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Using acoustic telemetry to quantify potential contaminant exposure of Vermilion Rockfish (*Sebastes miniatus*), Hornyhead Turbot (*Pleuronichthys verticalis*), and White Croaker (*Genyonemus lineatus*) at wastewater outfalls in southern California

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ABSTRACT

Contaminant Exposure Models (CEMs) were developed to predict population-level tissue contaminant concentrations in fishes by pairing sediment-bound contaminant concentrations (DDTs, PCBs) and fine-scale acoustic telemetry data from a habitat-associated species (Vermilion Rockfish, *Sebastes miniatus*), nomadic flatfish species (Hornyhead Turbot, *Pleuronichthys verticalis*), and nomadic benthic/midwater schooling species (White Croaker, *Genyonemus lineatus*) tagged near wastewater outfalls in southern California. Model results were compared to contaminant concentrations in tissue samples. The CEMs developed require further refinement before implementation into management efforts but may act as steppingstones to help shift primary monitoring methods away from the regular field collection of fish for tissue contaminant analyses and towards behavioral modeling and habitat mapping. We also developed Kernel Density Estimates that can be used by managers immediately to identify regions that contribute most to contaminant exposure in species of concern. Prioritizing remediation efforts in these areas are likely to be most effective at improving fish health.

1. Introduction

Contaminants predominantly enter the bodies of animals through environmental or dietary exposure (Barber 2008; Pruell et al., 1993; Rubinstein et al., 1984). Contaminants that are present in animal tissues often reflect not only their environments at the site of capture, but also the environments in which they had been in or foraged in previously. As such, the levels of contaminants in the tissues of species of concern are often used as a proxy of contaminant exposure in these species' presumed environments and prey communities. However, mobile species can select particular habitats and prey items, which decouples the animals' environmental exposure from the average conditions of the environment.

The assumption that species of concern captured at a site reflect the distribution of contaminants within the site is implicit in site-based contaminant monitoring work. However, this assumption is only satisfied if sampled individuals reside at the site. Acoustic telemetry technology can allow documentation of diverse behavioral patterns made by tracked marine species of concern (e.g., fishes). By "tagging" individuals with acoustic transmitters, movement patterns of marine species of concern can be inferred from patterns in transmitter detections via stationed acoustic receivers. For example, Moser et al. (2013) demonstrated that acoustically tagged English Sole (*Parophrys vetulus*) leave an area with high sediment-bound polycyclic aromatic hydrocarbon (PAH) levels, but over half return seasonally, indicating a potential for repeated exposure to PAHs. Taylor et al. (2018) used acoustic telemetry within an estuary with regional differences in contamination levels and found that the spatial distribution of tagged fishes could help predict tissue contaminant concentrations. Both studies employed traditional passive acoustic telemetry, which provides presence information from tagged individuals that are detected by stationary acoustic receivers at a detection efficiency of approximately 250

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m in estuarine environments (Taylor et al., 2018) and 650 m in seawater (Huveneers et al., 2016, Fig. 1A).

Recent advances in acoustic telemetry technology have improved the spatial resolution at which species can be tracked (Espinoza et al., 2011). For example, the VEMCO Positioning System (VPS) uses a grid of acoustic receivers with overlapping detection ranges to triangulate a tagged fish's geolocation within 15 m of accuracy (AMIRIX Systems Inc, 2013, Fig. 1B). Wolfe and Lowe (2015) used an 8 km^2 VPS array to characterize the movement of a roaming species of concern, White Croaker (*Genyonemus lineatus*), around a sediment contaminant hotspot. By comparing the locations of tracked White Croaker to the underlying sediment-bound contaminant concentrations, Wolfe and Lowe (2015) calculated an expected distribution of contaminant exposure that was similar to the distribution of tissue contamination levels from fish sampled across the surrounding areas. This study demonstrated that repeated constrained movements near a contaminant hotspot could potentially explain tissue contamination patterns on a regional scale, even for nomadic species.

The recent availability of movement data with greatly improved spatial resolution could improve the precision with which species of concern can be used as environmental proxies. Understanding a species' fine-scale movements through an area could allow for the identification of key habitats responsible for contamination levels observed in tissue samples. Furthermore, the coupling of movement data and tissue contaminant levels are increasingly important in management areas that are point sources of legacy contaminants and that introduce ecotones (edges) of sand and high-relief structures (e.g., wastewater outfall pipes) that increase the residency and fidelity of structure-associated species. However, inherent to all acoustic telemetry data are irregular time gaps between fish detections (due to changes in receiver detection efficiency over time from environmental conditions like tides or storms) and the degree of spatial error in the predicted locations of individuals. From a management perspective, irregular detections and spatial error could bias the estimates of a species' habitat use or rate of contaminant exposure, which could hinder the efficacy of regulations that are developed from these estimates. In addition, tagged animals are likely to exhibit a range of behavioral patterns throughout the times in which they are being tracked (e.g., rapid, direct transit across an area of interest vs. slow, recurring movements in a habitat or patch consistent with intensive use). This variability has not yet been included in such contaminant monitoring studies.

This study builds on previous work on the movements of species of concern towards increased ecological realism. We use acoustic telemetry data from species of concern that were previously tagged and studied by Wolfe and Lowe (2015) and Burns et al. (2019), who described the movement patterns, habitat use, and site fidelity of these fishes to outfall sites. We employ continuous-time correlated random walk modeling to develop a framework that more accurately predicts contaminant distributions in species of concern, while overcoming the existing issues in the application of fine-scale movement data. Our models account for the irregular time gaps between subsequent acoustic telemetry-rendered detections, spatial error in detected locations, and variation in the predicted behaviors that are exhibited over the course of the study (Fig. 1C). A modeling framework that successfully predicts contaminant distributions in species of concern can initiate a shift away from field-collected tissue samples that must be collected frequently and towards less invasive methods, like movement modeling and habitat mapping. We also use these data to develop kernel density estimates that identify regions within each study site where contaminant exposure is most likely to occur and where remediation efforts may be most effective for improving fish and overall ecosystem health.

2. Methods

2.1. Study sites

Two areas of management were used for this study, the Los Angeles County Sanitation Districts (LACSD) and the Orange County Sanitation District (OC San). The LACSD is located in Carson, California, USA, and serves approximately 5.6 million people in Los Angeles County (LACSD 2019). Four hundred million gallons of wastewater are treated by the LACSD each day to the secondary or tertiary level, depending on the treatment location (LACSD 2019). Los Angeles is a highly industrial area and the LACSD was responsible for the discharge of contaminants from large manufacturers of organochlorines in the mid-1900s (US EPA, 2009; Wolfe and Lowe 2015). Because of the lipophilic nature and the slow degradation of most organochlorine legacy contaminants of concern (e.g., polychlorinated biphenyl [PCB], dichlorodiphenyltrichloroethane [DDT]), these contaminants persist in high concentrations in sediments today even though they are no longer being used or discharged. The LACSD has four operational outfall pipes on the Palos Verdes Shelf. Two regularly active outfalls terminate offshore in 60 m of water and the diffuser portion runs parallel to shore, while two additional outfalls are used occasionally and terminate at shallower depths (33°42′11.543″N, 118°19′42.993″W; Fig. 2). These pipes are surrounded by ballast rock and the Palos Verdes Shelf is comprised mostly of sandy habitats with occasional reef outcroppings (Wolfe and Lowe 2015). The area that is known to have the highest concentrations of sediment-bound contaminants lies between the 20 and 60 m isobaths (Wolfe and Lowe 2015).

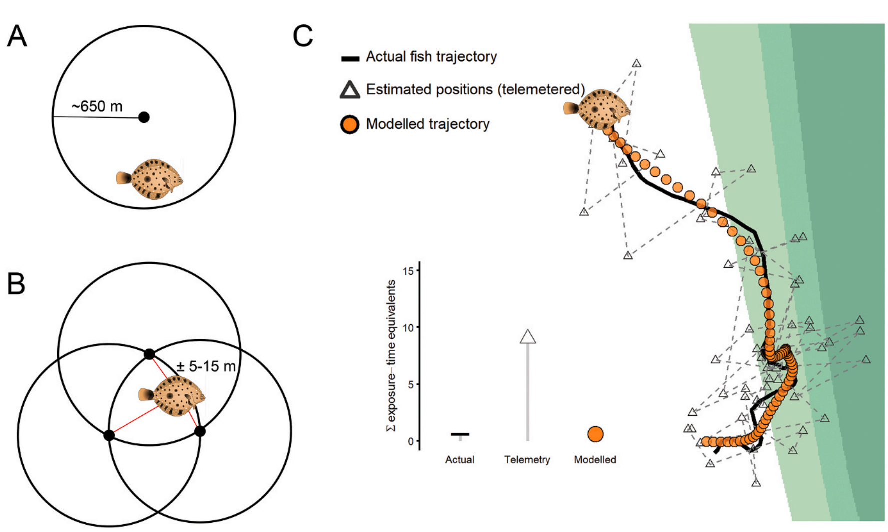

Fig. 1. Advancements in the resolution and predictive potential of acoustic telemetry. A) Acoustic telemetry studies use receivers (black dot) to gather presence data from tagged individuals when they are within detection range (large circle). B) VPS arrays are composed of acoustic receivers that are placed close together so that their detection ranges overlap, which allows for the triangulation of the geoposition of a tagged animal within 15 m accuracy. C) The present study accounts for differences in detection times, positional accuracy, and fish behavior by incorporating a continuous-time correlated random walk model of VPS data to predict contaminant exposure values that more accurately reflect reality.

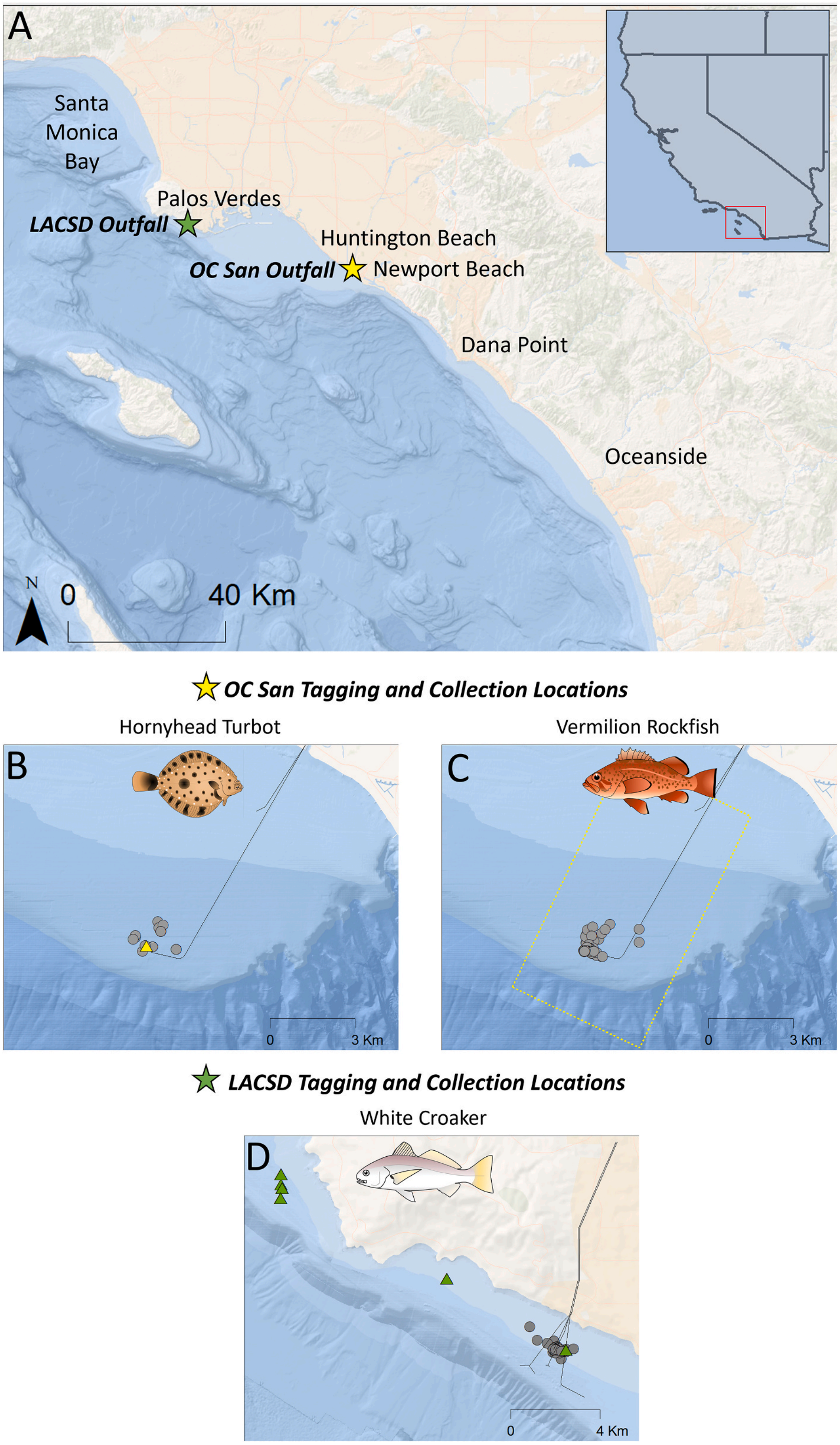

Fig. 2. Study sites and tagging locations. A) Map of the LACSD outfall (green star) and OC San outfall (yellow star) locations off the coast of southern California. Southern California is represented in grey in the top-right corner of the figure, with a red rectangle around the region of California in which the study takes place. B-D) Collection locations of Hornyhead Turbot (B) and Vermilion Rockfish (C) at the OC San outfall site and White Croaker (D) at the LACSD outfall site. Tagging locations are represented by grey circles and colored triangles represent collection locations of fishes for tissue contaminant analyses. Samples of Vermilion Rockfish were collected from various locations within the yellow rectangle for tissue contaminant analyses. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The OC San serves approximately 2.6 million people in the Orange County area of California, USA and treats an average of 190 million gallons of wastewater per day to the secondary level (OC San, 2020). Since Orange County is less industrial than Los Angeles County, sediment-bound concentrations of contaminants are typically under the limit of biological concern (OC San, 2020). In addition, although contaminants are not actively being discharged, they are still present in the bioactive layers surrounding the diffuser region of the OC San outfall (OC San, 2020). The primary outfall has been operational since the 1970s and is located between Huntington Beach and Newport Beach, California, USA (33°34′26.742″N, 117°59′54.987″W; Fig. 2). It extends perpendicular to the coastline for ~7.1 km, terminating at 60 m depth on the San Pedro Shelf. The pipe itself is surrounded by ballast rock in an otherwise sandy habitat and treated wastewater is discharged along the diffuser section of the pipe that runs parallel to the shore (OC San, 2020).

2.2. Study species

Vermilion Rockfish (*Sebastes miniatus*, Class Actinopterygii, Order Scorpaeniformes, Family Sebastidae), Hornyhead Turbot (*Pleuronichthys verticalis*, Class Actinopterygii, Order Pleuronectiformes, Family Pleuronectidae), and White Croaker (*Genyonemus lineatus*, Class Actinopterygii, Order Perciformes, Family Sciaenidae) were chosen for this study because they are targeted for tissue contaminant monitoring by the OC San and the LACSD, as required in their National Pollution Discharge Elimination System (NPDES) permit. In addition, these species differ in their diets, habitat utilization, and movement patterns. Vermilion Rockfish is a demersal species that shows site fidelity and residency to habitats with structural complexity, often leaving their home ranges briefly to form spawning aggregations (Anthony et al., 2012; Kells et al., 2016). This species feeds at high trophic levels (trophic index mean ± SE: 3.9 ± 0.7 [Eschmeyer and Herald 1999]) and can live up to 60 y (fully mature at 9 y of age or 47 cm total length [Love 2011]), which makes individuals particularly susceptible to the bioaccumulation and biomagnification of harmful contaminants. Vermilion Rockfish muscle tissues analyzed by OC San (2020) at the outfall site in the 2018–2019 monitoring period contained mean DDT concentrations of 9.84 μg/kg (range 3.10–16.58) and mean PCB concentrations of 1.62 μg/kg (range 0–3.25). These ranges are below concentrations considered "safe" for human consumption as defined by the State of California Office of Environmental Health Hazard Assessment (<520 μg/kg for DDT for three 8 oz meals per week; < 21 μg/kg for PCB for three 8 oz meals per week; LACSD 2020).

Alternatively, recent research efforts have found Hornyhead Turbot and White Croaker to be nomadic species that use soft-bottom habitats (Burns et al., 2019; Wolfe and Lowe 2015). Hornyhead Turbot were historically abundant at the OC San site and are known to show a close association to sediments by using sand for concealment and foraging (Forsgren et al., 2012). Alternatively, White Croaker have shown historically high catch rates and contaminant loads when collected near the outfalls, which were thought to indicate an association with outfalls and the underlying sediments (Puffer and Gossett 1983). Hornyhead Turbot and White Croaker are still currently considered species of concern in the NPDES permits for the LACSD and OC San, respectively. Both Hornyhead Turbot and White Croaker have shorter lifespans than the Vermilion Rockfish (Hornyhead Turbot: 25 y [Cooper 1992]; White Croaker: 15 y [Moore 1999]) and feed at comparatively lower trophic levels (Hornyhead Turbot: trophic index 3.1 ± 0.32 [Eschmeyer and Herald 1999]; White Croaker: trophic index 3.4 ± 0.49 [Eschmeyer and Herald 1999]). However, Hornyhead Turbot differ from White Croaker in the way they use the water column; Hornyhead Turbot spend most of their time along the seafloor, which may make individuals more susceptible to chronic exposure of sediment-bound contaminants (Love 2011). Alternatively, White Croaker have been found in both benthic and midwater schools, making it more likely that contaminant exposure is driven by consuming demersal prey, such as polychaetes (Ahr et al., 2015). Hornyhead Turbot muscle tissues analyzed by OC San (2020) at the outfall site in 2018–2019 contained safe levels of DDTs (mean: 1.72 μg/kg, range: 0–4.49) and PCBs (mean: 1.62 μg/kg; range: 1.30–2.20). Hornyhead Turbot liver tissues also contained safe levels of DDTs (mean: 99.66 μg/kg; range: 61.90–148.00) and non-detectable levels of PCBs (OC San, 2020). Alternatively, White Croaker muscle tissues that were collected near the LACSD outfalls in 2018–2019 had mean total DDT and PCB concentrations that exceeded "safe" levels (DDT mean: 1950 μg/kg; PCB mean: 554 μg/kg; LACSD 2020). While Hornyhead Turbot are not taken for human consumption, Vermilion Rockfish and White Croaker are often prized by anglers, so high contaminant levels in these fishes may directly impact human health (Kells et al., 2016; Love 2011).

2.3. Acoustic telemetry

Passive acoustic telemetry was used to quantify the fine-scale movement patterns of the study species. Acoustic receivers were deployed in the water column to listen for individuals that had been tagged with acoustic transmitters. Each transmitter emits an ultrasonic signal linked to a unique identification that is detected by nearby receivers. Omni-directional acoustic receivers (VEMCO Ltd./Innovasea, VR2W) were used and placed in a VPS array so that the detection ranges of nearby receivers overlapped. Overlapping receiver ranges allowed a 2D geopositioned estimate (±15 m) of a tagged individual to be derived by comparing the time differences in the arrival of a transmitter pulse emission among adjacent receivers (Espinoza et al., 2011). This system allowed for simultaneous position estimates of all tagged individuals within the array throughout the study. Use of stationary reference transmitters in the array confirmed that transmitters could be consistently detected by multiple receivers that were spaced 500 m apart.

VPS arrays were deployed around the OC San outfall for Vermilion Rockfish and Hornyhead Turbot between 2016 and 2018 (Burns et al., 2019) and around the LACSD outfalls for White Croaker between 2010 and 2012 (Wolfe and Lowe 2015). Each array was deployed prior to fish tagging and remained in place, apart from periodic equipment swaps, until all transmitter battery lives had expired. Each array consisted of 24 acoustic receivers that were placed approximately 500 m apart (Figure S1). The OC San outfall array covered an area of approximately 12.02 km^2 (assuming a detection range of 500 m) at depths between 20 and 60 m (Burns et al., 2019) and the LACSD outfall array covered an area of approximately 8 km^2 at depths between 20 and 70 m (Wolfe and Lowe 2015).

Between February and August 2017, a total of 55 Vermilion Rockfish and 15 Hornyhead Turbot were captured and tagged at the OC San outfall site (Fig. 2B and C) based on their catchability. Vermilion Rockfish were collected using hook and line fishing and were anesthetized using tricaine methanesulfonate (MS-222; 100 mg/L seawater) prior to the surgical implantation of an acoustic transmitter (transmitter family V9-2x-069k-1, 9 mm diameter, 29 mm length, 2.9 g in water, power output 151 dB, pulse delay 100–180 s, battery life ~395 d) in the peritoneal cavity. Incisions were closed using absorbable sutures with two stitches. Fish were allowed to recover before being released at depth using a SeaQualizer pressure-activated descending device (Burns et al., 2019). Hornyhead Turbot were collected by otter trawls deployed at 5-min intervals and fish were externally tagged due to the small size of this species' peritoneal cavity (Burns et al., 2019). Acoustic transmitters (transmitter family V9-2x-069k-1, 9 mm diameter, 29 mm length, 2.9 g in water, power output 151 dB, pulse delay 100–180 s, battery life ~395 d) were each epoxy-glued to a Peterson disc (1 cm diameter) and a nickel alloy pin, which was inserted through the eyed-side of the fish below the dorsal branch of the lateral line and secured on the underside (Burns et al., 2019).

Between July 2010 and August 2011, a total of 82 White Croaker were captured using hook and line along the Palos Verdes Shelf (Fig. 2D) and were anesthetized using MS-222 (200 mg/L seawater) prior to the surgical implantation of an acoustic transmitter (transmitter family V9-1L, 9 mm diameter, 24 mm length, 2.2 g in water, power output 146 dB, pulse interval 50–130 s, battery life 236 d) into the peritoneal cavity. Incisions were closed using absorbable sutures with one to three stitches and fish were released after they had recovered from the anesthetic (Wolfe and Lowe 2015).

Differences in sample sizes across species are a result of local species abundances and catchability. Vermilion Rockfish and White Croaker were abundant in the OC San and the LACSD study sites, respectively, and were easy to catch using hook and line. Alternatively, Hornyhead Turbot appear to show local population declines at the OC San study site and were more difficult to capture using otter trawls, which collect a variety of species along the seafloor. All fish handling and tagging methods were approved by the California State University, Long Beach

Institutional Animal Care and Use Committee and are more thoroughly described in Burns et al. (2019) and Wolfe and Lowe (2015).

2.4. Data quality assurance

VPS positions are accompanied by a unitless measurement of horizontal position error (HPE), where larger HPE values represent location fixes with relatively low positional accuracy (Smith 2013). HPE values greater than 15 were removed from the dataset prior to analyses, as described by Burns et al. (2019). Positional data from the first 24 h after tagging were removed to reduce biases associated with tagging stress (Lowe et al., 2009; Papastamatiou et al., 2015). In addition, any fish that were thought to have died as a result of tagging, fishing, or predation, or any transmitters that appeared to have fallen off were removed from analyses (Figure S2; Burns et al., 2019). These protocols resulted in available acoustic telemetry datasets for 37 Vermilion Rockfish, 14 Hornyhead Turbot, and 48 White Croaker (Table S1).

2.5. Position interpolation

Locations between VPS positions were interpolated every 2 and every 5 min using a continuous-time correlated random walk model (*crwMLE*) with the *crawl* package (Johnson and London 2018; Johnson et al., 2008) in R (R Development Core Team, 2017), similar to the methods used by Bacheler et al. (2019). Two min was chosen based on the specifications of the coded transmitters, which have a nominal pulse delay of ~120 s. Five min was chosen as a proxy to simulate instances of greater variation in receiver performance, when detections may not be picked up as frequently due to changing environmental conditions. If consecutive VPS rendered positions were more than 2 h apart, positions were not interpolated. Two h was arbitrarily chosen as a conservative threshold with the assumption that the fish had left the study site and was not simply on the edge of the array, just outside of receiver coverage. To build a *crawl* model, parameter estimates of *tau* (location error variance), *beta* (autocorrelation parameter), and *sigma* (velocity variability) were optimized to allow the model to estimate the error of each unitless HPE class. HPE values were first grouped into 4 bins and converted to factors. Models were then run with a movement model parameter of ~1 and an error model of *list(x=~1)*. Models were run initially without priors and the resulting estimates of *tau* and *beta* were used as a starting point for defining appropriate prior distributions for the final models. Priors were defined for *tau* and *beta* for each species using an exhaustive search, but *sigma* was estimated by the model itself (London 2018). Model parameters that produced consistent *crawl* results (at least 6 runs per individual showing similar outputs) were selected for use in the final interpolation model (Supplementary Materials). Results from the *crawl* models were visually assessed on an individual basis and models were re-run if the results showed large inconsistencies.

2.6. Sediment-bound contaminants

The OC San collects sediment samples at 29 locations semi-annually during the summer (July–September) and winter (December–February) months, and at an additional 39 stations annually during the summer months. Samples are collected using a paired 0.1 m^2 Van Veen grab sampler and the top 2 cm of collected sediment are used for grain size and chemical and toxicity analyses (OC San, 2018). Concentrations of several organochlorines and metals are measured, including total (all congeners of) DDT and total PCB. Data from the summer sampling periods between 2013 and 2016 were obtained from the OC San. There was a high degree of variability in the sediment-bound contaminant concentrations for 3 of the 29 semi-annual sampling sites across the years. Therefore, data were averaged across years for each site prior to kriging.

Sediment contaminant maps were created from the OC San sampling locations close to the diffuser region of the outfall ($n = 33$) for total PCB and total DDT concentrations using ordinary kriging methods in ArcGIS Desktop Version 10.5.1. Kriged maps were clipped in ArcGIS to only include regions that overlapped with receiver coverage (Fig. 3A).

For the LACSD study site, sediment-bound concentrations of carbon-normalized DDTs were analyzed from the 0–8 cm sediment layer sampled across 59 locations along the Palos Verdes Shelf in 2009. Thirty-four of these locations were regularly sampled by the LACSD prior to the 2009 study to meet monitoring compliance guidelines. An additional 25 locations were sampled near the outfalls to provide higher spatial frequency of sediment-bound contaminants (ITSI-Gilbane and Smith 2013). Once considered one of the highest contaminated marine sediments in the USA, recent data have indicated a substantial reduction in the contaminant loads (non-detectable concentrations of DDT in the northeast [Whites Point] region of the outfalls since 2002 and PCBs since 1985) in the bioactive layer likely due to sediment burying (US Army Corps of Engineers, 2019). Sediment contaminant maps for the LACSD study site were obtained from ITSI-Gilbane and Smith (2013) (Fig. 3B).

2.7. Field-collected tissue contaminants

The OC San collects fishes for bioaccumulation analyses at the outfall site and at non-outfall sites on an annual basis (OC San, 2020). Individuals collected at these sites are typically sacrificed and taken to the lab, where liver and/or muscle tissue samples are excised and analyzed for a variety of contaminants and metals, including total PCB and total DDT. Data from fish collected near the outfall were provided by the OC San for the 2016–2017 and the 2017–2018 sampling periods. A total of 16 muscle samples from Vermillion Rockfish and 20 liver samples and 20 muscle samples from Hornyhead Turbot were used for comparison of model outputs in the present study (Fig. 2B and C). Fish that were sampled for bioaccumulation analyses were not the same as those that were fitted with acoustic transmitters.

The United States Environmental Protection Agency and National Oceanic and Atmospheric Administration led a multi-purpose survey of contaminants within marine fishes along southern California in 2002–2004. DDT concentrations (calculated from the wet weight of sampled individuals) were analyzed from the muscle tissues of 45 White Croaker collected at the Palos Verdes Shelf near the LACSD study site as part of the 2002–2004 study (Fig. 2D, DIVER 2020). These samples were used for comparison of model outputs in the present study.

2.8. Behavioral modeling

Because different behaviors may influence the degree of exposure to sediment-bound contaminants, behaviors of individuals were classified into three categories: non-moving, "random" (non-directional) movement, and directional movement. Step lengths and turning angles were calculated from the interpolated dataset (*crawl* dataset) for each individual using the *moveHMM* package (Michelot et al., 2016) in R. If a VPS position was collected more than 2 h after the previous position, the turning angle and step length were reset to null values to avoid any biases or extreme values that may result from large gaps in data (Bacheler et al., 2019). The 2 h threshold was chosen to maintain consistency with the *crawl* interpolation methods. Behaviors were classified using two different rate of movement thresholds (1 m/min, 3 m/min) between positions. If the distance between two subsequent locations was less than the orthogonal distance that would be traveled by moving at a rate of 1 m/min or 3 m/min, the animal was "non-moving". If the distance traveled exceeded this threshold, the animal was categorized as moving. If the animal was moving in the same direction ($\pm 45^\circ$) for ≥ 3 time steps, the animal was assigned as exhibiting "directional movement," otherwise, it was assigned as exhibiting "non-directional movement".

2.9. Contaminant Exposure Models (CEMs)

CEMs were calculated based on time-area metrics, similar to those

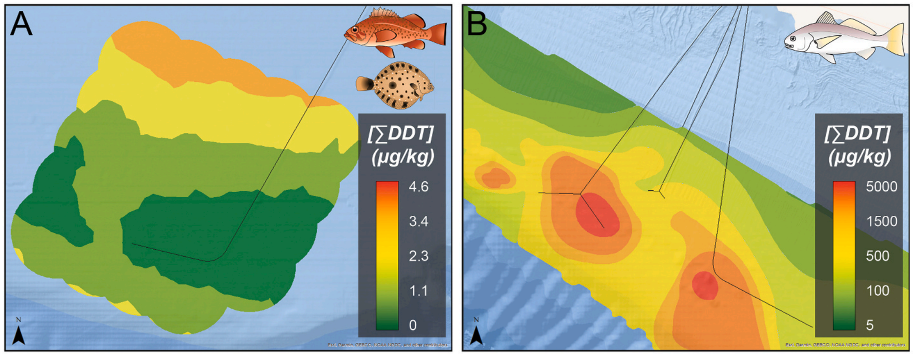

Fig. 3. Sediment-Bound DDT Contaminant Maps. A) Contaminant map developed for the OC San site, which was used in analyses for Vermilion Rockfish and Hornyhead Turbot. B) Contaminant map developed for the LACSD site, which was used in analyses for White Croaker. Contaminant maps for PCB concentrations at the OC San site can be found in the Supplementary Materials.

described by Wolfe and Lowe (2015). Two versions of CEMs were calculated for each model run: one that used interpolated positions only (positional data only) and one that combined interpolated positions with behavioral classification data. For CEMs that used only positional data, the potential for contaminant exposure at any given location was equal to the sediment-bound concentration of the contaminant. For models that used a combination of positional and behavioral data, the degree of potential contaminant exposure was arbitrarily scaled based on behavioral classification. If an individual was classified as exhibiting periods of "non-moving", the potential of contaminant exposure was equal to the sediment-bound concentration of the contaminant; little to no movement indicates the individual could be in close association to the sediment. If an individual was classified as exhibiting periods of "non-directional movement", it was arbitrarily assigned a potential of contaminant exposure that was equal to one half of the sediment-bound concentration of the contaminant; non-directional movement may indicate the fish is feeding and actively interacting with the sediment, or that the fish is moving along or above the seafloor in response to other environmental cues. If an individual was classified as exhibiting periods of "directional movement", it was assigned a potential contaminant exposure value of 0; the fish appears to be moving in a particular direction and is probably not foraging or directly accessing sediment-bound contaminants (Barraquand and Benhamou 2008). If a fish's position was rendered outside of the kriged contaminant map, it was assigned a contaminant exposure value of 0 for that time step. Total contaminant exposure was calculated as the sum of contaminant values at each rendered position. Because results from CEMs were going to be compared to field-collected tissue samples, which are not temporally explicit, CEM results were not converted to a standardized temporal scale (e.g., contaminants accumulated per y). CEM results were grouped by species and model (8 per species per contaminant, using all possible combinations of data interpolation [every 2 or 5 min], rate of movement threshold [1 m/min, 3 m/min], use or disuse behavioral scaling) for analyses.

2.10. Data analyses

2.10.1. Distribution Fitting

Each CEM run (predicted tissue contaminant concentrations) and each field-collected contaminant dataset (observed tissue contaminant concentrations) was scaled for direct comparison. Values were scaled using the median of each dataset. Results from scaled CEMs and field samples were fit to several different distributions, including gamma, normal, exponential, and logistic functions. Data were fit to these distributions using the *fitdist()* function from the *fitdistrplus* package in R using the moment matching estimation method (Delignette-Muller and Dutang 2015). This method was chosen for two reasons: it is computationally efficient and it is centered around the central limit theorem (Han et al., 2018). Since our sample sizes are relatively small, using the moment matching estimation method should be suitable for approximating distribution parameters that can be refined as more data are collected. The "best" model was chosen for each set of data by comparing the Akaike Information Criterion (AIC) values of subsequent models, but Bayesian Information Criterion (BIC) and log-likelihoods were also examined; overfit models (infinite AIC or BIC scores) were excluded.

Fitted distributions were compared across CEMs and compared to field samples for each species and each contaminant. Distributions were arbitrarily considered similar if the "best" model was of the same distribution and if the values of estimated parameters were similar (within 10% of each other).

2.10.2. Distribution comparisons

A second analysis was conducted to determine whether CEM results were comparable to field-collected contaminant concentrations. Frequency distributions were first scaled by the median of the dataset. The scaled dataset was then converted to *z*-scores using the theoretical mean and standard deviation of the best fit model from the *Distribution Fitting* section. *Z*-scores from each CEM distribution were compared to *z*-scores from field-collected contaminant distributions using Kolmogorov-Smirnov (KS) tests.

2.10.3. Kernel Density Estimations

To determine key areas that may contribute most to contaminant exposure, spatial Kernel Density Estimations (KDEs) were generated using all data for each species via *sp.kde()* in the *SpatialEco* package in R (Evans 2020). KDEs can be particularly useful in site-based management efforts, allowing managers to prioritize remediation of areas that show high overlap with animal space use. Locations for the KDEs were derived from *crawl* models (interpolation rates of 2 or 5 min) and were weighted by their sediment-bound contaminant concentrations; behavior classification was not included.

3. Results

3.1. Residency

Specific movement patterns and habitat associations of Vermilion Rockfish and Hornyhead Turbot tagged at the OC San site have been thoroughly described in Burns et al. (2019) and are briefly described below. Over the course of the one-year study, Vermilion Rockfish showed a mean residency (days detected/days at liberty ± standard error [SE]) of 0.414 ± 0.044 at the OC San site, with 97.3% of individuals detected within the site for >10 d (max date detected – min date detected) and 67.6% of individuals detected within the site for >100 d (Table S1). Most individuals remained in relatively small areas (mean area of 0.002 [daytime] - 0.013 [nighttime] km^2) near the diffuser region of the outfall where they were tagged (Fig. 2C). Alternatively, Hornyhead Turbot showed a mean residency of 0.127 ± 0.008, with 92.9% of individuals detected within the site for >10 d and 42.9% of individuals detected within the site for >100 d (Table S1). Hornyhead Turbot spent most of their time using similarly small areas (mean area of 0.002 [daytime] - 0.004 [nighttime] km^2) near the diffuser region of the outfall where they were tagged (Fig. 2B) and in the sandy regions immediately north of the outfall before swimming out of the VPS array.

The movement patterns of White Croaker tagged at the LACSD site have been previously described in Wolfe and Lowe (2015) for 83 tagged white croaker. The subset of fish used in the present study ($n = 48$) showed a mean residency of 0.077 ± 0.014 (Table S1), with 64.6% of individuals detected within the site for >10 d and 14.6% of individuals detected within the site for >100 d. When in the LACSD array, areas close to the LACSD active outfall pipes (depths 30–50 m) and areas close to where individuals were tagged (depths 25–35 m, Fig. 2D) were used most extensively by White Croaker (Wolfe and Lowe 2015).

3.2. Behavioral modeling

The distributions of behavioral categories for Vermilion Rockfish and Hornyhead Turbot were similar across all CEM runs. More than 95% of all Vermilion Rockfish and 98% of all Hornyhead Turbot behavior classifications were non-moving (Fig. 4A, D). White Croaker, on the other hand, showed different distributions of behaviors among CEMs. The greatest distribution of behavioral classifications was achieved when locations were interpolated at 2 min intervals and the rate of movement threshold was 1 m/min (Fig. 4G). To reduce redundancy and maintain consistency among species, we will only discuss results from CEMs that were scaled by behavior and run with these parameters; results from all other CEM runs can be found in the Supplementary Materials.

3.3. Distribution Fitting

PCB concentrations in fish tissues were most often recorded as zeros (non-detects), which made statistical comparisons to CEMs difficult. CEM results for PCB predictions can be found in the Supplementary Materials. DDT concentrations in fish tissues were able to be compared to CEM results and are described below.

3.3.1. Vermilion Rockfish

The distribution of scaled DDT concentrations in the 16 Vermilion Rockfish muscle samples best fit the gamma distribution with parameter estimates of $shape = 2.36$ and $rate = 1.78$ (Table 1, Fig. 4B). CEM results best fit the exponential distribution function with a *rate* parameter of 0.79 (Table 1, Fig. 4C).

3.3.2. Hornyhead Turbot

The distribution of scaled DDT levels in the liver samples collected from 20 Hornyhead Turbot best fit the exponential distribution with a *rate* parameter estimate of 0.69 (Table 1, Fig. 4E). Scaled DDT levels in the muscle samples best fit the normal distribution with parameter estimates of $mean = 0.90$ and $sd = 0.50$ (Table 1, Figure S5). CEM results best fit the exponential distribution with an estimated *rate* parameter of 0.71, which was similar (<10% different) to that of the liver samples collected by the OC San (Table 1, Fig. 4F).

3.3.3. White Croaker

Scaled DDT concentrations in muscle samples from 45 White Croaker best fit the exponential distribution with an estimated *rate* parameter of

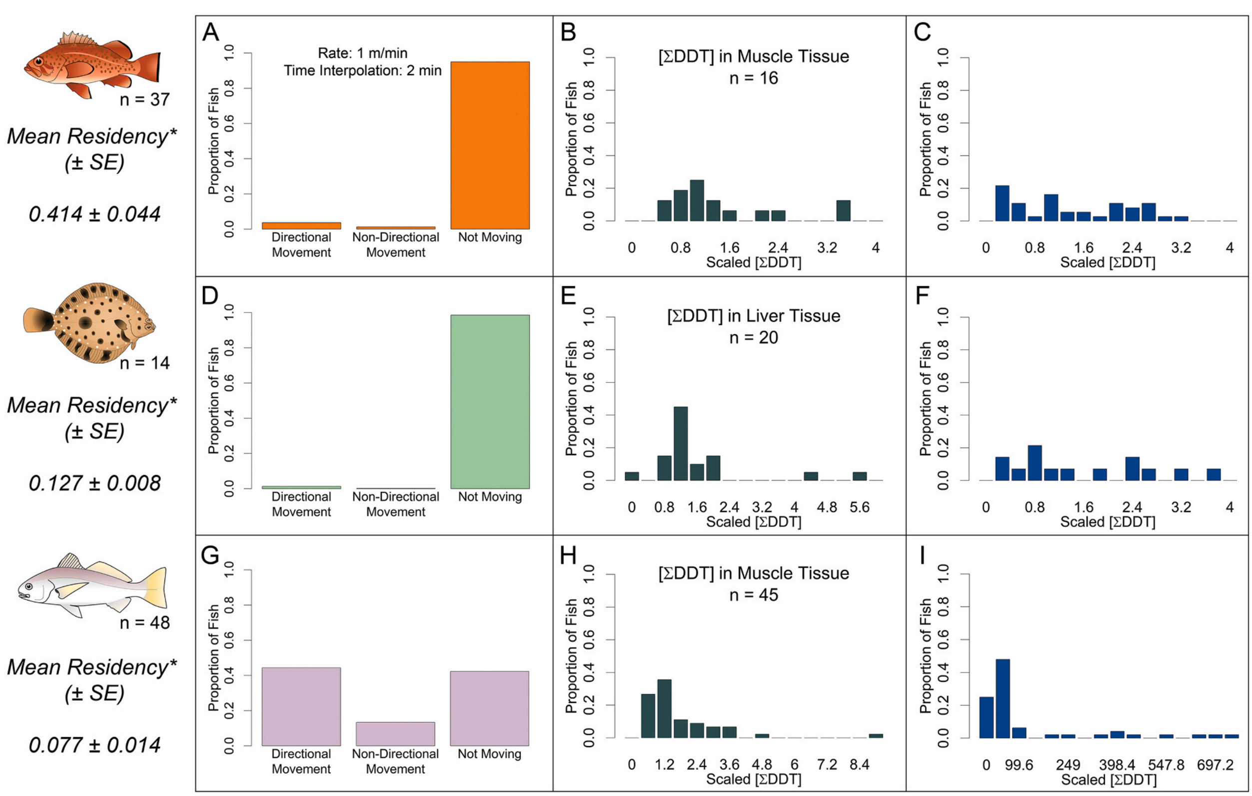

Fig. 4. CEM results. Behavioral classifications were derived for A) Vermilion Rockfish, D) Hornyhead Turbot, and G) White Croaker using a rate of movement threshold of 1 m/min and an interpolation period of 2 min. Behavioral classifications were incorporated into CEMs and used to predict DDT concentrations in each of these species (C, F, I). The CEM-derived distributions were compared to the distributions of field-collected tissue samples (B, E, H). *Mean residencies were reported by Burns et al. (2019) for Vermilion Rockfish and Hornyhead Turbot and were calculated from a subset of White Croaker tagged by Wolfe and Lowe (2015). Results for all other model runs can be found in the Supplementary Materials.

Table 1
Best-fit distributions for DDT concentrations. Best fit distributions and parameter estimates for Vermilion Rockfish, Hornyhead Turbot, and White Croaker DDT concentrations derived from CEMs and field-collected tissue samples. Data were first scaled by dividing by the median. The best model was chosen based on the lowest AIC score. The results displayed are from CEMs run with a 2 min interpolation, 1 m/min rate of movement threshold, and behavioral data included. Results from all model runs can be found in the Supplementary Materials.

Species	Data Source	Distribution	Parameter	Parameter Estimate	AIC	BIC	Log Likelihood
Vermilion Rockfish	*Muscle Tissue*	*Gamma*	*shape*	*2.36*	*37.88*	*39.43*	*−16.94*
			rate	*1.78*			
	CEM	Exponential	rate	0.79	93.60	95.21	−45.80
Hornyhead Turbot	*Muscle Tissue*	*Normal*	*mean*	*0.90*	*32.86*	*34.85*	*−14.43*
			sd	*0.50*			
	Liver Tissue	*Exponential*	*rate*	*0.69*	*56.58*	*57.58*	*−27.29*
	CEM	Exponential	rate	0.71	39.55	40.19	−18.77
White Croaker	*Muscle Tissue*	*Exponential*	*rate*	*0.69*	*125.88*	*127.69*	*−61.94*
	CEM	Exponential	rate	0.01	540.07	541.94	−269.03

0.69 (Table 1, Fig. 4H). CEM results best fit the exponential distribution with an estimated *rate* parameter of 0.01 (Table 1, Fig. 4I).

3.4. Distribution comparisons

3.4.1. Vermilion Rockfish

The CEM distribution for DDT concentrations in Vermilion Rockfish showed no statistical difference compared to the distribution of the contaminant within the muscle samples collected by the OC San (KS test, $D = 0.2382$, $p = 0.55$, Table 2). Although the distributions were similar, visual assessment of the scaled concentration distributions indicated that the CEM appears to overestimate both high (>1.6 scaled bin) and low (within the 0.2 scaled bin) DDT concentrations but underestimates low to moderate concentrations (within the 0.4–1.6 scaled bins) in field-collected muscle samples (Fig. 4B and C).

3.4.2. Hornyhead Turbot

There was no significant difference in the distribution of DDT concentrations between liver and muscle samples ($D = 0.25$, $p = 0.56$). Scaled CEM distributions for DDT in Hornyhead Turbot and the actual distribution of DDTs in liver samples were not statistically different ($D = 0.3286$, $p = 0.27$, Table 2). Visual assessment of the scaled concentration distributions indicated that the CEM was able to predict the range of DDT concentrations that were present in liver samples but overestimated high and underestimated low DDT concentrations (Fig. 4E and F). There was also no significant difference in distributions when the CEMs were compared to DDT concentrations within the muscle samples ($D = 0.2071$, $p = 0.87$, Table S4; Figure S5).

3.4.3. White Croaker

The scaled CEM distribution for DDT concentrations in White Croaker was significantly different than the distribution of DDT concentrations within the muscle samples ($D = 0.6667$, $p < 0.0001$, Table 2). Visual assessment of the scaled concentration distributions indicates that the CEM consistently overestimated high DDT concentrations in White Croaker muscle samples (up to 697 for scaled CEM results vs. 8.4 for muscle samples, Fig. 4H and I). The CEM also appeared to overestimate the zeros present in scaled DDT concentrations from muscle samples.

Table 2
Differences in model predicted and field collected DDT distributions. Results from Kolmogorov-Smirnov tests that compared the distributions generated from CEMs to field-collected samples. Data were scaled individually for each dataset by the median. The results displayed are from CEMs run with a 2 min interpolation, 1 m/min rate of movement threshold, and behavioral data included. Results from all model runs can be found in the Supplementary Materials.

	CEM vs [Tissue] Distribution		
Species	*D*	*p-value*	Tissue Type
Vermilion Rockfish	0.2382	0.5506	Muscle
Hornyhead Turbo	0.3286	0.2713	Liver
White Croaker	0.6667	**< 0.0001**	Muscle

3.5. Kernel Density Estimations

KDE results were relatively similar across 2 and 5 min *crawl* intervals. Below, we describe the results for KDEs run at 2 min intervals, but the results from KDEs run at 5 min intervals can be found in the Supplementary Materials.

For Vermilion Rockfish, KDE results indicated that the terminus of the diffuser region of the OC San outfall likely contributes the most to population contaminant exposure (Fig. 5A). Sediment-bound contaminant concentrations in this area were less than 1.1 μg/kg (Fig. 5A). The highest KDE values for Hornyhead Turbot began near the tip of the diffuser region of the OC San outfall and extended towards the northern edge of the outfall array, where sediment-bound DDT concentrations were less than 1.1 μg/kg (Fig. 5B). White Croaker showed the highest KDEs near the northern edge of the receiver array on the Palos Verdes Shelf, where sediment bound DDT concentrations were relatively low (<200 μg/kg, Fig. 5C).

4. Discussion

4.1. Acoustic telemetry and predicting contaminant concentrations

Passive acoustic telemetry data have shown potential in explaining contaminant exposure across a variety of different species to enhance habitat monitoring and aquatic toxicology research (Brooks et al., 2017; Hellström et al., 2016; Taylor et al., 2018; Wolfe and Lowe 2015). Our results indicate that while acoustic telemetry may be a useful contribution to CEMs, additional ecological and environmental parameters are needed to predict contaminant concentrations more accurately, especially for fish populations across different habitats, life history traits, and movement patterns. We propose that the differences between expected and observed values can be attributed to a combination of environmental and biological factors, as well as experimental design challenges. Such challenges include the small sample size for muscle and liver samples in Hornyhead Turbot and muscle samples in Vermilion Rockfish, short duration of the study periods due to transmitter battery life, positional accuracy of VPS data, and the time difference between collection of acoustic telemetry and field-collected tissue contaminant data.

Due to the lipophilic nature of organochlorines like DDTs, one would expect that tissues with higher lipid content would exhibit higher contaminant concentrations. When examining the data associated with field-collected samples, we found that the lipid concentration (%) in the Hornyhead Turbot liver samples was 4.20 ± 3.94 (mean ± standard deviation [SD]) compared to 0.04 ± 0.11 percent lipid in muscle samples. Differences in lipid content may explain why the best fit

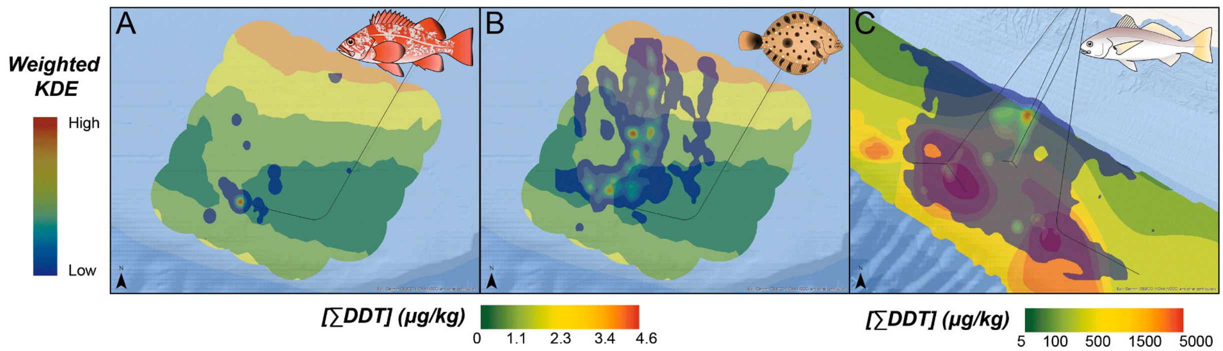

Fig. 5. Kernel Density Estimations. Kernel Density Estimations for A) Vermilion Rockfish, B) Hornyhead Turbot, C) and White Croaker, weighted by the underlying sediment-bound contaminant concentrations of DDT. Positions were interpolated using the *crawl* model at 2 min time intervals. Results from positions interpolated at 5 min can be found in the Supplementary Materials.

distributions were similar for DDTs in Hornyhead Turbot liver samples and CEM results. However, this does not explain the statistically similar results from KS tests between Vermilion Rockfish muscle tissues (1.22 ± 0.85 percent lipid) and the CEM. Sample sizes were low for tissue-contaminant analyses for these species (20 Hornyhead Turbot, 16 Vermilion Rockfish) and for Hornyhead Turbot telemetry data (14 Hornyhead Turbot), so it is possible that more samples would improve the predictive power of CEMs for different analyzed tissues.

Lipid content is unlikely to be the sole driving factor of contaminant concentrations in fish tissues, especially in models that account for the movement of fish in relation to the spatial distribution of contaminants. We posit that a second driver may be the distribution of sediment-bound contaminants themselves. Sediment-bound concentrations of DDT were relatively uniform across the OC San site and were substantially lower than those around the LACSD site, which has more outfalls and has historically discharged larger volumes of contaminants. Species that spend time in homogenous contaminant fields are more likely to accumulate similar concentrations of contaminants regardless of where they are within the study site and which behaviors they are exhibiting. Therefore, CEMs developed for these regions are likely to be more robust to positional error. The VPS positioning is theoretically within 15 m of the true location of the animal (AMIRIX Systems Inc, 2013). If sediment-bound contaminants are evenly distributed, a change in 15 m is unlikely to result in an animal being exposed to significantly different contaminant fields. Alternatively, CEM outputs could be affected if sediment-bound contaminant concentrations change drastically across small spatial scales, like the LACSD outfall pipes that are close together and retain contaminants for longer periods of time while also providing suitable foraging habitats.

Another explanation for differences in CEM results and field-collected samples may stem from the vast differences in prey items, habitat association, and movement patterns of the species studied. Hornyhead Turbot typically spend most of their time near the seafloor and have a diet that consists primarily of invertebrates buried in the sand (Cooper 1992; Love 2011; Manzanilla and Cross 1982). This species is also nomadic in nature, with individuals staying in the study site for ~2 mo before leaving (Burns et al., 2019). Therefore, contaminants within Hornyhead Turbot tissues may have been acquired from areas outside the study site, and likely reflect contaminant concentrations in the greater Southern California Bight. In general, the LACSD and the OC San monitor benthic community structure within their study sites, but do not directly test the contaminant levels within invertebrates (OC San, 2020). Understanding the contaminant loads in potential prey items in these sites may also help to improve CEM predictions.

Vermilion Rockfish is a longer lived, structure-associated species that feeds at higher trophic levels, and the tracked individuals stayed at the OC San outfall for up to 40% of the entire 1-y study period (Burns et al., 2019; Love et al., 2002). One would expect that individuals that are resident to areas with high sediment-bound contaminants would exhibit higher contaminant levels due to chronic exposure. However, this was not the case for Vermilion Rockfish, where most muscle tissues had non-detectable levels of PCBs. It is likely that Vermilion Rockfish established territories within the spaces between the structures associated with the outfall pipe (articulated concrete mats, ballast rock) and did not feed on prey that were directly associated with the contaminated sediments. In addition, while there is a possibility of trophic magnification of contaminants within Vermilion Rockfish, this was not the case in our study, and we suggest that individuals with lower contaminant levels ate nomadic prey with similarly low contaminant levels.

White Croaker is considered a nomadic species, and half of the individuals in this study left the study site within 7 d of tagging (Wolfe and Lowe 2015). Like the Hornyhead Turbot, it is likely that the contaminants within the muscle tissues of White Croaker reflect acquisition from the greater Southern California Bight area. However, White Croaker was the only species whose CEM results significantly overestimated high and negligible (zero) contaminant concentrations, but underestimated contaminant exposure at low to moderate concentrations. This may be due to the overlap between the acoustic receiver array and the underlying sediment contaminant distribution. It was clear that tagged White Croaker spent a lot of time along the northern boundary of the contaminant field (Fig. 5C). While some of these points were assigned contaminant values, positions that fell just outside of the measured contaminant field were given contaminant exposure values of zero. If the contaminant field was expanded to shallower waters, the White Croaker CEM could have accounted for more time spent on sediments of relatively low contaminant concentrations.

Another possibility is that the CEMs simply produced a much larger estimate of maximum DDT concentrations in White Croaker than field-collected samples (8.4 for muscle samples; 697 for CEM results, Fig. 4H and I). Compared to the OC San outfall site, sediment-bound contaminant concentrations at the LACSD outfall site were up to two orders of magnitude higher and likely reflected the historical discharge of industrial products. CEMs generated for the few White Croaker that spent more time within the study site may have reflected the accumulation of these high contaminant values and resulted in scaled concentration values that were much higher than the population median.

4.2. Fine-tuning model parameters and biological realism

Despite using different rates of movement and time interpolation thresholds, Hornyhead Turbot and Vermilion Rockfish showed little differences in the frequency distributions of different behavioral classifications. For both species, most points were identified as non-moving, so the difference in predicted contaminant exposures across different CEMs was predictably low. According to Burns et al. (2019), both Hornyhead Turbot and Vermilion Rockfish showed low rates of movement within the OC San study site, explained by the resident behavior of Vermilion Rockfish and the foraging behavior of Hornyhead Turbot. To categorize different behaviors for species with low rates of movement, stricter rate of movement thresholds would need to be implemented. However, as stricter thresholds are implemented, stationary fish are more likely to be incorrectly identified as moving, due to VPS positional error (AMIRIX Systems Inc, 2013). Furthermore, it appears that behavioral classifications are not a large driver in CEM outputs, as White Croaker showed large differences in behavioral groupings, and yet the CEM results did not change dramatically (Supplementary Materials). Moreover, there were no differences in CEM results when time interpolation thresholds were increased from 2 to 5 min (Supplementary Materials). This illustrates the robustness of VPS data and the reproducibility of the *crawl* models. Interpolating positions at regular 2 or 5 min intervals can be computationally expensive and result in incredibly large datasets for multi-year and multi-species studies. Being able to use larger time gaps between location fixes will allow future models to be run with more sophisticated and more meaningful parameters, without having to compromise positional accuracy.

Because several biological and oceanographic parameters likely affect contaminant exposure and uptake, a model that perfectly predicts contaminant concentrations in fish tissues from movement patterns alone would be unexpected. While the models we developed accounted for individual variation within and among species movements, they did not account for variations in lipid concentrations, probability of contaminant uptake, or probability of contaminant depuration. To account for individual variation, incorporating a scaling factor for contaminant exposure that is randomly selected from a normal distribution for each location of each fish may significantly impact CEM results. Alternatively, if uptake and depuration rates are known, such parameters could be incorporated into the model. In addition, there were no available data for the maturity or sex of the individuals used in this study. Incorporating these parameters could help account for maternal offloading or energy transfer away from liver or muscle tissues and to gonadal tissues for reproduction, thereby increasing accuracy of CEM results (Lyons et al., 2014; Wootton 1985).

Finally, sediment-bound contaminant concentrations are not static over space or time. Contaminants present in the top layers of sediment become buried, making them less of a threat to marine species (Walker et al., 2013). However, as earthquakes, dredging, and other physical disturbances occur, these contaminants can be re-suspended in the water column, making them available to marine species (Hedman et al., 2009). Being able to accurately predict the concentration of contaminants in the bioavailable layer and fluctuations of contaminants present in the water column while a fish is actively using the area may also help to increase accuracy in CEMs. Implementation of accelerometers and biologgers could allow ground truthing of assumptions about foraging and rates of sediment contact while additionally compensating for limitations in the spatial resolution of telemetry data (Adam et al., 2019).

4.3. Spatial prioritization

CEMs in combination with KDEs may be increasingly useful for Publicly Owned Treatment Works (POTWs) that are interested in the spatial prioritization of future remediation or management efforts. While the CEMs presented here require refinement before becoming alternatives to current monitoring methods, KDE results can be immediately applied for management. For example, at the OC San site, the regions most likely to affect contaminant exposure in Vermilion Rockfish and Hornyhead Turbot are spatially distinct, but both are in areas with low levels of sediment-bound DDT concentrations. Choosing the best location to begin remediation is difficult and likely to result in the favoring of one species over the other. However, species that show affinity to the OC San outfall (Vermilion Rockfish) are more likely to experience chronic exposure to site-based contaminants and prioritizing key areas for these species may be most effective. Alternatively, remediation efforts at the LACSD outfalls should focus on areas in the northern end of the study region, where contaminant concentrations were low and White Croaker KDEs were high. Although seemingly counterintuitive, remediation efforts that are targeted in these areas, as opposed to areas with the highest sediment-bound contaminant concentrations, are likely to have the largest impact on contaminant concentrations within White Croaker and species with similar life history characteristics.

5. Conclusions

CEMs can be increasingly useful at POTW discharge sites and other areas with high sediment-bound contaminant concentrations that require regular monitoring to meet permit requirements. Current methods for gathering data on contaminant concentrations in tissue samples within a small-bodied species often require the collection and sacrificing of sample species and bycatch (OC San, 2020). As CEMs continue to be developed and refined, methods may shift from primarily collecting individuals from the field towards a combination of movement modeling and habitat mapping that are only periodically validated by field collections. The CEMs performed relatively well at predicting the range of DDT concentrations that are likely to be present within Hornyhead Turbot and Vermilion Rockfish tissues. Future iterations of these models might be useful for monitoring and management efforts that target fishes that are most likely to show adverse effects to wastewater effluent. Alternatively, although CEMs did not accurately predict DDT concentrations in White Croaker muscle samples, White Croaker was the only species to show a clear difference in the distribution of behavioral classifications. Therefore, future CEMs that incorporate behavioral data show the most promise for nomadic species. The presented models may serve to complement broader-scale acoustic telemetry studies and act as steppingstones towards the development of more sophisticated models. The best model for predicting tissue contaminant concentrations does not rely on movement patterns alone, but is better defined by a combination of factors, such as lipid content, maturation, and the habitat use of prey species. While CEMs continue to be refined, KDEs can be used immediately to inform managers of areas that are most used by species of concern and are, therefore, the best candidates for remediation efforts.

Authorship statement

E. S. Burns: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Visualization; Writing - original draft; Writing - review & editing.

B. Wolfe: Data curation; Formal analysis; Investigation; Methodology; Project administration; Writing - review & editing.

J. Armstrong: Conceptualization; Funding acquisition; Investigation; Resources; Supervision; Writing - review & editing.

D. Tang: Funding acquisition; Supervision; Investigation; Resources; Supervision; Writing - review & editing.

K. Sakamoto: Funding acquisition; Supervision; Investigation; Resources; Supervision; Writing - review & editing.

C. G. Lowe: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Supervision; Validation; Writing - original draft; Writing - review & editing.

Data accessibility statement

All code has been added to a public repository in GitHub that can be accessed and cited through Zenodo (https://doi.org/10.5281/zenodo.4625049). Raw tracking datasets and the final results presented in this study can be accessed and cited through Dryad (https://doi.org/10.25349/D97314). All other input data sources have been referenced in the Dryad dataset description, and specific instructions for accessing tissue-contaminant data for White Croaker using the DIVER database have been added to the Supplemental Materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2021.105452.

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