they were smaller than the smallest size at maturity but larger than YOY (<1 yr old) sizes, whereas sharks that measured between the smallest and largest reported size at maturity for the species were considered "near-maturity". Individuals exceeding the largest reported size at maturity were considered adults.

2.1.1. White sharks

YOY ($n = 21$) and juvenile ($n = 9$) white shark samples were collected from incidental mortalities of sharks caught by commercial fishers collaborating with Monterey Bay Aquarium's juvenile white shark research program in the Southern California Bight (SCB) from 2006 to 2012. Contaminant concentrations in white sharks were obtained from previously published data (Mull et al., 2012, 2013).

2.1.2. Salmon sharks

YOY and juvenile salmon sharks were sampled between 2006 and 2010 from Oregon and central California ($n = 34$ and $n = 2$, respectively). Additionally, one YOY salmon shark (80.3 cm FL) that stranded at Huntington Beach, California was donated by the California Department of Fish and Wildlife. One adult and near