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Patterns of home ranging, site fidelity, and seasonal spawning migration of barred sand bass caught within the Palos Verdes Shelf Superfund Site

Garry N. Teesdale*, Barrett W. Wolfe, Christopher G. Lowe

Department of Biological Sciences, California State University, Long Beach, 1250 Bellflower Blvd, Long Beach, California 90840, USA

ABSTRACT: Barred sand bass *Paralabrax nebulifer* (Family: Serranidae; BSB) are among the most popular recreational game fishes in southern California and an important food fish. Patterns of residency and habitat use are critical for determining the potential for BSB to be impacted by point source anthropogenic contaminants prevalent in the densely populated coastal environment near Los Angeles, California. Home ranging behavior, degree of site fidelity, residency, habitat selection, and seasonal spawning migration of BSB were observed over 27 mo using a large, continuous coverage, fine-scale acoustic telemetry array (~20 km^2). The 55 tagged individuals used small core areas (mean ± SD = 2682 ± 2005 m^2 over 329 ± 227 d) and showed high affinity for the rock/sand ecotone at a depth of 20 to 30 m. Overall weekly residency to the array was 70 ± 25% of tagged fish present from the first tag date through the end of the study, with lower residency during the summer spawning season (June to August). Individuals leaving the array emigrated in a southeasterly direction 98% of the time, and 100% of the BSB detections outside the array occurred to the southeast of the Palos Verdes Shelf Superfund Site (PVSSS; 26.4 ± 0.8 km). BSB of legal size (>360 mm TL) exhibit high long-term site fidelity to small areas within the PVSSS and make seasonal migrations to spawning aggregations beyond the boundaries of the 'do not consume' zone defined by the Office of Environmental Health Hazard Assessment in 2009.

KEY WORDS: Barred sand bass · *Paralabrax* · Serranidae · Home range · Site fidelity · Spawning migration · Palos Verdes · Superfund · DDT · Acoustic telemetry · VPS

INTRODUCTION

A major obstacle to any effort to manage a marine area is the need for more complete information about the behavioral ecology of the species involved. For fish species, data on patterns of movement, habitat use, site fidelity, migration, and trophic level may all be required to create effective management strategies (Zeller 1997, Rice 2005). This is especially true in densely populated coastal areas where fishing pressure, habitat loss, and anthropogenic pollution present challenges for resource managers. Information regarding home range, site fidelity, and migratory patterns is particularly valuable in determining the potential exposure, accumulation, and export of contaminants by important food fish species from point source contamination sites (Moser et al. 2013, Ahr et al. 2015, Wolfe & Lowe 2015).

The Palos Verdes Shelf Superfund Site (PVSSS), located on the densely populated coastline south of Los Angeles, California, remains one of the most concentrated marine point source contamination sites in the world (Eganhouse & Pontolillo 2008, Chen et al. 2012). From 1953 until 1972, effluent from submarine outfall pipes released on the Palos Verdes Shelf included wastewater from industrial manufacturing sources

*Corresponding author: gnteesdale@gmail.com

(MacGregor 1976, Eganhouse & Pontolillo 2000, Schiff et al. 2000). This introduced millions of kilograms of DDT (dichlorodiphenyltrichloroethane) and PCB (polychlorinated biphenyl) to the sediments off of White Point, on the eastern end of the Palos Verdes Shelf (PV Shelf) (MacGregor 1976, Eganhouse & Pontolillo 2000, Schiff et al. 2000). These environmentally persistent organochlorine compounds are lipophilic and have deleterious effects on animals (Smith 2000, Johnson-Restrepo et al. 2005, Udoji et al. 2010). Within marine fishes, direct exposure and accumulation of organochlorines causes acute damage such as fin rot, epidermal tumors, and reproductive impairment (Schiff et al. 2000, Jarvis et al. 2007). Accumulated organochlorine contaminants are biomagnified as they are passed along the marine food chain, resulting in exponential increases in body burdens for animals at the highest trophic levels (Clarkson 1995, Gobas et al. 1999, Kwong et al. 2008). Human exposure to organochlorines has been linked to long-term risks, including neurological damage, immunosuppression, endocrine disruption, cancer, and reproductive damage (Smith 2000, Beard 2006, Udoji et al. 2010).

Many species of fish living along the PV Shelf have been exposed to contaminants found in the sediments (Schiff et al. 2000, Jarvis et al. 2007, Klasing et al. 2009). Samples of epaxial muscle taken from barred sand bass *Paralabrax nebulifer* (BSB) captured on the southeastern end of PV Shelf near the White Point outfall had extremely high concentrations of DDT and PCB, prompting their inclusion in a 'do not consume' advisory issued for fish caught along a 65 km stretch of coastline between the Santa Monica and Seal Beach piers (NOAA 2007, Klasing et al. 2009). Barred sand bass (Serranidae), a medium sized (up to 65 cm total length, L_{50} mature ~23 cm), largely benthic sedentary predator (Love et al. 1996a), are one of the most popular marine sport and food fish in southern California and have been one of the top 2 species targeted by the recreational fishery for several decades (Love et al. 1996a, Allen & Hovey 2001, Jarvis et al. 2010, 2014, Miller & Erisman 2014). Determining the degree of long-term residency of BSB to home ranges within the PVSSS and proximity of BSB to the most contaminated sediments at White Point is essential for quantifying potential exposure of a resident predatory fish to this contamination point source and the potential risk to southern California recreational anglers, but little of this movement information is available for the population associated with the PVSSS.

Behavior such as habitat use and movements of BSB in other locations have been characterized via diver observation and studied with traditional tagging and acoustic telemetry technology (Feder et al. 1974, Jarvis et al. 2010, Mason & Lowe 2010, McKinzie et al. 2014). Over shorter time frames (days to months) BSB have high site fidelity to specific home ranges of ~3000 to 10 000 m^2 at depths of 10 to 60 m (Mason & Lowe 2010, McKinzie et al. 2014). If BSB, a relatively long-lived species (up to 24 yr), exhibit long-term site fidelity or a high degree of residency to similar habitats at White Point, then long-term exposure of resident fish might explain the high concentrations of contaminants typically found in individuals taken within the PVSSS. Defining home ranges of BSB at White Point and quantifying proximity to the highest levels of sediment contamination are both important for assessing how individuals accumulate such high contaminant concentrations.

BSB are known to form seasonal spawning aggregations from June through August (Love et al. 1996a, Jarvis et al. 2010, McKinzie et al. 2014). While evidence of spawning migration was not directly identified in BSB tracked at Santa Catalina Island (Mason & Lowe 2010), large-scale traditional tag and recapture studies of BSB along the southern California coastline have identified spawning aggregations and migrations (Jarvis et al. 2010). Recaptures of tagged fish suggested high site fidelity to both spawning season and non-spawning season capture locations and residence times within the aggregations to be 7 to 35 d for individual fish, with females capable of spawning daily (Jarvis et al. 2010, 2014). Spawning peaks in July and August just before full and new moons, and females are estimated to spawn 42 times per season (Jarvis et al. 2014). The PVSSS lies between 2 known spawning aggregation sites, Santa Monica Bay and Huntington Flats, and the possible spawning migration of BSB from White Point to these sites outside of the current 'do not consume' warning area may result in the biological export of contaminants and a seasonal expansion of the potential human health risk.

The objective of this study was to employ a suite of passive acoustic telemetry techniques to allow for characterization of movement over varying spatial scales (~3 m to 20 km^2) in order to quantify the home range area, residency, habitat use, site fidelity, and spawning migration behavior of BSB caught within the PVSSS over periods of 4 to 27 mo. We hypothesized that BSB caught and tagged at White Point will remain in the PVSSS throughout much of the year, but will emigrate from White Point at the beginning of the spawning season to nearby aggregations in Santa Monica Bay or Huntington Flats and then return at the end of the summer.

MATERIALS AND METHODS

Acoustic receiver array

To determine the residency and home ranges size of BSB and the degree of site fidelity to White Point, as well as the timing of potential spawning migrations and extent of those movements, a suite of acoustic telemetry approaches were used. A large grid array of 42 omni-directional acoustic receivers (Vemco VR2W) fixed to the ocean floor recorded the coded pulse trains of transmitters (Vemco V9-2L) surgically implanted in BSB caught within the acoustic receiver array location (Fig. 1). Based on range testing and calibration conducted within the study site, 24 of the 42 receivers were placed approximately 500 m apart in a staggered Vemco VR2W Positioning System (VPS)-enabled array (hereafter 'main array') to quantify both coarse-scale and fine-scale movements of tagged individuals across an 8.5 km^2 rectangular area encompassing the area of highest sediment contamination surrounding the outfall. Additional acoustic receivers were placed ~1000 m apart on both the northwest and southeast ends (6 receivers each) of the main array to form 'brackets' that monitored directionality of emigration and immigration of tagged individuals from and to the study site, expanding the total coverage to ~20 km^2. The remaining 6 receivers were placed just inside and outside of Angel's and Queen's Gates of the Los Angeles/Long Beach Harbor Federal Breakwater to act as acoustic 'gates' to monitor any movements in and out of the harbor. All 42 receivers were taut moored 3 to 5 m above the sea floor using 2 floats (7.2 kg of buoyancy) in order to decrease acoustic shadows created by low-relief reefs and outfall pipes. Individual transmissions detected by a single acoustic receiver provided coarse-scale data (detection efficiency of 57.8% at 100 m and 11.5% at 500 m) that indicated presence of tagged BSB and their general location within the acoustic array. The VPS enabled main array also allowed for high-resolution positioning (±5 m) via trilateration when tagged individuals were detected by ≥3 VR2W receivers added by co-located V-16 synchronization tags (see Espinoza et al. 2011 for further description of VPS and Wolfe & Lowe 2015 for the VPS array design of the present study). These finer-scale position data were used to determine the size, location, and habitat use within home ranges for tagged BSB.

Temperature data loggers (Onset TidBits) were attached to 8 receivers (2 at each 10 m isobath) within the main array and set to record the temperature every 30 min. Receivers were recovered and data downloaded approximately every 2 to 3 mo, and batteries were replaced once every year.

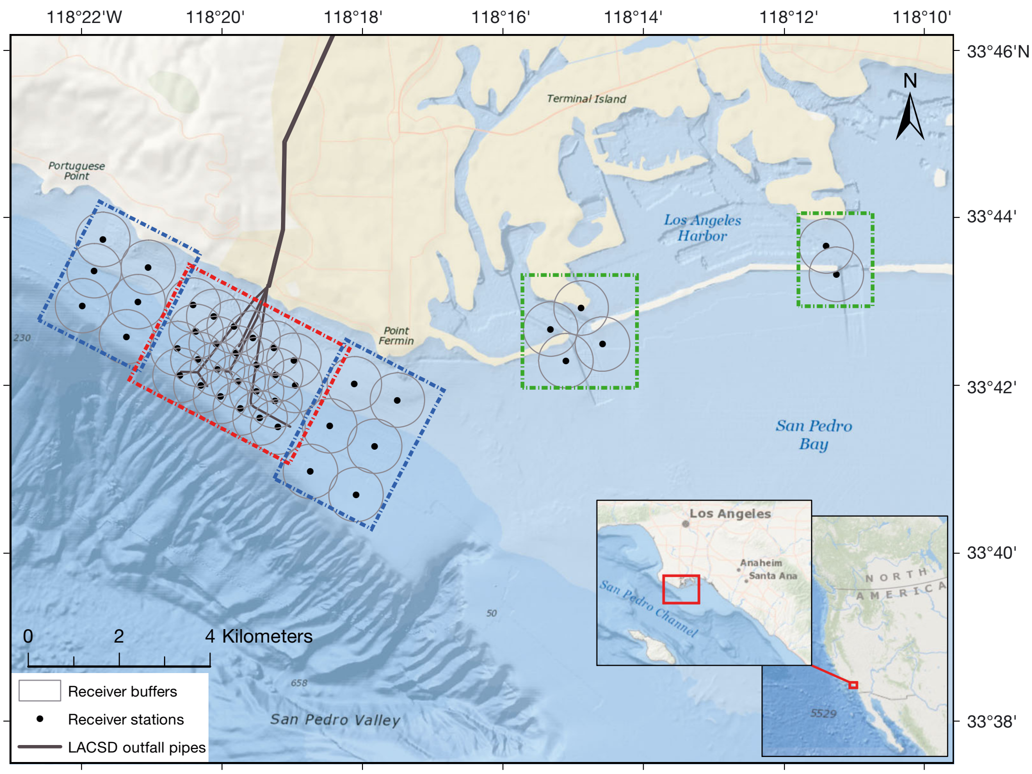

Fig. 1. Locations of Vemco VR2W acoustic receivers (•) deployed on the Palos Verdes Shelf and at the entrances to Los Angeles/Long Beach Harbor. Red dashed box represents the 24 receivers that make up the VPS-enabled array around the White Point outfall pipes (main array), blue dashed boxes represent the east and west bracket array, and the green dashed boxes represent the harbor gates

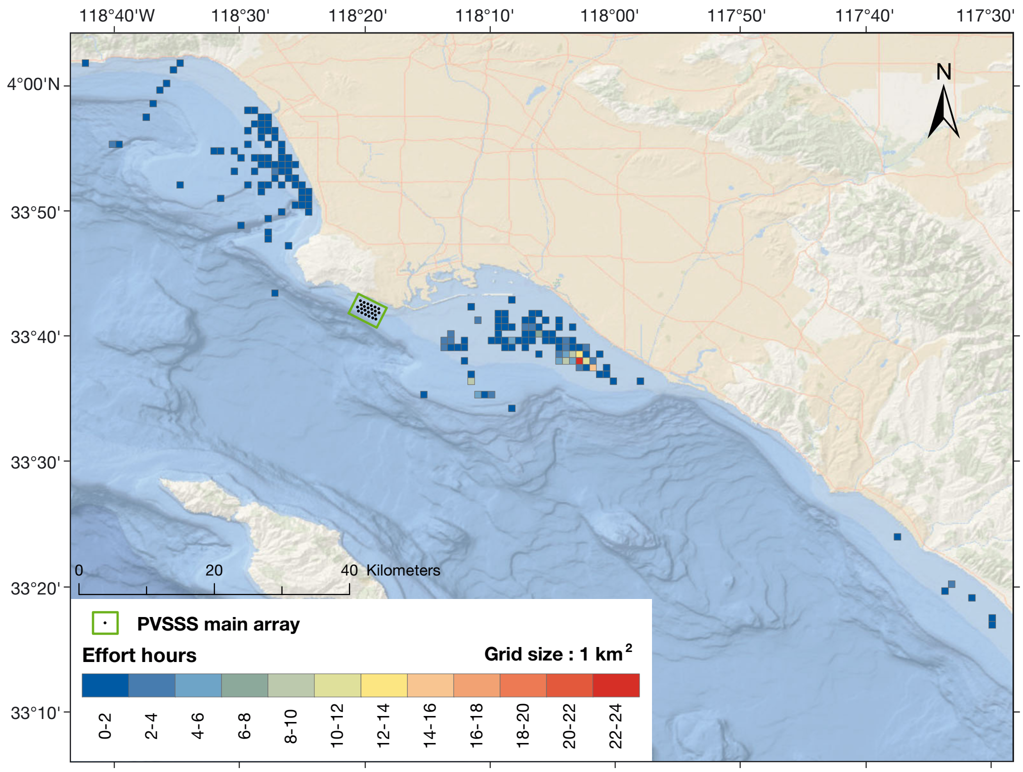

Fig. 2. Map of mobile receiver deployments from vessels with effort (hours of listening time) per km^2. Grid size is 1 km^2. Green box represents fixed Palos Verdes Shelf Superfund Site (PVSSS) acoustic receiver array location

Mobile receiver deployment

Additional acoustic receivers (Vemco VR2W) were opportunistically deployed from sport fishing vessels during the spawning season (June to August) around known spawning areas outside of the PVSSS array (Fig. 2). These 'mobile' receivers were deployed on a weighted line from vessels to a depth of approximately 10 to 15 m while the vessel was at anchor. GPS location and time in the water for each deployment were logged, and receiver detection data were downloaded monthly. The location of mobile receiver deployments ranged from northern Santa Monica Bay to San Onofre. The majority of the effort was focused on the largest known spawning aggregation site, Huntington Flats, located 25 km southeast of the PVSSS (~200 km^2), which is heavily targeted by local commercial passenger fishing vessels. Smaller aggregations are also known to form 35 km to the northwest in Santa Monica Bay and 65 km to the south off Dana Point, but Huntington Flats is the location nearest to the PVSSS where tagged BSB are expected to spawn.

Tagging methods

BSB were caught using hook and line or baited trap with efforts concentrated on areas of rocky relief within the array, including ballast rock piled on sections of the outfall pipes and natural rocky reef on the PV Shelf near Los Angeles County Sanitation District's (LACSD) White Point outfall. Vemco V9-2L acoustic transmitters (9 mm × 29 mm, 4.7 g in air) operating at 69 kHz (power output of 146 dB) producing a quasi-random pulse train within a programmed minimum and maximum interval of 110 to 250 s (~759 d battery life) were surgically implanted in fish >240 mm total length (TL) (sexually mature), but preferentially >360 mm (legal size limit), and >235 g. All transmitters were coated with a mixture of beeswax and paraffin (1:2.3) to reduce risk of immunorejection (Lowe et al. 2003). Captured fish were bathed in an anesthetic (MS-222, 200 mg l^{-1}) until reaching a level-4 state of sedation (Summerfelt & Smith 1990). Fish were then removed from the anesthetic and placed in a bath of fresh seawater, the transmitter inserted through a 1.5 cm incision in the abdominal wall and peritoneum into the body cavity, and the incision closed with 1 or 2 interrupted stitches of PSD II suture. Immediately following surgery, an external dart tag (with 'Do Not Eat' warning and contact information) was inserted into the dorsal musculature, the fish were measured and weighed, then allowed to recover from the anesthetic in a cooler of fresh seawater before release. Fish handling and surgical methods were both approved by the CSULB IACUC committee (protocol #283).

Residency analysis

It was hypothesized that BSB from the PVSSS would make seasonal migrations; therefore, the degree of residency was determined over a weekly time scale. Weekly presence in the area surrounding the White Point outfall was defined as a tagged individual being detected at least twice on 2 or more days during a single week by any receiver within the main array. Although requiring at least 2 detections on 2 or more days as benchmark criteria for presence may underestimate actual presence of tagged BSB, it reduces any possibility of false detections. Residency was defined as the proportion of tagged fish present within the array each week from the first tag date through the end of the study. Weekly residency was compared during the spawning season (June to August) and non-spawning season (September to May) using a Mann-Whitney *U*-test.

Home range and habitat selection analysis

Home range areas within the main array were estimated for all tagged BSB with a minimum of 100 VPS positions, using kernel utilization distributions (KUDs) derived from the kernelUD function of the adehabitatHR package in R (v. 2.15.2). Some fish had a greater number of VPS position estimates than others; therefore, KUDs were calculated by randomly sampling 100 positions from all rendered positions for each fish. Core use areas (50% KUD contour) and overall use areas (95% KUD contour) were calculated based on this sampling method using an ad hoc smoothing parameter (h = 8). Using 1000-iteration bootstrapping to reduce the bias of spatial autocorrelation, the mean value of KUDs for each individual fish was used in estimating the size of home range areas.

Euclidean distance between VPS positions and nearest rock/sand ecotones was calculated using ArcGIS (ESRI v. 10.2) to determine the edge response, or affinity of BSB to rocky reef or outfall pipe edges. Euclidean distances were also used to determine proximity of VPS positions to PVSSS 'hot spots', areas of sediment with very high concentrations of DDT (>5000 ppb) by layering onto a sediment concentration map (ITSI 2013). Euclidean distance analysis (EDA) results were compared to a random distribution of positions within the minimum convex polygon encompassing observed VPS positions using a chi-squared test. Habitat selection was analyzed by layering rendered VPS positions over a benthic composition map (USGS Data Series 552, Seafloor Geology and Benthic Habitats, San Pedro Shelf, Southern California) in ArcGIS (ESRI v. 10.2). The number of VPS-rendered positions in each habitat type was compared to a random distribution of positions in the habitat available using a chi-squared test, and standardized residuals were examined to determine if a particular habitat type was causing any significant difference. A habitat selection index (HSI) was then calculated by dividing the proportion of positions in each habitat type by the proportion of available habitat (Manly et al. 2002). VPS positions were binned by 10 m isobaths for depth analysis, and observed positions were compared to a random distribution using a chi-squared test.

Spawning migration and seasonal site fidelity

Individual receiver detections were used to determine the direction of emigration movements during spawning season. An emigration was defined as an individual leaving the array area. This was characterized as an individual detected ≥2 times by any of the 6 bracket receivers on the southeast or northwest ends (the edge of the array) during a given day with no return detected to the 24 receivers of the main array within 7 d. This eliminated short forays and brief periods of poor detection coverage due to weather conditions and reduced mischaracterization as potential spawning migrations. Emigration movements out of the main array made by individual BSB were assigned to 1 of 2 directions (NW or SE), based on bracket receiver detections. Frequencies of observed movement directions were compared to frequencies of a random (50:50) direction of movement with a chi-squared test.

Spawning migrations were defined by periods of absence from the PV array and concurrent detections by mobile receivers at known spawning locations (late May through late September). Individual detections of BSB outside of the PVSSS by acoustic receivers deployed from vessels throughout the duration of the study were used to determine the degree of connectivity between the PVSSS and nearby spawning aggregations. Migrations of individual BSB were assigned to 1 of 2 destinations, Huntington Flats or Santa Monica Bay, based on the GPS location of mobile receiver detections, and the observed distribution of aggregation site use by all tagged BSB was compared to random distribution (50:50) with a chi-squared test.

The timing of spawning migrations (number of departures within ± 3 d) was examined in relationship to several environmental factors at White Point to identify potential spawning migration cues. Temperature data loggers were deployed on receivers 3 to 5 m off the seafloor. Therefore, sea surface and bottom (23 m) temperature data sets used for seasonal migration analyses were acquired from NOAA and the Los Angeles County Sanitation District (LACSD). The influence of sea surface temperature, daily tidal flux (maximum-minimum), and photoperiod averaged over the previous 7 d were considered in relation to timing of departures using a generalized additive model (GAM) in the R (v. 2.15.2) package 'mgcv' (Wood 2011). The model with the best-fit combination of predictor parameters was selected with Akaike information criteria (AIC).

Non-spawning interseasonal site fidelity was estimated by quantifying the number of fish that returned to the main array after an emigration movement during a given year.

RESULTS

Tag deployment

In total, 55 BSB were captured, tagged, and released over the course of the study. There was no apparent mortality of tagged fish in periods immediately following release based on subsequent detection patterns. The mean (±1 SD) capture and release depth of tagged fish was 24.9 ± 3.6 m (range 17.4 m to 34.9 m). These fish ranged in size from 280 to 480 mm (386 ± 45 mm) total length and, using a von Bertalanffy growth curve (Love et al. 1996b), ranged in estimated age from 4.2 to 13.5 yr (8.5 ± 2.1 yr).

Residency

A total of 844 656 transmitter detections were recorded on all 42 receivers for 55 BSB tagged. Overall weekly residency was 70 ± 25% (mean ± SD) of tagged fish present from the first tag date through the end of the study (Fig. 3). Mean (±1 SD) weekly residency during non-spawning season (September through May; 77 ± 15%) was higher than the mean during spawning season (June through August; 52 ± 35%) (Mann-Whitney: $U = 889$, $p = 0.001$).

Home range and habitat selection

A total of 17 374 VPS positions were rendered throughout the study. There were 31 BSB with >100 VPS positions (mean ± SD; 538 ± 400) over periods ranging from 120 to 814 d (Fig. 4A). Home range area estimates were 18 510 ± 12 429 m^2 for the 95% KUD (Figs. 4B & 5A) and 2682 ± 2005 m^2 for the 50% KUD over 329 ± 227 d (Figs. 4B & 5B) (Table 1).

EDA of rendered VPS positions indicated that tagged fish were more highly associated with rock/sand ecotones than a random distribution of points in the same area of benthic habitat ($\chi^2 = 13357$, df = 56, $p < 0.001$) (Fig. 6A). BSB selection for these rock reef edge habitats was also seen in the HSI analysis, showing a higher degree of association with the ecotone and both rock and sand substrata during the day, and selecting for the neighboring rock/sand mix substratum type (at a greater distance from the reef ecotone) at night (Figs. 6B & 7). An analysis of standardized residuals indicated that all habitat types contributed to the difference between VPS locations and random use ($\chi^2 = 750$, df = 5, $p < 0.001$).

While the core areas used by BSB were located in areas of elevated contaminant concentration (5 to 500 ppb DDT) and overall use extended into even

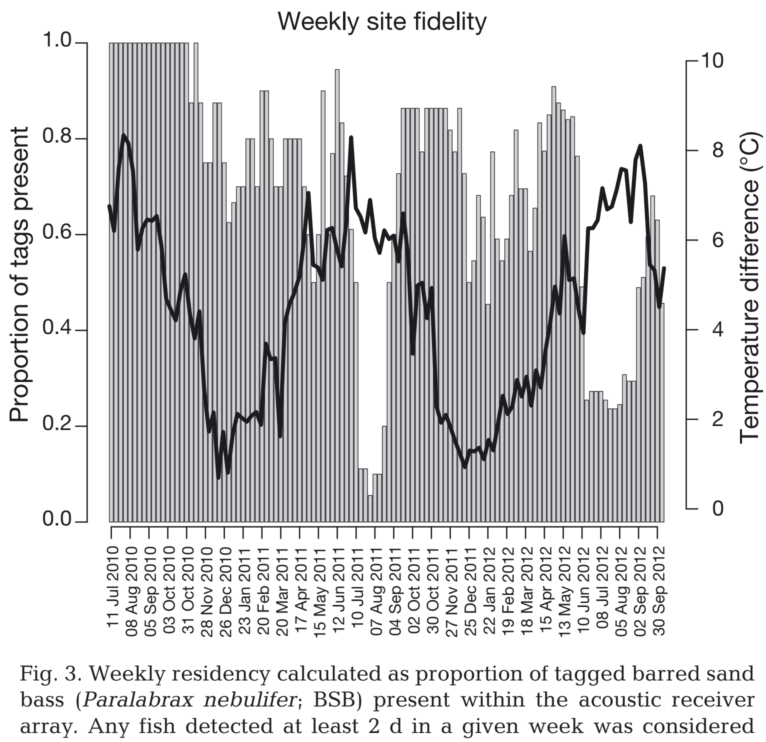

Fig. 3. Weekly residency calculated as proportion of tagged barred sand bass (*Paralabrax nebulifer*; BSB) present within the acoustic receiver array. Any fish detected at least 2 d in a given week was considered present. The 2 sharp dips in proportion of tagged fish present occur during summer spawning seasons in 2011 and 2012. Difference between sea surface and bottom temperature represents a proxy for the seasonal development of a thermocline (black line)

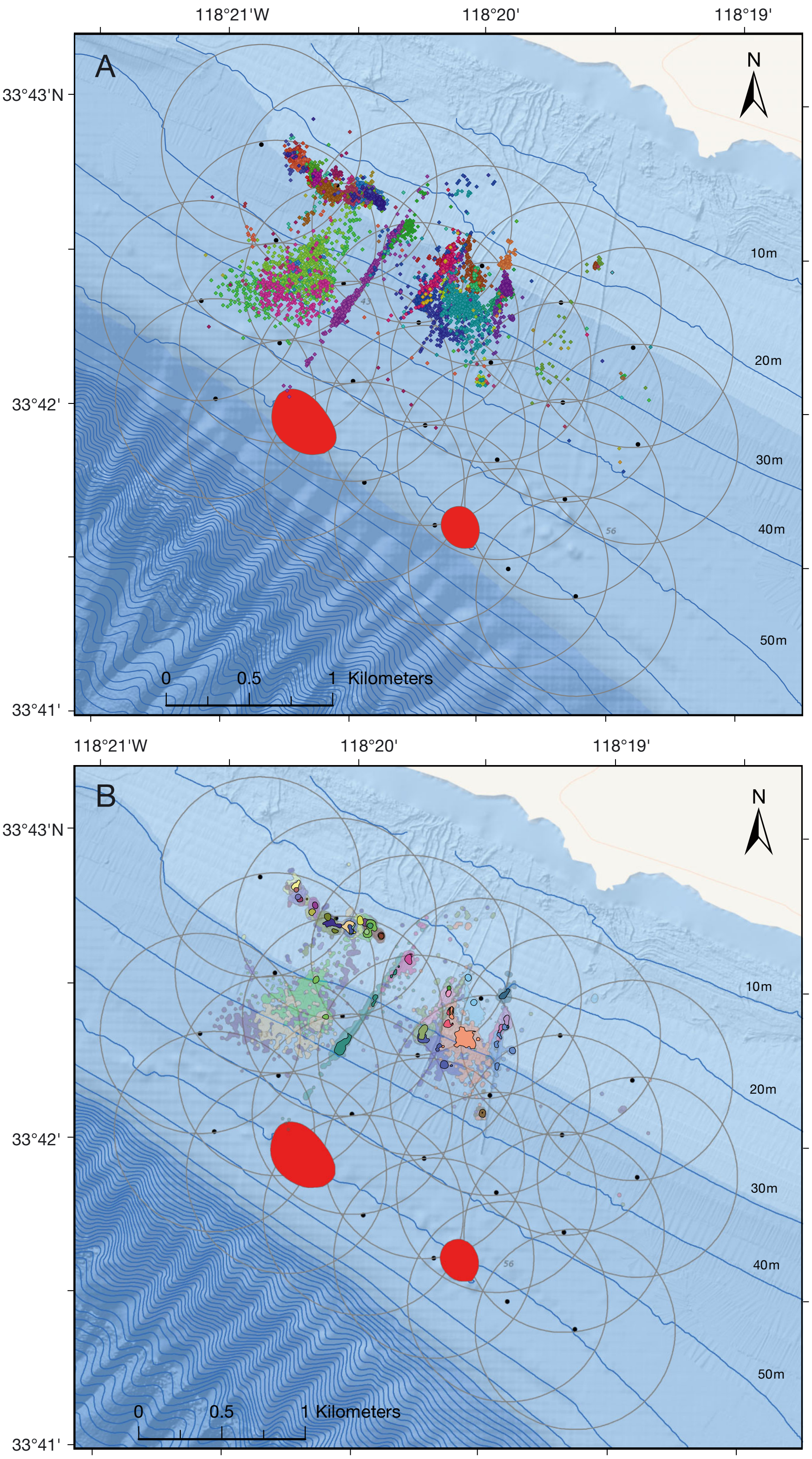

Fig. 4. Map of (A) VPS relocations for all tagged fish (different colors = individual BSB) and (B) home range estimates for all tagged fish (50 % kernel utilization distribution [KUD] = shaded, 95 % KUD = outline). Red shaded areas are 'hot spots', areas with sediment concentrations >5000 ppb DDT. Gray circles represent acoustic receiver detection buffers

higher concentrations (>2000 ppb DDT), tagged BSB did not use the most contaminated (>5000 ppb) areas of sediment found in deeper water (>50 m) (Fig. 4B). Proximity of rendered VPS positions to edges of the 2 contamination 'hot spots' demarcated by the >5000 ppb DDT isocline ranged from 0 to 1701 m (1151 ± 205 m), which was significantly different than a random distribution (χ^2 = 14985, df = 38, $p < 0.001$). The distribution of VPS positions ranged in depth from 10 to 60 m, and the number of positions was significantly higher in the 20 to 30 m (14 608 positions [~84 %]) and 30 to 40 m (2347 positions [~14 %]) bins (χ^2 = 45657, df = 4, $p < 0.001$).

Spawning migration and site fidelity

As tagged BSB left the main array over the course of the study, the emigrations of 52 individual fish were detected on the bracket receivers (Fig. 8A,B). The direction of these movements was not random, as 51 (98 %) fish moved to the southeast and only one (2 %) moved to the northwest (χ^2 = 28.8139, df = 1, $p < 0.001$). Individuals were detected on bracket receivers when returning to the array from the southeast 37 times (73 %) and never from the northwest (0 %). Periods of absence from the array ranged from 16 to 154 d (mean ± SD; 79.2 ± 23.5 d) for tagged fish that returned (n = 37). During 2011, 17 of 17 tagged BSB (100 %) emigrated, and 35 of 49 fish (71.4 %) emigrated during the spawning season of 2012. Dates of departure for the 17 emigrations during the spawning season of 2011 ranged from 15 June through 12 August with a median departure date of 10 July. In 2012, 35 spawning season emigrations ranged from 13 May through 25 July with a median departure date of 6 June. Median return date of migratory BSB detected by the acoustic array in 2011 (30 August) was similar to that of 2012 (9 September). Average daily surface

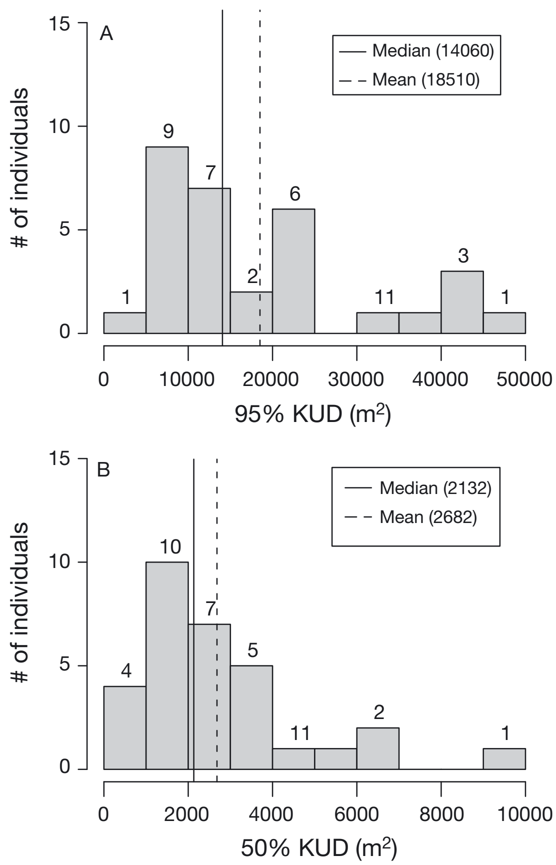

Fig. 5. Estimated area values for (A) overall home range (95 % KUD) and (B) core use (50 % KUD)

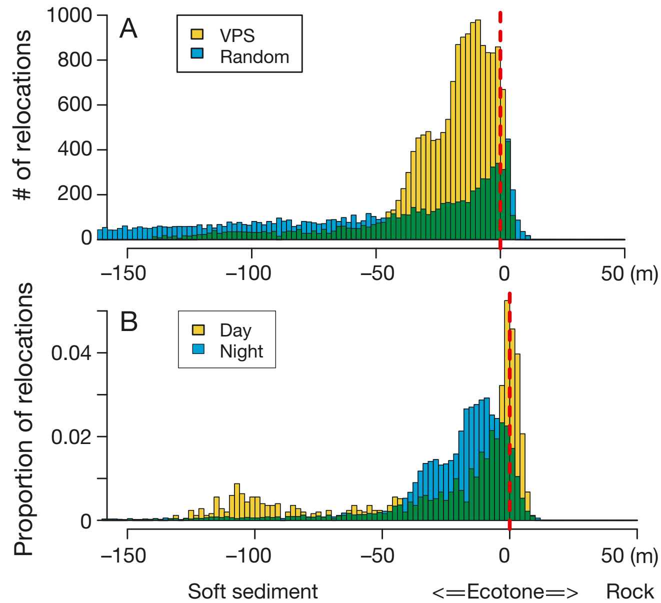

Fig. 6. (A) Euclidean distance analysis (EDA) habitat edge response (ecotone affinity) of rendered VPS positions (n = 17 374) for BSB to the ecotone (red dashed line) of the rock sand interface compared to an equal number of randomly distributed points within the same minimum convex polygon. Distribution of the observed ecotone affinity was significantly non-random (χ^2 = 13 357, df = 56, p < 0.001). (B) EDA edge response of rendered VPS positions for BSB to the ecotone of the rock sand interface during the day (n = 1258) compared to night (n = 16 116) (χ^2 = 1018, df = 30, p < 0.001). Green areas represent where the 2 histograms overlap

temperature calculated from NOAA data (www.ncdc.noaa.gov) ranged from 11.8 to 22.4°C (16.7 ± 2.1°C), and average daily temperature at depth (20 to 23 m) acquired from LACSD ranged from 9.6 to 17.3°C (12.5 ± 1.4°C).

All environmental data (sea surface temperature [SST], photoperiod, and tidal range; all at 7 d running

Table 1. General additive model parameters and fit statistics. Best fit model is indicated in **bold**

Model parameters	AIC	ΔAIC	% deviance explained
Temp × TideRange × Photoperiod	**−5592.406**	**0**	**76.5**
Temp × Photoperiod	−5248.676	343.73	53.7
Photoperiod	−4978.402	614.004	28.6
TideRange × Photoperiod	−4973.045	619.361	29.6
Temp × TideRange	−4926.593	665.813	27.3
Temp	−4852.056	740.35	15.4
TideRange	−4757.775	834.631	2.4

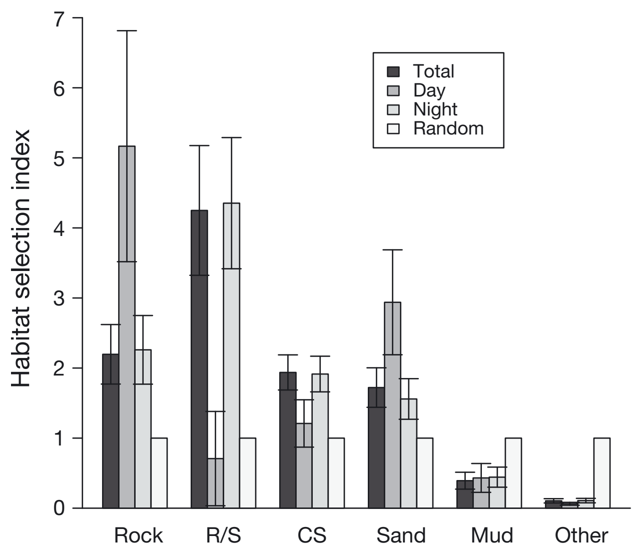

Fig. 7. Habitat selection index ratios for VPS Total, VPS Day, VPS Night, and Random relocations intersected with benthic substrate types (Rock, Rock and Sand mix [R/S], Coarse Sand [CS], Sand, Mud, and Other) with standard error. Substrate associations of VPS relocations were different than random (χ^2 = 750, df = 5, p < 0.001), and substrate associations of VPS relocations during the day were different than those at night (χ^2 = 718, df = 5, p < 0.001)

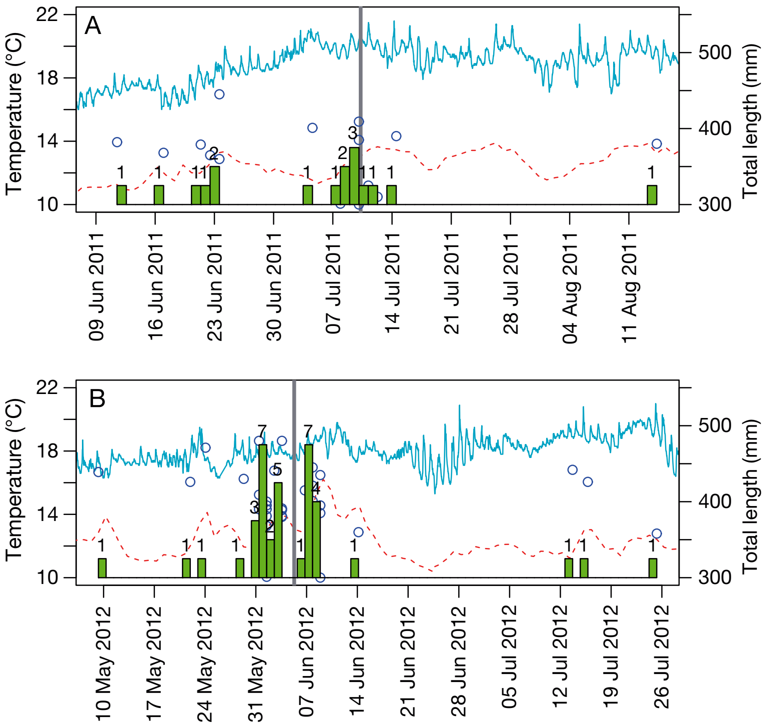

Fig. 8. Histogram of individual spawning season migration departures during (A) 2011 and (B) 2012. Blue lines are average daily sea surface temperature, red dashed lines are bottom temperature, blue circles are total length of emigrating BSB, and vertical grey line is median departure date

averages) utilized in the GAM were normally distributed (Shapiro-Wilk normality test). The best fit model included all 3 parameters, tidal change, SST, and photoperiod, explaining 77% of the deviation in departure frequency (AIC = 5592, Table 1). Single and 2-term models explained between 2.4% and 55% of deviance.

Mobile receivers were deployed in 175 distinct 1 km^2 grid cells for a total soak time of 279 h (1.6 ± 2.8 h per cell) across a wide expanse of potential spawning aggregation sites (Fig. 2). Also, 1 receiver was opportunistically moored in the Horseshoe Kelp area for a total of 66 d. There were 24 tagged BSB detected by the mobile receivers resulting in 1107 detections. Of these, 96 detections of 22 individuals were recorded on mobile receivers deployed throughout the area of Huntington Flats (Fig. 9), 1011 detections of 5 individuals were recorded on the receiver at Horseshoe Kelp, and no detections of the tagged fish were recorded on mobile receivers deployed in the areas of Santa Monica Bay or San Onofre. The average maximum linear distance from tagging locations within the PV array to locations of detections on mobile receivers was 26.4 ± 0.8 km.

DISCUSSION

Site fidelity, seasonal patterns, and residency

The repeated presence of tagged individuals monitored within the study site over the multi-year study period indicates a high degree of long-term site fidelity to White Point and suggests that satisfactory habitat quality exists within the PVSSS for individual BSB to remain resident during non-spawning season. Consistent with previous findings, tagged BSB preferred a bottom depth range of 20 to 40 m and showed high affinity to rock/sand ecotone habitat (Anderson et al. 1989, Love et al. 1996b, Mason & Lowe 2010). Differences in movement patterns, benthic complexity of home range, and degree of interaction with conspecifics may have contributed to the vari-

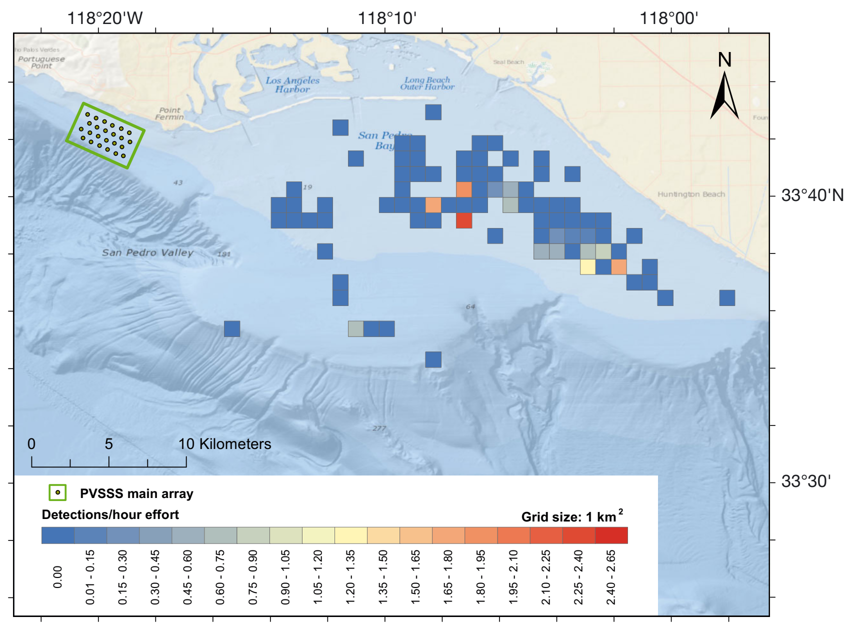

Fig. 9. Detection locations of tagged BSB by mobile receivers relative to main array at the White Point tagging site (detections h^{-1} effort) per km^2. Grid size is 1 km^2. Green box represents fixed PV Shelf acoustic receiver array location

ations in site fidelity and residency among individuals. The detection efficiency of passive acoustic telemetry is limited by detection range of the transmitters and code collisions of multiple transmitter signals. Ambient noise levels and structural complexity of the habitat in which BSB tend to occupy also affect detection efficiency (Meyer et al. 2000, Heupel et al. 2006, Payne et al. 2010, Claisse et al. 2011). Therefore, the number of recorded detections of tagged fish represents a minimum measure of actual presence of tagged individuals in the PVSSS array.

The BSB is a warm temperate rocky reef predator that shares many life history characteristics of related tropical taxa. High site fidelity and residency is common in both temperate reef fish (e.g. kelp bass *Paralabrax clathratus* and California sheephead *Semicossyphus pulcher*) as well as related tropical reef epinephelids (e.g. leopard coral grouper *Plectropomus leopardus* and leopard grouper *Mycteroperca Rosacea*) (Johnson et al. 1994, Zeller 1997, Lowe et al. 2003, Topping et al. 2005, TinHan et al. 2014). Repeated use of an area has many perceived advantages, including familiarity with both shelter and prey locations that likely increase overall fitness for an individual (Zeller 1997). The diet of BSB includes mostly epibenthic prey from rocky reef and sand substrata but also includes forage fish from the water column as well as infaunal prey items, such as worms and clams that are disinterred directly from soft sediments (Roberts et al. 1984). Patches of rocky reef bordered by mud/sand sediments occur frequently to depths beyond 40 m and run parallel to the shore along the entirety of the PV Shelf. At White Point in particular, ballast rock covering the outfall pipes that run roughly perpendicular to rocky headlands create artificial reefs that provide additional ecotone habitat for BSB. Contamination 'hot spots' (>5000 ppb DDT) occur at the ends of the outfall pipes (~60 m depth); however, sediment contamination varies greatly within the PVSSS (5 to >5000 ppb DDT), generally decreasing with distance from the most contaminated sediments. This mosaic of habitat composition and contaminant concentrations likely results in variable degrees of exposure for individual BSB that associate with different areas of complex substrata.

While overall residency to White Point was high, seasonal periods of prolonged absence were observed in a majority of tagged individuals during the summers. This seasonal pattern and timing of reduced home range residency is indicative of migratory spawning behavior of BSB. The return of individual BSB to the same reef locations further strengthens the evidence for homing behavior and long-term site fidelity to the PVSSS.

No shifts by tagged individuals to deeper water were observed over the course of the study, nor was there a relationship between size (age) and depth of home range for tagged BSB. This suggests that patterns of site fidelity and residency among mature BSB are not driven by an ontogenetic shift. Planktonic larval duration in BSB is relatively short, with recruitment to protected bays and estuaries or shallow nearshore coastal habitat typically occurring in 1 lunar cycle (Butler et al. 1982, Allen 2012). Juveniles and young adults eventually move into slightly deeper coastal environments where they associate with edges of complex substrata (Quast 1968, Turner et al. 1969, Feder et al. 1974, Allen 2012). The evidence of homing behavior to tagging locations and the high degree of site fidelity observed in tagged individuals suggest that once adult BSB settle into a suitable location on the reef, the potential for long-term residency exists for a species that can live decades. This life history pattern is consistent with other temperate reef associated species, such as kelp bass, California sheephead, and ocean whitefish (Lowe et al. 2003, Topping et al. 2005, Bellquist et al. 2008). This propensity for BSB to exhibit such long-term high residency to rocky ecotones at White Point provides an opportunity for an individual to be subjected to long-term dietary exposure to elevated contaminant concentrations within the PVSSS. This is likely representative of many other large reef predator species with similar residency to the White Point area.

Home range size and habitat selection

Home range size estimates determined for tagged BSB in the current study are consistent with those from previous studies of the species as the home ranges are small relative to the available habitat, with well-defined core areas of activity (Mason & Lowe 2010, McKinzie et al. 2014). They are also consistent with reported home range size for other reef-associated species, such as kelp bass, California sheephead, and leopard coral grouper (Zeller 1997, Lowe et al. 2003, Topping et al. 2005). Despite efforts to standardize the number of positions used in calculating KUD estimates, differences in days at liberty among individuals may have resulted in increased variation in overall home range area estimates. These estimates likely provide robust core area estimates or 50% KUDs that revolve around 1 to 3 repeatedly used locations on the rocky reef (Fig. 4b) but may underestimate the actual overall home ranges or 95% KUDs that commonly include sporadic forays into surrounding habitat (Fig. 4a) (Zeller 1997, Kern et al. 2003). For individual fish, the direction, distance, and frequency of these forays from core areas to nearby habitat are dependent on specific habitat characteristics, such as reef complexity and distance to nearby soft-bottom foraging/resting sites, as well as both intra-specific and inter-specific competition within individual home ranges (Zeller 1997, Heupel et al. 2004, Topping et al. 2005). This behavior may lead to high individual variability in degree of long-term exposure to contaminants.

A strong association with the rock/sand ecotone was observed, as in all previous studies, and virtually mirrors the edge response observed by Mason & Lowe (2010). There was a diel pattern observed in the proximity of VPS relocations to the ecotone similar to the pattern reported by Mason & Lowe (2010). Daytime relocations occurred more frequently above the rocky reef and occasionally farther into the coarse sand sediments, which may be representative of daytime foraging behavior. It appeared that individuals rest at night in areas of rock/sand mix near the reef ecotone (<40 m from ecotone), consistent with the observations of Turner et al. (1969), then make forays in either direction to surrounding soft substrata (75 to 125 m from ecotone) or rocky reef (<5 m from ecotone) habitats during the day. HSI values show a similar diel pattern, with use of the rock substrate being high during the day and low at night while use of the bordering rock/sand mix is low during the day and high at night, consistent with previous work on the species (Mason & Lowe 2010, McKinzie et al. 2014). In addition to varying degrees of proximity to the most contaminated sediments, individual home ranges are also likely to have differences in habitat composition and prey types available based on the benthic complexity at their specific location.

Although the tags used in this study did not measure pressure (depth in the water column), the movements observed in tagged BSB likely represent the unique variety of feeding behaviors in which this generalist species engages, including movements away from the reef over sediments as well as into the water column. Between depths of 20 and 40 m, habitat composition and availability of prey items at multiple trophic levels varies considerably across the PV Shelf surrounding White Point. The diets of individual BSB are likely dependent on prey availability and individual preference, resulting in spatial and temporal differences in exposure to contaminated prey items, which may explain, to some degree, the high variability in muscle contaminant loads for BSB sampled (NOAA 2007). Home ranges for tagged BSB from this study may not have included the most highly contaminated areas of the PVSSS, but some individuals occupied areas with DDT concentrations over 2 orders of magnitude greater than other nearby rocky reefs. Therefore, BSB from White Point with the highest body burdens of DDT likely accumulate organochlorines via long-term dietary exposure to prey with elevated levels of contamination that have been increased through mechanisms of bio-magnification in the trophic system.

Spawning migration

Seasonal patterns of site fidelity observed in this study are consistent with the timing of fisheries reported catch data from several southern California spawning aggregation sites and the expected behavior of seasonal spawning migration by BSB. Evidence of large-scale movements by individual BSB documented by traditional mark and recapture studies in the Southern California Bight reported distances between spawning season and non-spawning season recaptures averaged 13 ± 8 km (Jarvis et al. 2010). Earlier observations of BSB by Turner et al. (1969) found seasonal population declines on reefs consistent with seasonal spawning migration, and breeding aggregations over sandy areas were observed. Mason & Lowe (2010) later reported year-round residency in 50% of the individuals tagged at Santa Catalina Island. Mason & Lowe (2010) and Jarvis et al. (2010) hypothesized that this could be evidence of either partial migration, when only part of a population is migratory, or intraspecific differences in spawning behavior of BSB. Similar partial migration behavior has been reported in many other reef-associated species (e.g. Zeller 1998, Papastamatiou et al. 2013, TinHan et al. 2014). Existence of partial migration has been attributed to a potential evolutionary advantage selecting for multiple reproductive strategies due to spatial and temporal differences in habitat quality and dynamic environmental factors (Jonsson & Jonsson 1993, Chapman et al. 2012, TinHan et al. 2014). Inter-annual changes in environmental conditions can decrease the fitness of some individuals, reducing energy stores and making reproductive investment and energetically expensive long-distance migration risky (Chapman et al. 2012). While BSB that migrate to an aggregation during a given season are known to be spawners (Jarvis et al. 2014), it is not known if non-migrating fish spawn annually. Partial transient spawning migration observed in this study suggests the possibility of either dynamic spawning periodicity or both migratory and resident spawning behaviors in BSB, with variation in thresholds for environmental conditions affecting an individual's tendency to migrate (or spawn at all) (Chapman et al. 2012). While the proportion of individuals migrating from White Point may vary inter-annually, the existence of a transient migratory pattern in a potentially highly contaminated population expands the human health risk beyond the boundaries of the PVSSS.

The direction of BSB emigrations from the main array detected by bracket receivers combined with the high percentage (73%) of tagged fish being detected at Huntington Flats during the summer spawning season support the hypothesis of transient migratory spawning behavior. In addition, repeated migrations by individuals to the same spawning aggregation over multiple years and their subsequent return to established home ranges at White Point corroborate the high site fidelity to spawning and non-spawning locations reported from mark and recapture data by Jarvis et al. (2010). One emigration to the northwest makes spawning migrations to the Santa Monica Bay aggregation from the PVSSS possible, but the overwhelming majority (98%) of movements of BSB to the southeast suggest that the Huntington Flats aggregation is the destination for most migratory individuals in the population near White Point. Huntington Flats, the largest aggregation site reported for BSB and where nearly half of the landings in southern California occur annually, represents an attractive location because of its depth range, distance from nearby coastal rocky reefs, typically strong summer thermocline, prevailing onshore winds, and counterclockwise gyre (Johannes 1978). Individual BSB resident to the southeastern end of the PVSSS including the White Point outfall disproportionately frequent this Huntington Flats aggregation site during the summer spawning season, increasing the potential for export of contaminants and the associated human health risk beyond the southern boundary of the current warning area.

Timing and duration of individual migrations varied between tagged BSB and between spawning seasons, suggesting that BSB departures from home ranges within the PVSSS are driven by variability in water temperature in addition to more predictable cues such as daily tidal flux and photoperiod. More variable environmental cues reported as potential drivers for other species include upwelling events, water temperature, winds, currents, and meso-scale cyclonic eddies (Johannes 1978, Colin 1992, Heyman et al. 2005, Heyman & Kjerfve 2008). Major wind-driven upwelling events common in the spring months are interrelated with changes in SST and the temperature at the common depth range of BSB on the PVSSS. McKinzie et al. (2014) reported a strong association between BSB spawning activity on Huntington Flats and the presence of the thermocline. The thermocline strengthens in the summer as upwelling in the Southern California Bight ceases (Hickey 1998), and greater temperature differences between surface and depth develop. In both summer seasons of the present study, the timing of individual BSB departures was associated with increases in average water temperature and difference between sea surface temperature and temperature at depth (a proxy for the thermocline). Annual variability in possible environmental cues for spawning migrations by BSB from the PVSSS requires that management decisions regarding potential seasonal closures account for inter-annual differences in the timing of movements by potentially contaminated BSB.

While there was no relationship between departure date and fish length, there was a general trend of longer duration of absence with an increase in size for BSB tagged in this study. Smaller fish were also observed leaving the White Point area around the same dates as other larger fish, while a few larger fish departed either earlier or later on days when no other fish were leaving the array (Fig. 8). This may provide some preliminary evidence that migration timing and direction is a learned behavior in BSB, as has been hypothesized for other species (Sadovy & Domeier 2005). When combined with the increased minimum size limit for BSB, this extended duration of absence increases the probability of larger and potentially more contaminated individuals being landed by anglers during the spawning aggregation. The extended duration of absence also suggest larger fish have a protracted spawning season, which has implications for stock assessments based on reproductive potential (Fitzhugh et al. 2012).

Passive acoustic telemetry proved to be an effective tool for providing long-term coarse-scale presence/absence data and fine-scale positional data from a large sample of fish tagged within a large study site. In addition to the fixed array, using receivers deployed from vessels to locate migrating fish in a ~55 km^2 spawning aggregation produced 5.5-fold more relocations than traditional angler recaptures during the same time frame. The efficiency with which these data were gathered using a suite of passive acoustic telemetry methods displays its potential for use in future studies designed to inform management decisions for other environmental contaminant sites or even marine protected areas requiring similar information.

All fish tagged in the study were estimated to be at least 4 yr old, with some 3-fold greater than that age. BSB are a relatively long-lived (up to 24 yr) demersal species, and the results of this study show that once settled into long-term home ranges, adult BSB reside within the PVSSS. The generalist diet of BSB also includes mobile prey items, such as small pelagic fish, which raises the possibility that some of these prey species are spending time in even more highly contaminated areas of the shelf. Even transient bait species sampled in southern California have been shown to carry elevated concentrations of contaminants (Jarvis et al. 2007). Dietary uptake of DDT by an Asian bass species from a similarly high trophic level as BSB was reported to be 14.8% in the muscle tissue and 98% in the whole fish over a period of 42 d (Bayen et al. 2005). Differences in the proximity of individual home ranges to areas of highly contaminated sediments, the age and past residency patterns of individual fish, and the common prey in their diet may subject different individuals to a broad range of exposure to contaminants, contributing to the variability of body burdens seen in BSB along the Southern California Bight and the extremely high levels seen in some fish sampled in the White Point area of the PVSSS (NOAA 2007).

Conclusions

Results of the current study provide important insight into transient aggregative migratory behavior and environmental spawning cues and confirm the migration of individual BSB to Huntington Flats. This connectivity between White Point and Huntington Flats creates an additional dynamic in the potential for this species to act as a vector for export and human consumption of legacy contaminants from the PVSSS. While it may be difficult to quantify human health risk without more demographic data on the population of BSB at White Point and the spawning aggregation, there were 4 BSB (7.8%) that were reported caught by recreational anglers at Huntington Flats. Several other BSB did not return to the array, possibly due in part to unreported angler landings. The current 'do not consume' advisory zone for BSB does not include Huntington Flats (Klasing et al. 2009); therefore, during spawning season, the advisory zone may not provide adequate protection to recreational fishers who are consuming BSB migrating from the PVSSS that potentially carry unhealthy levels of contaminants.

Future management decisions designed to remediate the sediment-bound legacy contaminants in the PVSSS should consider the results of this study, as solutions focusing only on the most contaminated areas of sediment (e.g. placing a sediment cap on just the 'hot spots') may fail to prevent or reduce the bioaccumulation of DDT by BSB and other resident predators that are frequently using shallower areas with more moderate concentrations of contaminants (Wolfe & Lowe 2015).

Efforts to effectively mitigate the human health risk from potential export of DDT accumulated by BSB should consider the timing and duration of seasonal migrations by these fish to aggregations in Huntington Flats. Estimating the degree to which these migrations pose a risk to the public will require sampling BSB from the spawning aggregation during the summer months when 90% of the annual catch is landed and individuals from the PVSSS are likely to be present. Seasonal expansions of the current 'do not consume' zone should also consider the inter-seasonal variability in migration timing and potential environmental cues.

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