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Contaminant Risk and Social Vulnerability Associated with Crustacean Shellfish Harvest in the Highly Urbanized San Diego Bay, USA

Theresa Sinicrope Talley [1,*], Chad Loflen [2], Nina Venuti [1,3], David Pedersen [4], Richard Gossett [5] and Mark D. Baker [5]

1 California Sea Grant, University of California, San Diego, CA 92093, USA; nevenuti@ucdavis.edu
2 San Diego Regional Water Quality Control Board, San Diego, CA 92108, USA; chad.loflen@waterboards.ca.gov
3 Department of Plant Sciences, University of California, Davis, CA 95616, USA
4 Department of Anthropology, University of California, San Diego, CA 92093, USA; dpedersen@ucsd.edu
5 Physis Environmental Laboratories, Inc., 1904 E Wright Cir, Anaheim, CA 92806, USA; richgossett@physislabs.com (R.G.); markbaker@physislabs.com (M.D.B.)
* Correspondence: tstalley@ucsd.edu

Abstract: People in coastal cities around the world harvest seafood from local bays despite well-documented health risks. In cities such as San Diego, California, USA, much information about contaminants and human consumption patterns exists for finfish but is largely lacking for shellfish. This study sought to better understand shellfish contamination risks and human vulnerability to inform management and advisories. In summer 2018 and winter 2019, we sampled crustaceans for chemical contaminants and anthropogenic debris and throughout the year surveyed people harvesting from three public fishing piers around San Diego Bay. Of the emerging contaminants found, pyrethroids, benzylbutyl phthalate, PFOS and anthropogenic debris were in differing concentrations in the muscle and viscera of the California spiny lobster and two species of crabs. Combined with previous metal and organic contaminant data from the lobster, 22 contaminants were detected with 5 exceeding consumption thresholds and 8 lacking defined thresholds. California spiny lobster was the main crustacean harvested from piers, attracting shellfishers from a range of ages, incomes, home locations and self-identified racial/ethnic groups. Consumption preferences (e.g., muscle or viscera) were non-discriminant, making lobster contamination a community-wide risk. More monitoring of emerging contaminants and different shellfish species (and tissues) of interest is recommended to capture the spatial and temporal dynamics of health risks, especially because the use of bivalves as sentinels may not reveal the same risks (e.g., PFAS, phosphate flame retardants).

Keywords: crab; decapods; estuary health; lobster; plastic fibers; pollutants; recreational fishing; shellfish harvest; water quality

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1. Introduction

People from coastal urban centers around the world harvest and consume seafood from local embayments despite the recognition that this seafood often contains chemical and biological contaminants that pose human health risks [1–4]. Crustacean shellfish, such as rock crabs (*Cancer productus*, *Metacarcinus anthonyi*, *Romaleon antennarium*) and California spiny lobster (*Panulirus interruptus*), are recognized recreational fisheries and while they are of concern for both their biological and chemical contaminant risks to humans across the country (e.g., [1,5,6]), they have received less attention than finfish (e.g., [7–9]) in the literature on contamination risk and human consumption patterns. In urbanized San Diego Bay, people from a variety of ethnic backgrounds and socio-economic levels, in particular people from middle to lower income levels, catch and consume finfish from piers and other access points around the bay [8,10,11]. While shellfish harvest is documented in other parts of the country [1,5,6], there is little understanding of the risks of shellfish and those who harvest shellfish in this region.

1.1. The Risks

There is a wealth of recent information about contaminants in sediments, water and some taxa in San Diego Bay (e.g., finfish of fishing interest, benthic macrofauna, zooplankton, bird eggs, mussels) [9,12]. Largely missing from recent efforts is information on benthic species likely being harvested for food (e.g., crabs and spiny lobster). An exception was a 2014–2015 survey that revealed that whole California spiny lobster contained levels of PCBs, PBDEs, cadmium and selenium that, in at least one of two samples, exceeded consumption threshold guidelines [13]. The whole lobster also contained detectable concentrations of organochlorine pesticides, chlordanes and eight other metals, including arsenic, chromium, copper, lead and zinc, though these contaminants were all found to be below consumption threshold levels. Further, 60% (18 of 30) of lobster tails tested contained concentrations of mercury that exceeded no-consumption thresholds with a strong positive relationship between mercury concentration and carapace size (i.e., age), indicating bioaccumulation [13]. This snapshot of mercury concentrations was valuable in setting recreational consumption guidelines for spiny lobster tails in San Diego Bay [14], but uncertainty remains about the risks associated with the consumption of whole lobster or viscera (vs. muscle only), loads of contaminants of emerging concern, including personal care products and pharmaceuticals [15,16], recently trending pesticides (e.g., neonicotinoids; [17]) and anthropogenic debris, including small natural and synthetic textile fibers and plasticizers (phthalates) (e.g., [18–20]). The impacts of small plastics on organisms are very well documented and include toxicity associated with compounds within and adhering to the plastics, as well as physical damage and interference with organismal functioning, including entanglement in digestive tracts and gills [21]. These physical interferences may also be caused by natural materials (e.g., cotton, wool or hemp fibers) that are common in the ocean [20]. The effects of ingesting small plastics on human health are still being understood, but may include inflammation, necrosis and the disruption of ordinary immune responses [22].

1.2. Those Who Harvest Shellfish

As with finfish, understanding shellfish contamination risks requires not only knowledge of shellfish availability and contamination, but also information about the people harvesting, the frequency and abundance of consumption and the modes of preparation [8]. Individual harvesters exhibit different consumption patterns and employ different preparation methods, which may be linked to their ethnic/cultural and socioeconomic backgrounds [7]. The preparation of shellfish, as with finfish, may influence contamination risk and may make some harvesters more vulnerable to that risk than others. Viscera can store or accumulate biological and chemical contaminants, such as domoic acid, saxitoxins, metals (e.g., lead and cadmium) and polychlorinated biphenyls [23–26]. Therefore, those who eat raw shellfish, or who consume or boil and then drink the broth of the whole animal, may be at higher risk of exposure to some contaminants than those who eat only cooked muscle tissue. In spite of this possibility for differential vulnerability, the consumption guidelines for finfish and shellfish species focus on muscle tissue alone and do not include viscera [14,27]. Further, while whole organism and viscera monitoring does exist, the bulk of advisories for shellfish target paralytic and analytic shellfish poisoning [26,28] and overlook other contaminants of concern. Therefore, information to craft basic guidelines, as well as socially sensitive guidelines informed by harvester demographics, consumption and preparation patterns, is urgently needed.

The goal of this study was, therefore, to better understand self-harvested shellfish contamination risk and consumer vulnerability in order to inform management decisions and the crafting of harvest guidelines and advisories for San Diego Bay and beyond. This goal was met by determining: (1.) the chemical contaminant risks associated with publicly accessible crustacean shellfish; and (2.) the demographics (age, gender, income, ethnicity) and consumption patterns (frequencies, amounts, preparation techniques) of those harvesting shellfish in San Diego Bay.

2. Materials and Methods

2.1. Field Sampling

Crustacean shellfish were collected during the October 2018–March 2019 California spiny lobster season near three public fishing piers in San Diego Bay: Shelter Island pier, Embarcadero pier and Pepper Park pier. All three of these piers had been used as study sites in previous contaminant and fish consumption surveys [8,9,12]. Crustaceans were collected using hoopnets deployed from Shelter Island pier in October (two spiny lobsters, *P. interruptus*) and from a boat near the pier in March (two spiny lobsters, one yellow rock crab (*Metacarcinus anthonyii*), one spider crab (also known as sheep crab, *Loxorhynchus grandis*)). Divers collected shellfish from beneath the Embarcadero and Pepper Park piers (three spiny lobsters each) in March 2019 (Figure 1). All crustaceans collected were at or near legal size limits of 82.5 mm carapace length for spiny lobster and 108 mm carapace width for rock crab (spider crab has no legal size) [29] to gain a representative look at risks to recreational harvesters (Table 1).

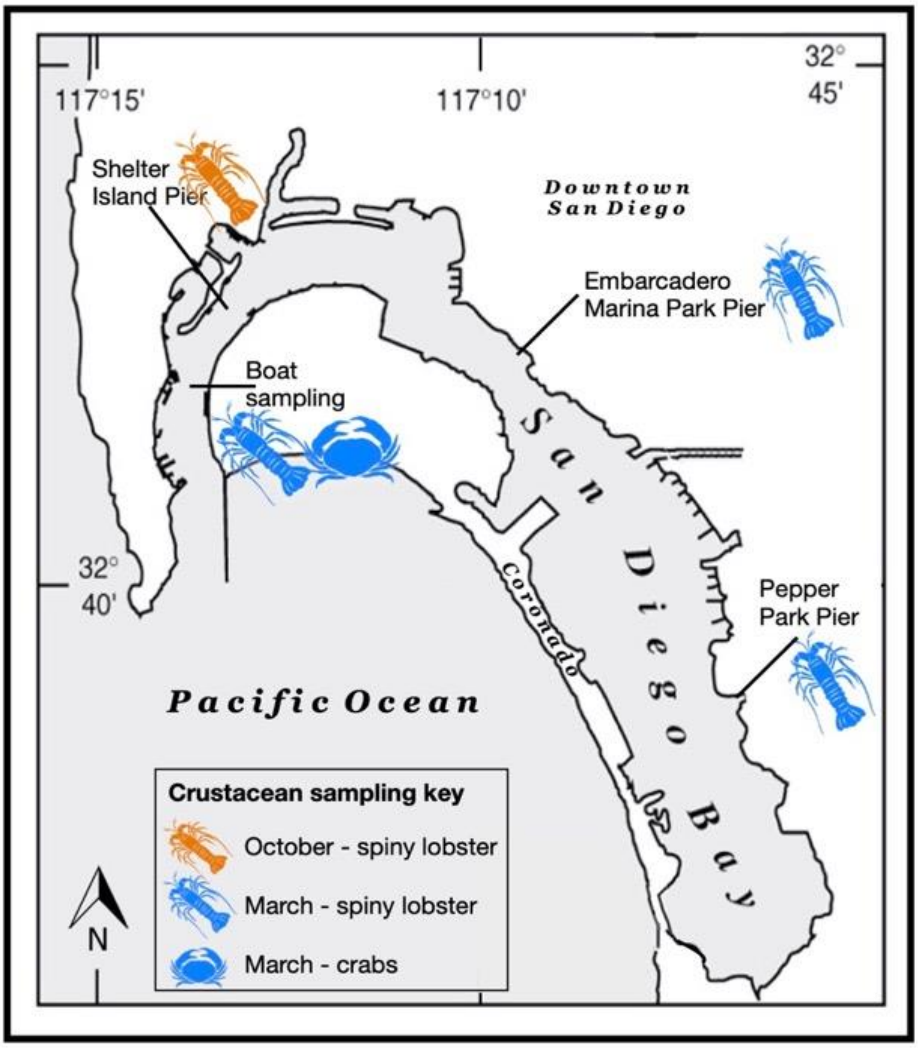

Figure 1. Sampling locations in San Diego Bay, California, including three public fishing piers from which shellfish samples and harvester surveys were collected and a fore bay open water location from which additional shellfish samples were collected. Surveys were conducted on piers throughout summer 2018–spring 2019; crustaceans were sampled in October 2018 and March 2019.

Table 1. Biological information for the crustacean samples used in this study of shellfish contaminants in San Diego Bay, California.

Date Collected	Site	Sex	Avg ± 1SE Length (mm)	Avg ± 1SE Weight (g)	Viscera or Tail Muscle	% Moisture	% Lipids
California spiny lobster (*Panulirus interruptus*)							
October-18	Shelter Island	F,M	79 ± 0	558 ± 2	viscera muscle	64 71	58.50 0.75
March-19	Shelter Island	F,F	78 ± 2	549 ± 11	viscera muscle	70 72	36.20 0.82
March-19	Embarcadero	F,F,M	86 ± 2	624 ± 23	viscera muscle	70 76	13.10 1.01
March-19	Pepper Park	F,F,M	77 ± 4	526 ± 53	viscera muscle	67 77	20.30 1.01
Spider crab (*Loxorhynchus grandis)*							
March-19	Shelter Island	F	124	2721	viscera muscle	69 79	26.60 3.94
Yellow rock crab (*Metacarcinus anthonyii)*							
March-19	Shelter Island	M	108	411	viscera muscle	86 75	9.81 0.63

Between summer 2018 and spring 2019, we interviewed recreational shellfish harvesters at all three public fishing piers to gather information on shellfish harvest and consumption patterns using a stratified sampling design to capture information from harvesters who might be active across different times of day (morning, afternoon, evening, night), weekdays or weekends and seasons (summer, fall, winter, spring). Surveys (see Supplemental Information) were administered verbally in English, with at least one other language available at each visit (Spanish, Vietnamese and/or Tagalog). Surveys were only administered to people who had not previously participated in the study. Home zip codes provided were used to calculate the distance traveled to each pier from home using Google Maps and to estimate average household income for each participant's neighborhood using City-Data.com (accessed on 13 May 2019) [30]. At the start and end of each sampling session, the number of anglers and shellfishers (identified based on gear) actively fishing on the pier, the number of parties present (visually assessed according to how groups of anglers/shellfishers were situated in relation to others) and the number of poles or nets in use were counted.

2.2. Demographic Analysis

Differences in participant age, distance traveled and average household income (according to home zip codes provided) between piers were tested using one-way ANOVA. Differences in the proportion of participants from various self-identified racial/ethnic groups, the presence of harvesting and shellfish preparation and consumption preferences across piers were tested using Pearson Chi Square tests. Relationships between average household income and age and presence of crab harvesting and shellfish preparation and consumption preferences were tested using logistic regressions. Relationships between the frequency of shellfishing (days per season) and both the average household income of the participants' home zip code and their age were tested using simple linear regressions. Relationships between self-identified racial/ethnic groups and both frequency of shellfishing and consumption patterns were tested using one-way ANOVA. All statistical tests were run using JMP® Pro 15 [31].

2.3. Contaminant Analysis

Spiny lobster and crab were dissected using metal tools and trays cleaned with technical grade hexane (60–100%). Muscle from crab claws and legs and spiny lobster tails, antennae and legs (spiny lobster) as well as viscera (crabs and lobsters) were each removed and immediately placed into acid-washed, sterile glass jars and frozen until analyzed for contaminants. Samples within dates and locations were combined into the same jar to be analyzed as composite samples for 57 different analytes across 10 major contaminant classes (Table 2; n = 4 composite samples each for lobster muscle and lobster viscera; n = 1 sample for crab muscle and crab viscera for each species collected, with no composite samples due to low collection numbers). One bay-wide composite sample comprised of muscle from all four lobster samples was additionally analyzed for 12 pharmaceutical, personal care product, hormone and steroid analytes. The gills and digestive tract (fore gut, hind gut) of all crabs and lobsters were each removed and immediately placed into separate, clean ziptop bags and frozen again until anthropogenic debris analysis. Differences in contaminant concentrations between viscera and muscle were tested using paired t-tests on log (x + 1) transformed data. Due to low samples sizes of crabs (n = 1), differences between species could not be explored statistically.

Table 2. List of major contaminant classes and methods used in testing the muscle and viscera of California spiny lobster, yellow rock crab and spider crab collected from San Diego Bay. A total of 57 individual analytes were tested per each crustacean muscle and viscera sample and an additional 12 PCPP analytes were tested on a single composite spiny lobster muscle sample.

Contaminant Class	Analytical Method
Acid Extractable Compounds (phenols)	EPA 8270D
Base/Neutral Extractable Compounds (phthalates, caffeine)	EPA 8270D
Fipronil and Degradates	EPA 8270D-NCI
Neonicotinoid Compounds	EPA 8270D-NCI
Organophosphorus Pesticides (chlorpyrifos, DEET)	EPA 8270D
Organotins	[32]
Phosphate Flame Retardants	EPA 8270D
PolyBrominated Diphenyl Ethers (PBDEs)	EPA 8270D-NCI
Pyrethroid Pesticides	EPA 8270D-NCI
Perfluorooctane sulfonic acid (PFOS)	PFAS Isotope Dilution Method
Pharmaceuticals and Personal Care Products	Modified EPA 1694

Because muscle and viscera were analyzed separately, contaminant mass pollutant loading per whole individual was estimated for lobster and crab by multiplying the viscera and muscle contaminant concentrations by the relative amount of each tissue in a whole individual (spiny lobster: avg weight of 567 g × 25% muscle and 5.5% viscera; rock crab: 411 g and spider crab 2721 g × 15% meat and 5% viscera) (Talley unpublished data [33,34]).

2.4. Anthropogenic Debris Analysis

Gill, foregut and hind gut samples from the spiny lobster and crabs were further dissected and examined for anthropogenic debris a little at a time in a petri dish wet with deionized water using a dissecting microscope with a combination of external lighting and bright-field illumination and, when needed, compound microscope. Visual assessments during dissections were used to observe the exact locations and orientations of debris within the tissues. Hard debris in vials was digested with 10% hydrochloric acid for 24 h at room temperature (22 °C) to dissolve calcareous and chitinous material and particles remaining were rinsed with DI water. Particles that resembled naturally occurring organics (e.g., fibers or film that resembled plant and algal particles) were digested in 10%

hydrogen peroxide for at least 48 hrs at 22 °C [35]. Not all particles were exposed to acid and hydrogen peroxide to reduce risk of loss of some plastics [35]. Particles remaining after the digestions, presumably synthetic polymers and natural textile materials (e.g., wool, cotton, hemp) that are resistant to these solvents, were examined under a dissecting microscope using the polarization and Nile Red fluorescence detection method for microplastics [36]. Particles were classified (plastic or not plastic material, form, color) and counted. Proper micro-particle lab contaminant control measures were taken, including pre-cleaning work areas and tools, keeping clear lids on or over petri dishes as much as possible while sorting and using control dishes to measure and then deduct numbers of ambient particles from samples (e.g., [37]). Differences in abundance of debris between sites and season/month were assessed visually using descriptive statistics due to low replication (lack of statistical power).

3. Results

3.1. Shellfish Contamination

Each spiny lobster and crab tested contained five–nine of the focal contaminants. Tributyltin, pyrethroids, caffeine and PFOS were only found in the spiny lobster and not the crab species, while DEET was unique to the spider crab. Polybrominated diphenyl ether concentrations were one to two orders of magnitude greater in the crabs than the spiny lobster (Figure 2A,B). Given the small sample sizes and variable concentrations, however, it is difficult to draw conclusions about concentration differences between species.

Spiny lobster viscera tissue generally contained higher concentrations of PFOS and tributyltin (p = 0.03–0.09, t_3 = 2.4–4.0, n = 4), while muscle had higher concentrations of benzylbutyl phthalate (except at Embarcadero) (p = 0.09, t_3 = 2.3, n = 4). Caffeine, Galaxolide and phosphate flame retardants were only present in spiny lobster muscle from Shelter Island (Figure 2A). Pyrethroid concentrations were similarly low between viscera and muscle (data pooled across sites: p = 0.48, t_3 = 0.79, n = 4) and were detectable in muscle only (Embarcadero), viscera only (Shelter Island) and both tissues (Pepper Park). While PBDEs were present in the March samples of spiny lobster muscle only, concentrations were relatively low (near detection limits, 0.02–0.09 ng/g wet wt). Only the viscera of spider crab contained DEET and the viscera of both crab species had higher concentration of PBDEs than muscle (Figure 2B). As with the spiny lobster from Shelter Island in March, rock crab muscle contained benzylbutyl phthalate, Galaxolide and phosphate flame retardants (Figure 2B).

A comparison of the spiny lobster samples collected from the three regions of the bay (one composite sample comprised two–three lobsters per region) in March revealed that benzylbutyl phthalate, tributyltin, PBDEs and PFOS were present across the bay, at least in late winter (Figure 2A). Two contaminants were only found at Shelter Island—Galaxolide and phosphate flame retardants—while this was the only site to not contain pyrethroids. A comparison of the October and March spiny lobster samples from Shelter Island revealed that caffeine and a pyrethroid pesticide (danitol) were only detectable in October, while Galaxolide, phosphate flame retardants and PBDEs were only detectable in March 2019. Perfluorooctane sulfonic acid, pyrethroids and benzylbutyl phthalate were detectable in both seasons (Figure 2A).

3.2. Shellfish Anthropogenic Debris

Every one of the 12 crustaceans collected from around the bay and examined (10 spiny lobster, 1 rock crab, 1 spider crab) contained pieces of anthropogenic debris and the number per individual ranged from 1–130 pieces. Most debris pieces were plastic as indicated by birefringence when viewed with cross-polarization (Figure 3A(ii),B(ii)) and/or strongly fluoresced under blue light when stained with Nile Red [36]. The exception was one bundle of 126 white/clear fibers found in the foregut of one of the spiny lobsters (Figure 3 C(i)) that did not stain with Nile Red dye and therefore did not fluoresce under blue light (Figure 3 C(ii)) nor have birefringence under cross-polarization (Figure 3 C(ii)). While this bundle was likely not plastic, it had also resisted hydrogen peroxide digestion and was therefore likely a durable natural textile fiber (e.g., cotton, wool).

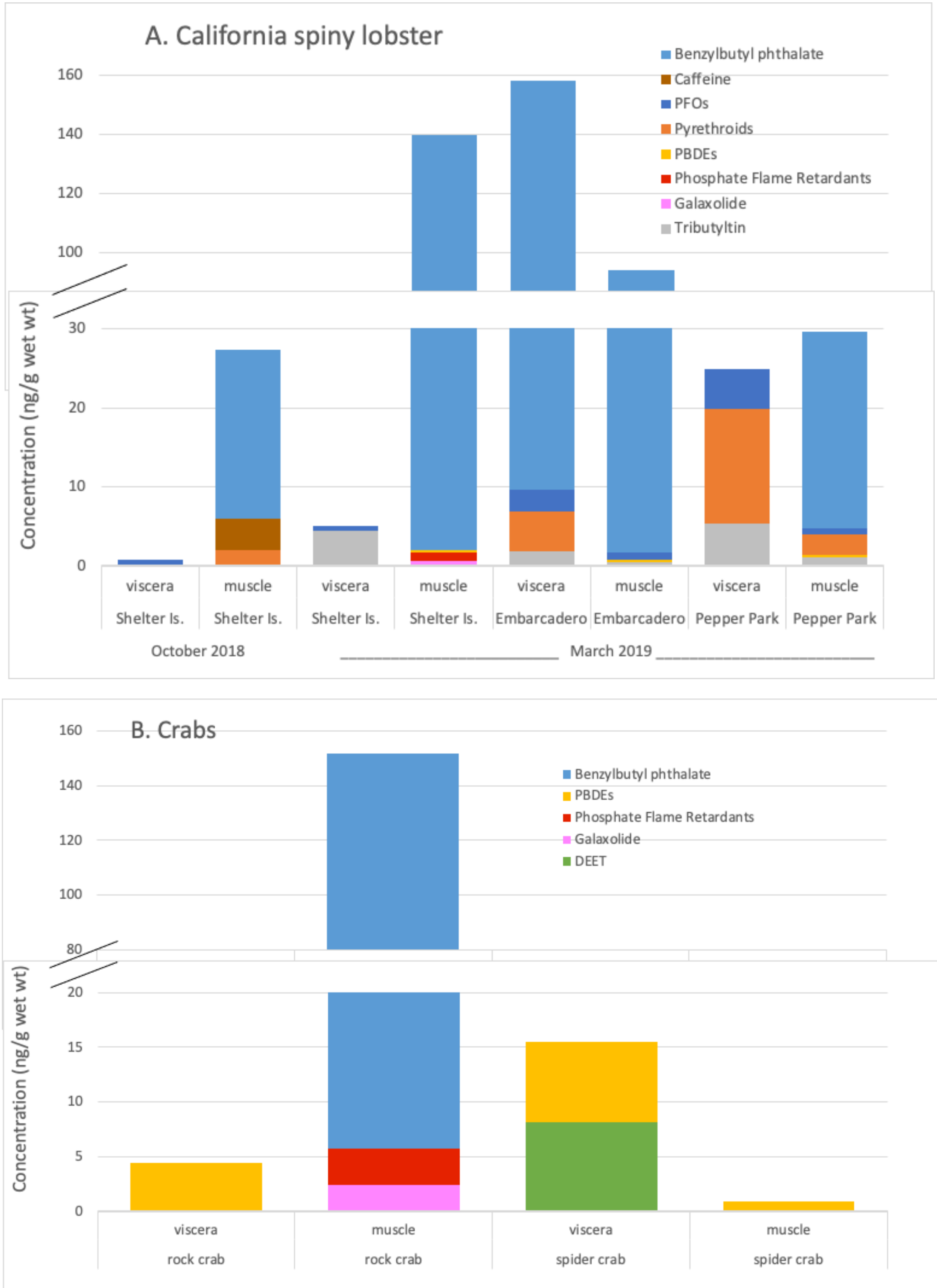

Figure 2. Contaminant concentrations in the viscera and muscle of (**A**) California spiny lobster and (**B**) yellow rock crab and spider crab. Spiny lobsters were collected from Shelter Island in October 2018 and from three locations throughout San Diego Bay, California, in March 2019. N = one sample per site and date that was comprised of a composite of two–three spiny lobster individuals. Crabs were collected from the forebay area of San Diego Bay, California, in March 2019; N = one individual of each species.

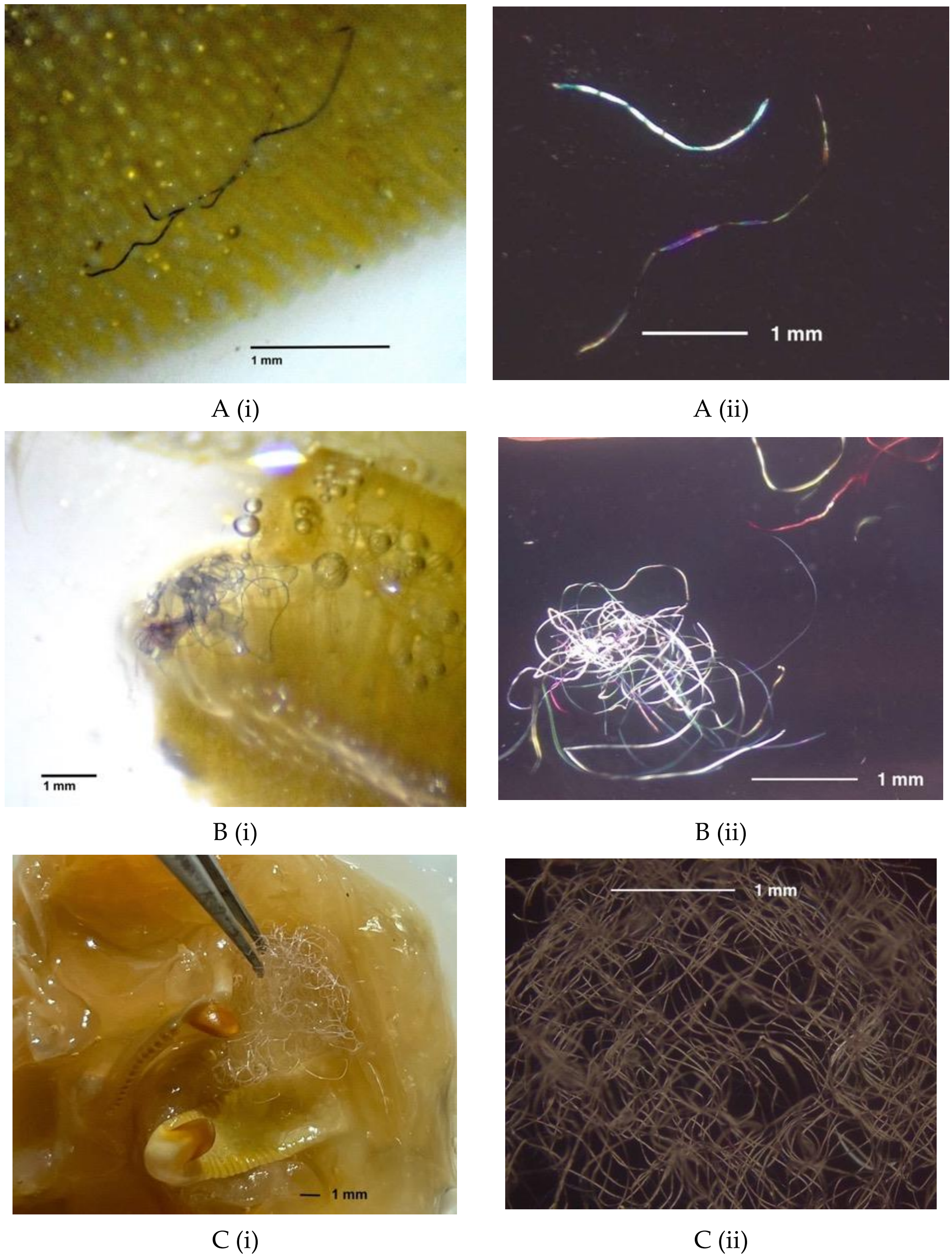

Figure 3. Fibers found within California spiny lobster individuals, including (**A** i and ii) an individual blue strand intertwined among the alveoli of a gill, (**B** i and ii) a bundle of four blue fibers in the gill and (**C** i and ii) a bundle of one hundred and twenty-six clear/white fibers in a foregut. Photos labeled as (i) were taken using light microscopy and (ii) using crossed-polarizers under which plastics are birefringent [36]. Spiny lobsters were collected in October 2018 and March 2019 from San Diego Bay.

Seven of the ten lobsters had pieces of debris in gills (Figure 3A,B), six had debris in foregut (Figure 3C) and one had debris in hindgut. Both crabs had pieces of debris in their gills, one crab had debris in the hindgut and neither had debris in the foregut. Fibers were most common (Figure 3A–C), making up 67–100% of debris found in lobster and the crabs. Fibers were found in all body parts examined (fore, hind gut, gills), while hard pieces and film were only found in the gut. In three individuals, including those with the highest abundances of debris pieces, fibers were found in tangled bundles (it is unclear whether they became entangled in the organism or were introduced that way). One individual had a bundle of 126 fibers in its foregut (Figure 3C) and two individuals had bundles of fibers in their gills, one with three bundles (3, 5 and 8 fibers each) and the other with one bundle of 4 fibers (Figure 3B).

Abundances of debris pieces per spiny lobster individual did not differ across sites in March 2019 ($F_{2,5}$ = 1.4, p = 0.33, n = 8), but the highest abundances at Pepper Park in the back bay were as much as 12–23 times higher than in the fore- (Shelter Island) or mid-bay (Embarcadero) (Figure 4). There were comparable abundances (4.5–6.5 pieces per individual; $F_{1,2}$ = 0.01, p = 0.99, n = 4) of debris in spiny lobster between seasons at Shelter Island (Figure 4).

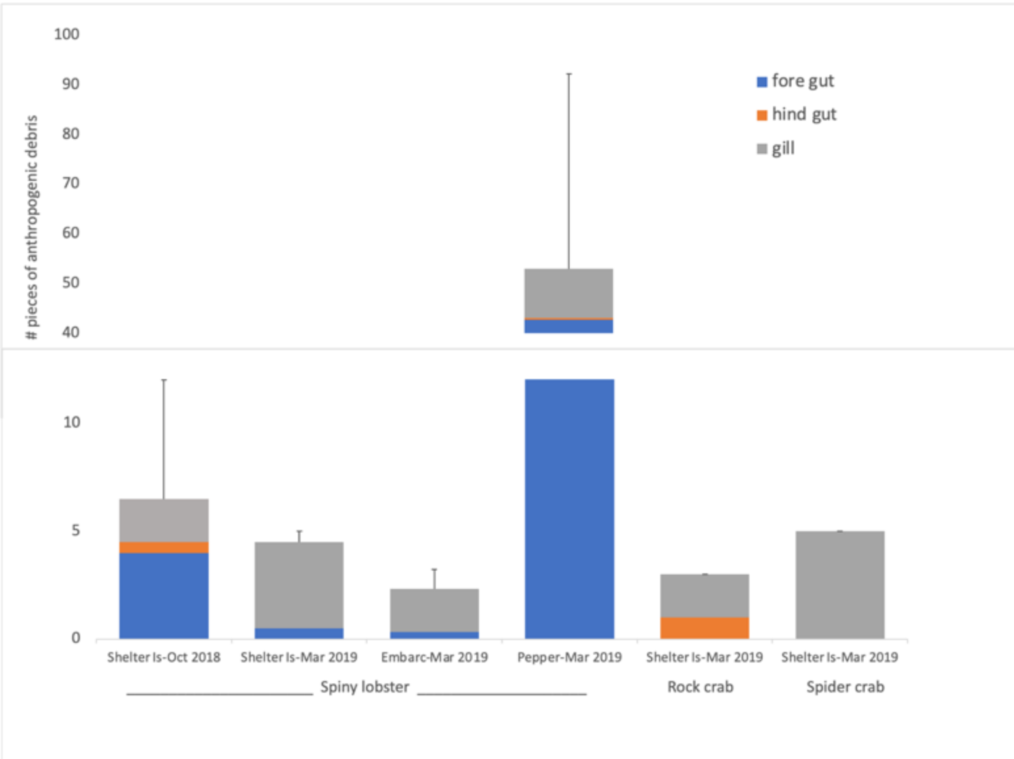

Figure 4. Average (±1SE) number of pieces of anthropogenic debris found in the gut and gills of crustaceans in San Diego Bay, California, in October 2018 and March 2019. N = two–three individuals per location and date. Shelter Is = Shelter Island Pier, Embarcadero = Embarcadero Marina Park South Pier, Pepper = Pepper Park Pier.

3.3. *Shellfish Harvesters*

The Shelter Island pier was the most popular fishing location throughout summer 2018 to spring 2019, with a total of 1405 people counted during our sampling sessions as compared to 775 people at Embarcadero pier and 209 people at Pepper Park pier. The majority (94%) of the people encountered on the three piers were recreational anglers (rod and reel fishers). People with hoopnets, the most common gear type for catching crustacean shellfish, were only seen on piers during the fall (60 people, 40 parties) and winter (74 people, 50 parties) during California spiny lobster season. The few catching shellfish in other seasons caught them on lines or handheld nets. During spiny lobster season, there were two to four parties (of one–four people) per night usually present and hoopnetting on Shelter Island pier, followed by Embarcadero, which had zero or one party shellfishing, and Pepper Park, which only had three shellfishing parties encountered throughout the lobster season (and year). Shellfishing (hoopnetting for spiny lobster) usually occurred at night on all piers, with a couple of exceptions, which corresponds with the nocturnal habits of spiny lobster.

A total of 61 surveys were conducted with crustacean shellfish harvesters. Most (86%) of the shellfishers we approached were willing to participate in this study so the survey participants are a good approximation of all those shellfishing on the piers in this study year. One of the participants identified as female and the rest identified as male. There were times when a female companion was present during the survey, but they deferred to the male in the party to participate. The age of participants did not differ between sites (p = 0.76, $F_{2,57}$ = 0.3) with the average (±1SE) age ranging from 42 ± 1.5 yrs at Embarcadero to 46 ± 1 yrs at Pepper Park, and an overall age range of 20–78 yrs old across all three piers. Participants traveled from all around western San Diego County to fish on these piers, traveling on average 22 ± 3 miles one way to Shelter Island, 11 ± 2 miles to Embarcadero pier and 6 ± 2 miles to Pepper Park pier (p = 0.52, $F_{2,54}$ = 0.7). Average (±1SE) household incomes of the home zip codes of participants at each pier were variable, ranging from USD 74,637 ± USD 6242 at Pepper Park to USD 99,902 ± USD 4892 at Shelter Island, with no large differences between piers (p = 0.14, $F_{2,53}$ = 2.1). Only one shellfisher, who was at Embarcadero, identified as homeless.

Most (41%) of the participants across all piers identified as white, Caucasian and/or of European descent, just under 20% each identified as Mexican and/or Hispanic and as Filipino and/or Filipino American, roughly 10% identified as Asian, Asian American and/or a specified Asian ethnicity, about 5% each identified as Black, African American and as Biracial and 3% said they were other or refused to specify (Figure 5). The proportions across piers were fairly similar to expected (p = 0.40, Chi square = 14.7, df = 14), with the greatest diversity at Embarcadero pier in terms of number of groups and evenness (Figure 5).

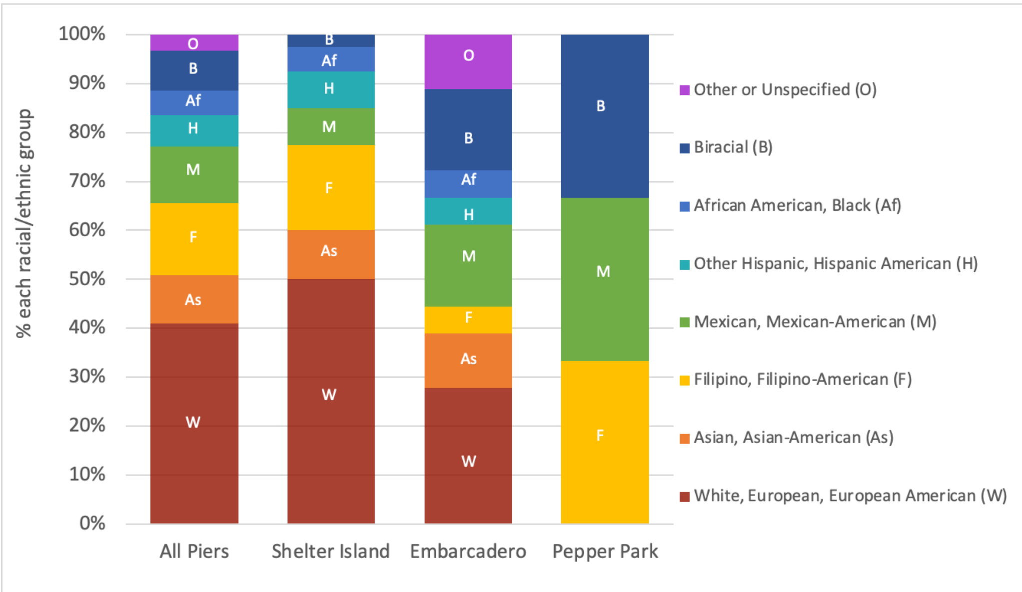

Figure 5. Composition of self-declared racial/ethnic identity of shellfisher survey participants across all three piers and at each of the three piers in San Diego Bay. N = 40 participants at Shelter Island, 18 at Embarcadero and 3 at Pepper Park. Data are from Summer 2018–Spring 2019. Asian (N = 6) included one person each identifying as Vietnamese, Korean, or Cambodian. Biracial (N = 5) included white and Asian, Black, or Mexican, Filipino and Pacific Islander and Korean and Mexican.

Consistent with the seasonal pattern of shellfishing, most participants were encountered during recreational California spiny lobster season, with 67% of people participating in the study in fall and 18% in winter (15% in summer, 0% in spring). Of those who shellfished during lobster season, throughout the fall and winter, nearly $\frac{1}{2}$ did so weekly or more frequently and another $\frac{1}{4}$ fished one–two times during the lobster season (Figure 6). The frequency of shellfishing was weakly positively correlated with the age of the shellfisher

($R^2 = 0.06$, $p = 0.06$, $F_{1,58} = 3.6$) and not associated with average household income ($p = 0.25$, $F_{1,54} = 1.3$) or self-identified race/ethnicity ($p = 0.82$, $F_{7,53} = 0.5$; Figure 6).

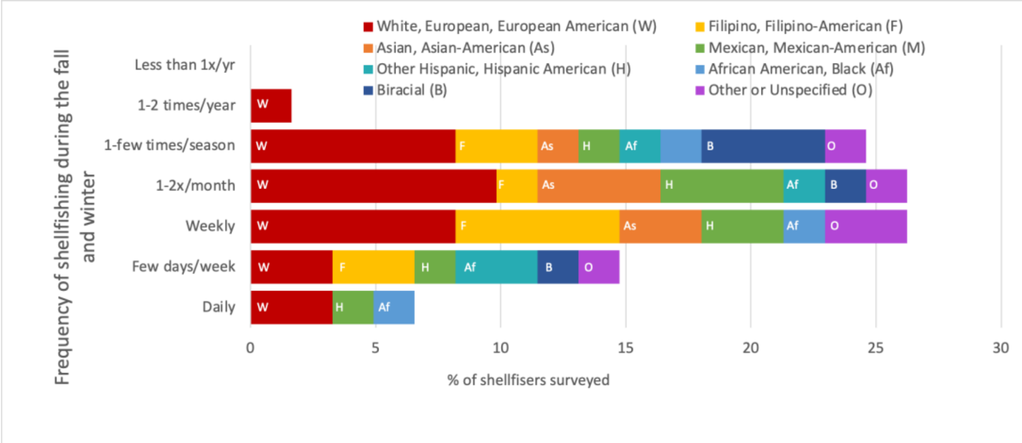

Figure 6. The frequency at which participants from each self-identified racial/ethnic group engage in shellfishing on three public piers in San Diego Bay during the fall and winter seasons (i.e., California spiny lobster season). Data are from fall 2018 to winter 2019, N = 61 surveys.

Almost everyone surveyed (58 of 61 people) said they fished for California spiny lobster. Two thirds of shellfishers said that they would take the legal limit of spiny lobster (seven per day) if they caught them, although a few noted that they usually catch fewer per day than the limit (zero–four per night). At least eight people commented that they share their catch with family and/or friends. Another $\frac{1}{4}$ said they would only take what they and their families could use, usually one to a few. About one third of people (20) said they also take crabs for food, including rock crab (likely *M. anthonyii*; two responses), spider/sheep crab (*L. grandis*, four responses), swimming crab (*Portunus xantusii*, three responses), blue crab (*Callinectes arcuatus*, two responses), kelp crab (likely *Taliepus nuttallii*, one response) and unspecified crabs (fourteen responses). People noted that they do not usually catch crab or, if they do, it is usually one–two individuals. There was a weak negative relationship between participant age and crab harvesting ($p = 0.02$, Chi square = 5.6, df = 1, n = 60) and no strong relationship between harvest of crab and self-identified racial/ethnic group ($p = 0.13$, Chi square = 11.2, df = 7, n = 61) or average household income of the participants' zip code ($p = 0.14$, Chi square = 2.2, df = 1, n = 56). Two additional participants who catch rock crab (likely *M. anthonyii;* two responses) and graceful rock crab (*Metacarcinus gracilis*, one response), stated that they do not keep the crabs for food due to worries about contamination, but said they would eat them if they were sure the crabs were safe. Two participants mentioned also harvesting for food Pismo clam, razor clam and other unspecified clams from the western shore of the bay and three participants mentioned harvesting mussels (*Mytilus galloprovincialis*), Pacific oyster (*Crassostrea gigas*), "sand fleas" (likely *Emerita analoga*) and/or the lined shore crab (*Pachygrapsus crassipes*) from the nearby shore for bait.

The most commonly cited motivation for shellfishing was the capture of food (90% of those surveyed). People from each pier, however, had on average two–three reasons for shellfishing. Two thirds of people (67%) said that they harvest both for recreation or relaxation and to eat their catch (i.e., not subsistence fishing). Only one person, a homeless individual, harvested shellfish for subsistence (on Embarcadero). Nearly one third of people (31%) cited the location of Shelter Island and Embarcadero piers as a motivating factor, with references to convenience (near home, near friends, easy access, no boat needed) and ambiance (cafés, calm waters). Almost one quarter cited shellfishing as a family tradition or activity (23% of people); and about 8% harvest shellfish from the nearby riprap as bait (e.g., oyster, mussel). A couple of people mentioned that they also came because it was an inexpensive activity (despite the 2018-19 California spiny lobster annual permit cost of USD 10.80).

All shellfishers who eat harvested shellfish consumed muscle, in particular the tails of spiny lobster and claws of crab, while only 13% said that they ate viscera in some form (e.g., directly or cooked in a broth or puree/bisque) (Figure 7). Over half (58%) of participants cook the meat and viscera together whether boiling, frying, grilling or baking, while the other 42% separate the meat from viscera before preparation. Of the 58% who cook meat and viscera together, most (77%) extracted and ate only the meat after cooking. Age, average household income and self-identified racial/ethnic group (Figure 7) were not associated with a preference for preparing and eating shellfish ($p \geq 0.11$, Chi square ≤ 2.7, df = 1–7, n = 56–60).

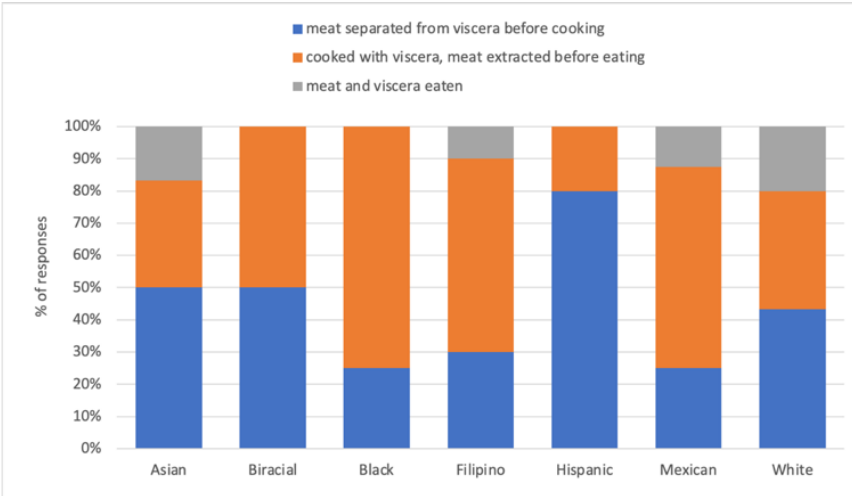

Figure 7. Proportion of each self-declared racial/ethnic identity that eat the muscle (meat) and/or viscera of crustacean shellfish harvested from San Diego Bay. N = 67 responses about preparation across 58 surveys. Data are from summer 2018–spring 2019.

4. Discussion

4.1. Contaminant Exposure Risks Associated with Eating Whole Lobster and Crab

Combining findings from 2014–2015 [13] and this study revealed that California spiny lobster may contain at least 22 classes of contaminants with 5 types exceeding current consumption guidelines (Table 3). In this study, the crabs did not contain as many classes of contaminants as the spiny lobster, but the small sample sizes (n = 1 crab from each species) limited a comprehensive assessment of variability in contaminant types and concentrations. As is expected in the presence of lipophilic contaminants, spiny lobster viscera in 2014–2015 had higher concentrations of PBDEs, PCBs, chlordanes and several metals and therefore exceeded more consumption thresholds than muscle. In this study, anthropogenic debris particles were more abundant in the viscera because they primarily enter these organisms via ingestion (i.e., digestive tracts) and intake associated with respiration (i.e., gills) with fewer pathways that lead to accumulation in muscle tissue (e.g., entanglement, inter-cellular transfer). Many of the other contaminants of emerging concern detected in spiny lobster and crabs in this study, however, had similar or greater concentrations in muscle than viscera (e.g., benzylbutyl phthalate, DEET, caffeine, Galaxolide, organotin, pyrethroids, PFOS, phosphate flame retardants, PBDE). While existing shellfish preparation and consumption guidelines, which focus on viscera to reduce the risk of exposure to algal toxins (e.g., eviscerating crabs before preparation to avoid domoic acid and saxitoxin), may confer some amount of protection against emerging viscera-associated contaminants (e.g., anthropogenic debris), they do not protect against those in muscle. Further, there is still much uncertainty about the accumulation rates and human health impacts of several of the muscle-associated compounds and plastics and therefore dose limits and consumption guidelines are lacking. Knowledge about human health risks from the intake of small plastics through seafood—or other foods or water—is in its infancy (e.g., [38]). Similarly, there is only an emerging awareness of the acute and chronic effects of Pyrethroids, initially considered safe for humans, and Galaxolide on humans [39,40] while both can be toxic to aquatic organisms [39,41]. Research on the human health effects of DEET has focused on transfer into the bloodstream and rates of metabolism after topical applications with little information on the effects of ingestion [42,43].

For the rest of the contaminants detected in this study, other types of dose advisories exist for comparison to levels found in spiny lobster and crab in this study. A primary concern was the level of PFOS found in both the muscle and viscera of spiny lobster. While State of California thresholds do not exist for PFOS (or PFAS), the European Food Safety Authority (EFSA) has published a tolerable weekly intake (4.4 ng/week per kg body weight; [44]) and other states have drafted risk thresholds for tissues (e.g., [45–47]). Using the EFSA weekly intake threshold, State of California assumptions for body weight (70 kg, see [48]) and this study's consumption rate results (meals per week x grams tissue type per meal), the maximum observed spiny lobster muscle and viscera concentrations exceeded calculated weekly thresholds for PFOS, with concentrations exceeding thresholds for the consumption of the muscle of three lobsters per week or viscera of one lobster per week. Risk would be further increased if consuming both muscle and viscera, with maximum mass loading observed in lobsters near the maximum weekly threshold for a 70 kg adult (see Table 3). A comparison to Maine CDC's PFOS criteria [46] found one sample of lobster organs exceeded Maine's one meal per week threshold (3.5 ng/g) but not the two meals per month threshold (7.5 ng/g), while a comparison to New Hampshire's screening levels [45] found PFOS exceeded screening levels for adults (organs) and children (organs and tail muscle).

Despite relatively low concentrations of many of the contaminants detected in shellfish tissues, the levels of PFOS in both lobster muscle and viscera are a concern, especially since elevated levels of mercury reported in 2018 [13] warranted the addition of spiny lobster (tail muscle) to the State of California's San Diego Bay consumption advisory, which recommends no more than one serving per week [14]. In addition, there remains much uncertainty about the additive or synergistic effects of multiple contaminants, even those that individually fall under dose or consumption limits [49–51]. Further, contaminant concentrations and therefore exposure risk can be variable in space, time and with species [19,52–55]. This variability was seen with PBDEs in 2014–2015 when they were detected (and exceeded thresholds) in only 1 of 32 samples (2 whole lobster and 30 lobster tail samples) and in 2018–2019 when they were detected in each of the 2 crab samples but were at or below the detection limit in spiny lobster. Shellfish harvest and consumption patterns, including the timing, amounts and frequency of harvest and consumption and preparation methods, all also influence contaminant exposure risks.

Using the same inputs for consumption rate and body weight as PFOS, all the samples fell below the published EFSA daily intake for organotins (250 ng/kg body weight/day), as well as the European Union threshold for tributyltin fish tissue (7 ng/g, [44]), which is consistent with findings for other countries where organotins have been banned from use [56]. Low risk is also likely for butylbenzyl phthalate and phosphate flame retardants. A risk evaluation for butylbenzyl phthalate is underway [57], but there is a daily oral dose limit of 1.2×10^9 ng/day for a 58 kg woman [58]. Reference doses of phosphate flame retardants inhaled via dust include tris-(2-chloroethyl) phosphate at 22,000 ng/kg body weight/day and tris-2-chloroisopropylphosphate at 80,000 ng/kg body weight/day [59]. The tissue results were four to five orders of magnitude lower in spiny lobster and crabs than any dose-based weekly consumption threshold for either pollutant (one–three meals per week). The maximum concentration of caffeine detected in spiny lobster was six orders of magnitude lower than one 8 oz-cup of coffee (95 mg), with about four cups of coffee (400 mg) per day considered safe for adults [60].

Table 3. Calculated mass loads of contaminants in individual California spiny lobster, rock crab and spider crab muscle + viscera and muscle only collected from San Diego Bay during October 2018 and March 2019 (this study) and throughout 2014–2015 as presented in [13]. Concentrations of anthropogenic debris are number of pieces per whole individual (N = 10 lobster, N = 1 each of the crab species), and contaminants are ng/individual wet weight (2018–2019: N = 4 composite samples of 2–3 individuals each, 2014–2015: 2 whole lobster samples (1 composite of 4 individuals and 1 individual) and N = 30 tail-only samples (30 individuals)). The 2018–2019 mass load contaminant concentrations were estimated by averaging viscera and muscle contaminant concentrations and multiplying those by the amount of each tissue harvested from each lobster. The 2014–2015 mass load concentrations were estimated by multiplying the concentration of each contaminant (ng g wet weight) by an estimate of the weights of viscera (5.5% or 32 g) and muscle (25% or 142 g) from a whole, shelled 1.25 lb (567 g) individual. Only the total Hg concentrations for 71.9–86.9 mm length spiny lobster were used to keep concentrations comparable to the individuals used for other contaminant analyses. The OEHHA seafood consumption advisory levels [14] are indicated by color and notation when contaminant concentrations exceed a threshold value.

	California spiny lobster						**yellow rock crab**		**spider crab**	
	viscera + muscle			**muscle only**			**viscera + muscle**	**muscle only**	**viscera + muscle**	**muscle only**
	avg	±1SD	max	avg	±1SD	max				
	2018-2019									
Anthropogenic debris †	19	40	130		--		3	--	5	--
Benzylbutyl phthalate †*	10958	8899	19500	9791	7964	19500	9304	9304	ND	ND
Caffeine †	138	276	553	138	276	553	ND	ND	ND	ND
DEET †*	ND			ND			ND	ND	ND	1106
Galaxolide †	24	47	94	24	47	94	155	155	ND	ND
Organotins †*	149	138	334	57	77	164	ND	ND	ND	ND
Pyrethroids †	316	350	809	162	189	354	ND	ND	ND	ND
PFOs †*	134	131	264	61	72	140	ND	ND	ND	ND
Phosphate Flame Retardants †*	38	77	153	38	77	153	210	210	ND	ND
PBDEs	7	6	12	7	6	12	92 [3]	ND	1389 [0]	388 [1]
2014-2015	**whole individual**			**muscle (tail) only**						
PBDEs	69277 [1]		69277 [1]	0						
PCBs	3970 [3]	18.0	7543 [2]	1590	45	1679	--	--	--	--
Chlordanes	349.00		349.36	0			--	--	--	--
Silver	180635		180635		--		--	--	--	--
Arsenic	10222750		10222750		--		--	--	--	--
Cadmium	206440 [0]		206440 [0]	553		14	--	--	--	--
Chromium	260035		260035		--		--	--	--	--
Copper	41883500		41883500		--		--	--	--	--
Manganese	369210		369210		--		--	--	--	--
Nickel	123070		123070		--		--	--	--	--
Lead	23820		23820	142		4	--	--	--	--
Selenium	837670 [0]		837670 [0]	187176	110179	375770 [2]	--	--	--	--
Zinc	23423000		23423000	--			--	--	--	--
Mercury		--		30771 [2]	12478	56862 [1]	--	--	--	--

OEHHA advisory (based on concentrations (ng) per g wet weight)	
[0]=no consumption advised	† = no OEHHA seafood consumption guidelines available
[1]= 1 serving/week limit	* = other dose guidelines exist
[2]= 2 servings/week limit	-- = no data
[3]= 3 servings/week limit	ND = not detected
no notation= no serving limit	

4.2. Who Is Shellfishing?

Shellfishing makes up a relatively small proportion of pier fishing in San Diego Bay both throughout the year and throughout the fall and winter (6% and 10% of all people fishing on piers, respectively). The people who shellfish are a fairly representative cross section of adults in San Diego, with self-identified race and ethnicity broadly reflecting city-wide data [30] and home zip codes located throughout the city (and greater metropolitan area) [29]. For most, the motivations for fishing are primarily focused on recreation and then eating the catch as supplemental food, not fishing out of necessity. The relatively low numbers of people shellfishing and their likely middle-class economic status may be due in part to the time and expenses associated with the gear (hoopnets) and, if people were seeking spiny lobster, the fishing license and report card (while no license is needed for pier finfishing).

4.3. Patterns of Shellfish Harvest and Potential Exposure

Despite the many species of crab that are present in the bay and the year-round season [29], crabbing was not as popular an activity as it is farther north (i.e., Dungeness crab territory) and on the east and Gulf coasts of the U.S. (e.g., [61,62]). The lack of popularity may be fueled by a lack of awareness of what crab species there are in the area for harvest, what the rules are for harvest and/or concerns about contamination. While we did not explicitly ask, several people said they were not taking crabs from the bay for food because of contamination concerns; therefore, if conditions were deemed 'safe,' the rate of crabbing would potentially increase (e.g., [63]).

With California spiny lobster season occurring between mid-October and mid-March and the nocturnal nature of these animals, it corresponded that most shellfish harvesting occurred at night during the fall and winter seasons. Further, there was more shellfishing activity at the start of spiny lobster season (fall) than later (late winter), which could influence types and levels of contaminants. For example, phosphate flame retardants and pyrethroids were at higher levels in spiny lobster at Shelter Island in October while tributyltin was higher in March. While sample sizes in this study were small, making it hard to be sure about temporal changes in contaminants, a concurrent study that included the same study locations revealed strong seasonal differences in suites of contaminants in Pacific oyster [19], and spiny lobster prey heavily upon bivalves (e.g., [64], Loflen, personal observation).

Most shellfishing occurred at Shelter Island, making the contaminants there a risk to a greater number of people overall. Although fewer shellfishers were present at the piers at Embarcadero and Pepper Park, there were higher proportions of people of color and those from home zip codes with lower average incomes, making the contaminants in these locations a potentially greater risk to people from these groups.

Consumption patterns also affect exposure. The consumption rates of spiny lobster may be relatively low overall due to low daily catch rates, often three–four lobster, which are then shared with family members and friends, but exposure is undoubtedly higher in nearly half of all people surveyed who fish weekly or more frequently and/or who manage to catch up to the limit of seven individuals during their outings. The study findings confirm a prior evaluation of CDFW lobster report card data for San Diego Bay [13], which found consumption rates to be low on average, but quite high for individuals who more frequently sought lobster in the bay. Exposure to contaminants in the muscle tissue and the viscera were both non-discriminant. Everyone surveyed said they consume lobster muscle. While relatively few (13%) said they directly consume viscera, the confirmation of this consumption is important for pollution management purposes, in addition to the potential acute risk from algal toxins. In addition, over half said they cook the meat and viscera together before consuming muscle, which may increase the chance of exposure to compounds in the viscera as with algal toxins (e.g., domoic acid, saxitoxin; [65]). Collectively, general preparation and consumption patterns were similar across all demographics, meaning all people fishing from these piers face these risks. Therefore, public information and guidelines will need to be accessible, understandable and meaningful to each group, which may require different messaging and modes of communication (e.g., [66]).

4.4. Monitoring Recommendations

This study expanded on previous efforts to characterize shellfish contamination [13,19] and recreational harvest patterns [8] in San Diego Bay through the incorporation of additional species (crab), tissue types (viscera), contaminants (e.g., PFOS) and harvester types (shellfishers/hoop netters). The results indicate a need for the additional monitoring of contaminants, especially PAHs, which have been detected in Pacific oysters and sediments of San Diego Bay [19,67] but were not examined in this study, and emerging contaminants such as perfluoroalkyl substances (PFAS). Assessments are needed to characterize the shellfish harvest and consumption patterns of people who frequent CPFVs as these may differ from those observed on the public fishing piers (e.g., [8,68]). Finally, monitoring should include more species and tissue types of interest to consumers.

Although not as popular as spiny lobster, there are several species of crabs harvested and consumed from the bay and species differences in contaminant exposure, uptake and accumulation can be significant so that relying on the popular crustacean, spiny lobster, to be an indicator of contamination risks may not be sufficient. For example, in this study organotin, pyrethroid and PFOS were only detected in spiny lobster, not the crabs, while DEET was detected in only the spider crab. Differences across broader taxonomic groups may be even greater given that taxonomy may be linked to differences in morphology and physiology (e.g., lipid content, rates of metabolism), lifestyle (e.g., hard vs. soft substrate dwelling), feeding or other functional groups any of which may influence contaminant exposure, uptake, metabolism and accumulation rates (e.g., [18,19,54,69]). This makes the use of commonly used fouling filter feeding shellfish (e.g., mussel, oyster) as indicators even less reliable for indicating potential risks associated with crabs in San Diego Bay, which are bottom-dwelling predators (and occasionally scavengers) [64,70–72]. In a simultaneous study [19], Pacific oyster from San Diego Bay contained many of the same contaminants in the crustaceans (benzylbutyl phthalate, chlordanes, Galaxolide, metals, PCBs, PDBEs, pyrethroids, tributyltin) and some not found in the crustaceans (neonicotinoid pesticides). However, several compounds were detected in the crustaceans that were not detected in Pacific oyster including caffeine, DEET, phosphate flame retardants and PFOS.

Monitoring that focuses on both contamination concentrations in shellfish and the people who are harvesting and consuming shellfish will inform how to prioritize the research of the health effects of common and/or particularly hazardous compounds and the crafting and outreach of consumption guidelines to ensure that they are effective and accessible to the diversity of recreational and subsistence shellfishers using (and potentially using) the coastal resources.

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