FINAL REPORT

MONITORING OF COASTAL CONTAMINANTS

USING SAND CRABS

Prepared for:

Central Coast Regional Water Quality Control Board

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INTRODUCTION

Naturally occurring organisms and entire communities have been used to monitor pollution and can serve as bioindicators. Such organisms and communities also have the potential to be used as indicators of ecosystem recovery from a spill or chronic contamination by pollutants. A range of bioindicator species or sentinel organisms for use in monitoring the level of pollutants present in coastal environments and assessing the recovery of damaged coastal ecosystems needs to be established for the California coast. Mussel Watch programs (Farrington et al. 1983, Goldberg et al., 1978, Martin et al. 1988, NOAA 1988, Phillips 1980) have been successfully used to describe the spatial and temporal variability of pollutants in marine and estuarine waters in many regions of the world, including California.   However, there are some important limitations to the use of mussels as bioindicators on the California coast, including habitat type and the limited availability of hard substrates in many areas.

Sandy beaches comprise approximately three-quarters of the world's shorelines (Bascom 1980). In southern California, 74%, 93% and 66% of the coasts of Santa Barbara, Ventura and Los Angeles Counties, respectively, are sandy beaches (Smith et al. 1976; Dugan et al. 1998). This high prevalence means that sandy beaches are likely to receive the majority of contamination from a spill or other impact associated with coastal and offshore oil and gas activities. This prediction has been confirmed repeatedly in recent years with significant spills of petroleum affecting the sandy beaches at Guadalupe, Avila, Santa Ynez River and San Antonio Creek, and Huntington Beach. Beaches are also exposed to contamination from sewage and urban, agricultural and industrial runoff, and many beaches are associated with stream, slough and river mouths.

Exposed sandy beaches in California are inhabited by an abundant and diverse invertebrate macroinfaunal community (Straughan 1982, 1983; Dugan et al. 1995, Dugan et al. 2000a, 2003) which is an important food resource for vertebrate predators including shorebirds, seabirds, marine mammals and fishes. This list of predators includes federally listed species, such as the western snowy plover. In addition, a number of sandy beaches of the region are nesting sites and/or critical habitat for two species of endangered birds: western snowy plovers and California least terns.   Sandy beaches are also considered extremely valuable as recreational and scenic resources for humans, both residents and tourists (Leatherman 1997).

The use of Mussel Watch programs to monitor pollutants in exposed sandy beach environments is severely limited due to the lack of hard substrate suitable for mussels. A different approach is needed to monitor pollutants along much of the California coastline. The suspension feeding sand crab (*Emerita analoga*), a dominant member of the sandy beach invertebrate community, occurs intertidally on almost every type and length of exposed sandy beach in California. This species reaches high abundance, exceeding 100,000 individuals per running meter of shoreline, and can be easily collected in large numbers over a range of tide conditions.

Populations of *E. analoga* have been used as bioindicators in a few studies (Siegel and Wenner 1984, Wenner 1988) and this species is known to bioaccumulate metals and hydrocarbons (e.g. Burnett 1971, Rossi et al. 1978, Wenner 1988, Dugan and Page unpublished). Tissue loadings of DDT in *E. analoga* were successfully used to describe the distribution of DDT associated with

the Whites Point Outfall in the Southern California Bight (Burnett 1971). High concentrations of petroleum hydrocarbons have been reported in *E. analoga* from selected southern California beaches (Rossi et al. 1978, Dugan et al. unpublished data, DFG unpublished data, Entrix 1996) and recent studies have indicated that sand crabs can accumulate significant concentrations of total hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) in their tissues and eggs on beaches in central and southern California (Dugan et al. unpublished). This species has also been shown to exhibit sensitive and plastic life history responses to environmental variation and anthropogenic impacts (Fusaro 1978, Siegel and Wenner 1984, Wenner et al. 1987, Dugan et al. 1991, 1994).

The goal of this study was to collect information that could be used to develop a monitoring program and provide baseline data for evaluating contaminants on sandy beaches using the common sand crab (*Emerita analoga*). This information is needed to assess the potential for this species to be incorporated into the Regional Water Quality Control Board's Central Coast Ambient Monitoring Program (CCAMP) as a way to monitor pollutants in exposed sandy beach environments.

STUDY OBJECTIVES

1)   Develop a monitoring program and baseline information (sampling time of year, size class, biomarkers) for contaminants on sandy beaches using the common sand crab, *Emerita analoga*, that can be incorporated into the Regional Water Quality Control Board's Central Coast Ambient Monitoring Program (CCAMP).

2)   Determine if there is ongoing petroleum contamination from the Guadalupe oil fields.

3)   Determine if there are elevated levels of petroleum in the Guadalupe and Avila areas relative to areas to the north and south in the central coast region of California .

4)   Compare contamination levels of petroleum hydrocarbons in sand crabs collected in areas near oil sources, river sources, urban beaches and reference areas.

BIOLOGY OF THE STUDY ANIMAL

Distribution
The anomuran crabs of the super family Hippidae are important components of the macrofaunal communities of exposed tropical and temperate sandy beaches throughout the world (Efford, 1976; Trueman, 1970; Trueman and Ansell, 1969; Haley, 1982; Dugan et al., 1995, Dugan et al. 2000 ab, 2003, Lastra et al. 2002). California beaches are inhabited by the suspension-feeding species, *Emerita analoga*, which occurs on exposed sandy beaches of all morphodynamic types on the eastern Pacific coasts of North and South America. The reported North American occurrence of this species spans over 20 degrees of latitude with records on beaches from Kodiak Island, Alaska (58° N) to Magdalena Bay, Baja California (26° N) and in the Gulf of California (Efford 1970, 1976). In South America, this species has been reported on sandy beaches from

Salavary, Peru to False Bay, Argentina (Efford 1970, 1976) (note: the Argentina record is a single report from one location just east of Cape Horn). The North American range of *E. analoga* spans Point Conception, an important transition zone between coastal oceanographic regimes and the Oregonian and California marine faunal provinces (Seapy and Littler 1980). Studies to date have found very little genetic variability in populations of this species across its North American range and recent results suggest they may be essentially panmictic (Beckwitt 1985, Barber et al. unpublished).

Habitat
Emerita analoga is a rapidly burrowing sediment generalist (sensu Alexander et al., 1993) with excellent orientation and swimming abilities that can successfully inhabit the full range of exposed sandy beaches from fully reflective to dissipative morphodynamic states (Dugan et al. 2000b, Jaramillo et al. 2000). This crab is an active tidal migrant and intertidal zonation patterns in this species vary across the tidal cycle, seasonally, and among beaches (Cubit 1969, Fusaro 1980, Jaramillo et al. 2000). Juveniles of *E. analoga* and other hippid crabs generally occupy a notably higher intertidal level than adult crabs (Fusaro 1980; Haley 1982), while adult crabs can occur as deep as the shallow subtidal zone during higher tides, periods of beach erosion, and on some beach types (Jaramillo et al. 2000). These highly mobile crabs generally aggregate in the active swash zone. The ability of *E. analoga* to burrow at similar speeds across a range of sediment grain sizes likely contributes to the success of this species even in the coarse sediments and harsher swash conditions typical of beaches with reflective characteristics (see Dugan and Hubbard, 1996; Dugan et al. 2000b). As such, *E. analoga* may also be able to survive temporal changes in sediment grain size, such as those occurring on many intermediate type beaches (Dugan unpublished).

Food habits
Emerita analoga is a suspension feeder that uses the plumose second antennae to sieve fine particles from the turbulent moving water in the swash zone (Efford 1966). This species feeds primarily on phytoplankton which is reflected in carbon and nitrogen stable isotope values (Dugan unpublished). In addition, individual growth rates (molt increments), and life history characteristics of *E. analoga* are significantly correlated with food availability estimated from surf zone chlorophyll concentrations (Dugan 1990, Dugan et al 1994).

Life history
As in many anomuran crabs, *E. analoga* has an extended planktonic larval life of 3-4 months, going through at least 9 molts as a zoea before metamorphosing to a megalopa and settling in the intertidal zone of sandy beaches. The planktonic larvae are the primary dispersal stage of this species, as megalopa and crabs move relatively small distances within the intertidal zone. Recruitment of megalopa to the beach occurs in distinct pulses which may be associated with shifts in nearshore oceanography and currents. In California, recruitment can occur from February or March though October in many years. Recruitment of this species is most intense in the spring months and tapers through the summer. A smaller late summer/fall pulse of recruitment can occur in some years in California.

Following recruitment to the intertidal zone from the plankton, megalopa of *Emerita analoga* spend approximately one month in the intertidal zone before molting to juvenile crabs.

Megalopa are distinguished from small juvenile crabs by their plumose pleopods and short eyestalks. Juvenile crabs grow rapidly in the spring and summer months and can mature in their first season. Crabs live a maximum of 2-3 years and overwintering mortality is very high in some populations. There is marked sexual dimorphism in size in this species (Efford 1967). Male crabs reach much smaller maximum sizes than female crabs and may have decreased survival over winter (Dugan 1990, Dugan et al. 1991, 1994)). This dimorphism is a product of differential growth rates in male and female crabs (Dugan 1990). Female crabs brood eggs/embryos and clutch size (fecundity) is a function of female size (Wenner et al. 1987, Dugan et al. 1991). Multiple clutches can be produced each season, and clutch size varies seasonally (Dugan 1990, Wenner et al. 1987, 1991). The length of the reproductive season varies geographically, ovigerous crabs are generally present from April to October in populations south of Point Conception, but may be present all year in populations living north of that point (Dugan 1990).

The life history of *Emerita analoga*, including size and age at maturity, growth rate, maximum male and female crab size, and survival, varies significantly across the geographic range in California and in South America (Osorio et al. 1967, Dugan 1990, Dugan et al 1991, 1994, Wenner et al. 1993) and on a local scale (Dugan and Hubbard 1996). This variation appears to be a function of variation in growth rates and age at maturity along with increased survival of larger individuals over winter. Molt increments and growth are greater in northern populations. This is likely related to delayed maturity and higher food availability in colder waters.

Ecological role
Populations of *Emerita analoga* are major components of invertebrate macrofaunal communities of exposed sandy beaches in North and South America, often making up the majority of the total intertidal abundance and biomass (Jaramillo and McLachlan 1993, Dugan et al. 1995, 1996, 2000a, 2003). Densities of sand crabs can exceed 100,000 individuals m^{-1} on beaches on the central coast of California and elsewhere (Dugan et al. 2003). This species is important as prey for vertebrate predators, such as shorebirds, seabirds, fishes, and marine mammals.

METHODS

Field methods:

Sampling Design
In cooperation with Vandenberg Air Force Base, Monterey Bay Marine Sanctuary, California State Parks, and the Nature Conservancy, scientists from the California Department of Fish and Game and Marine Science Institute at the University of California at Santa Barbara collected samples of the sand crab, *Emerita analoga* at 19 sandy beach sites on central coast of California (Region 3 Santa Barbara to Santa Cruz County) (Table 1, Figure 1a-d). Sample areas were selected to include four general categories: reference areas, urban beaches, beaches adjacent to agriculture areas and river mouths, and beaches adjacent to oil sources. Samples of crab*s* were collected at a minimum of three beaches fitting each category type (Table 1). At potential source/discharge areas, at least four beach locations were sampled in a spatial array (except for
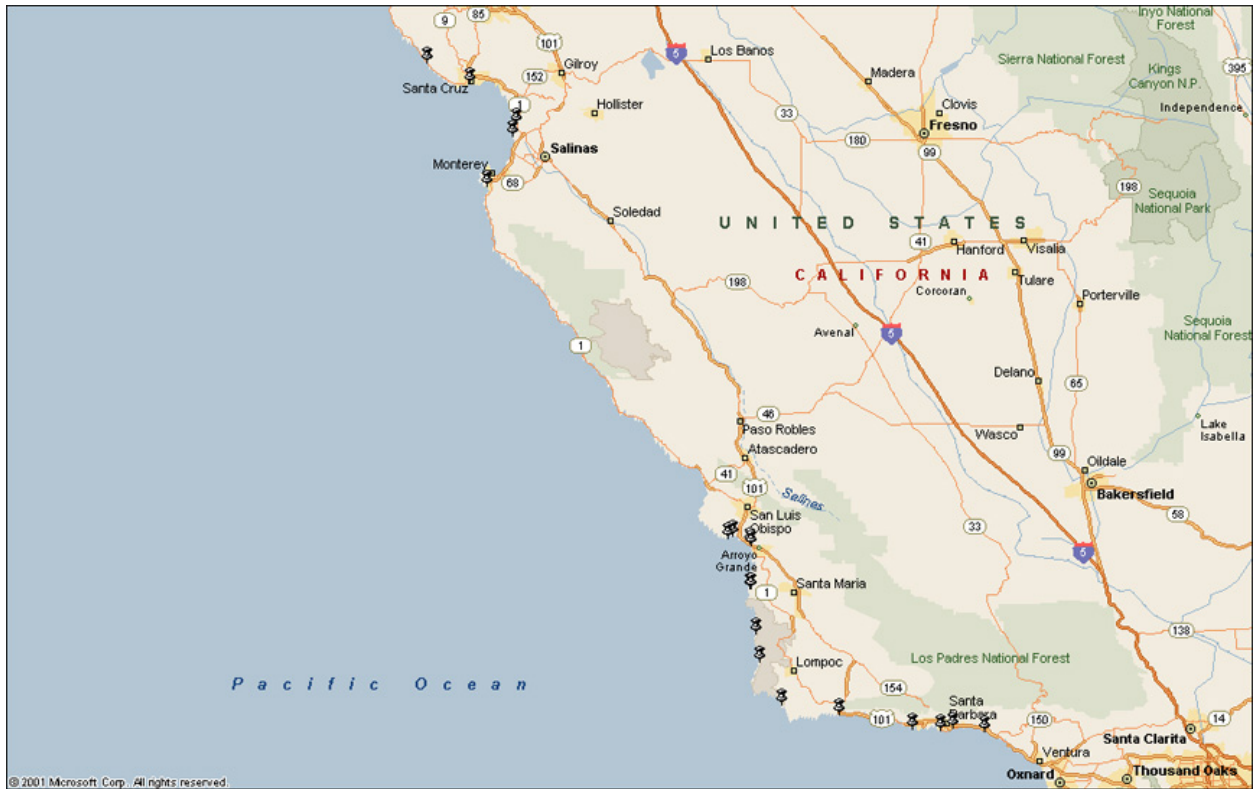
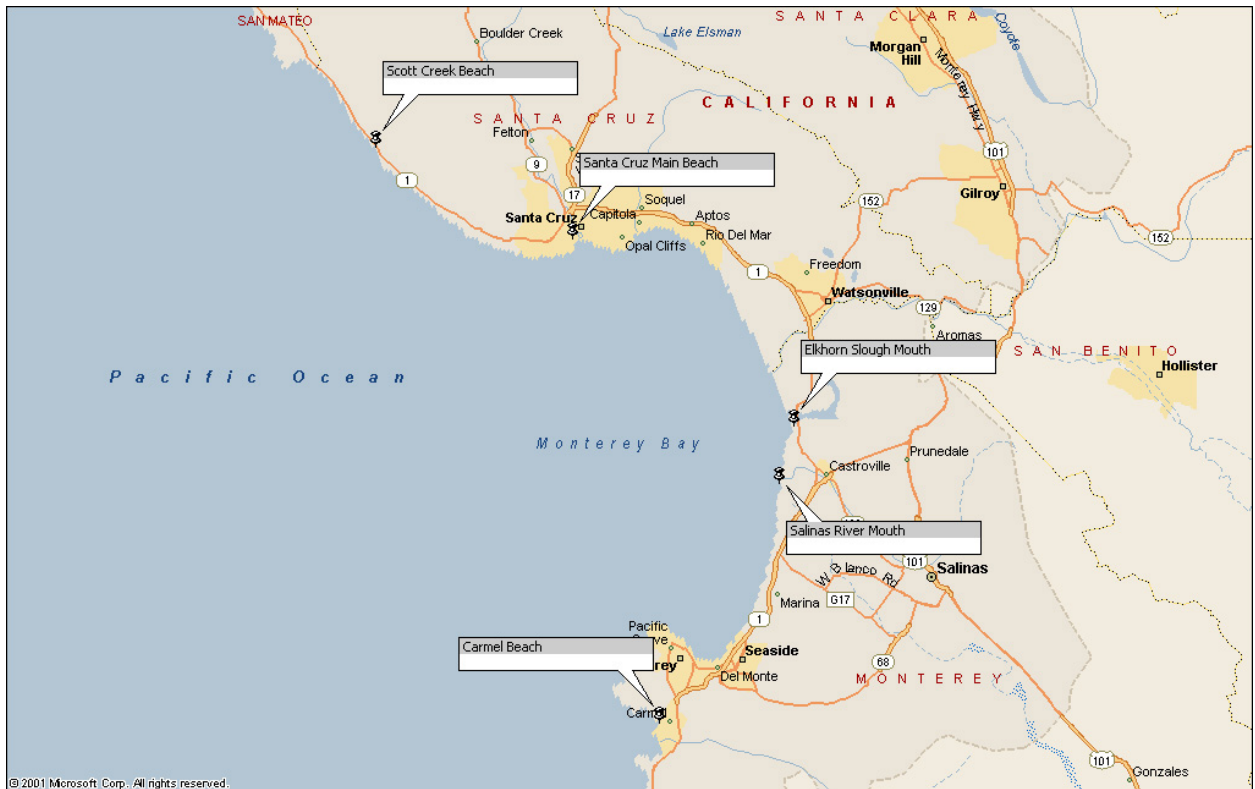Figure 1a. Map of the study area showing locations of the 19 sampling sites for sand crabs.

Figure 1b. Locations of sampling sites for sand crabs in Monterey and Santa Cruz Counties.

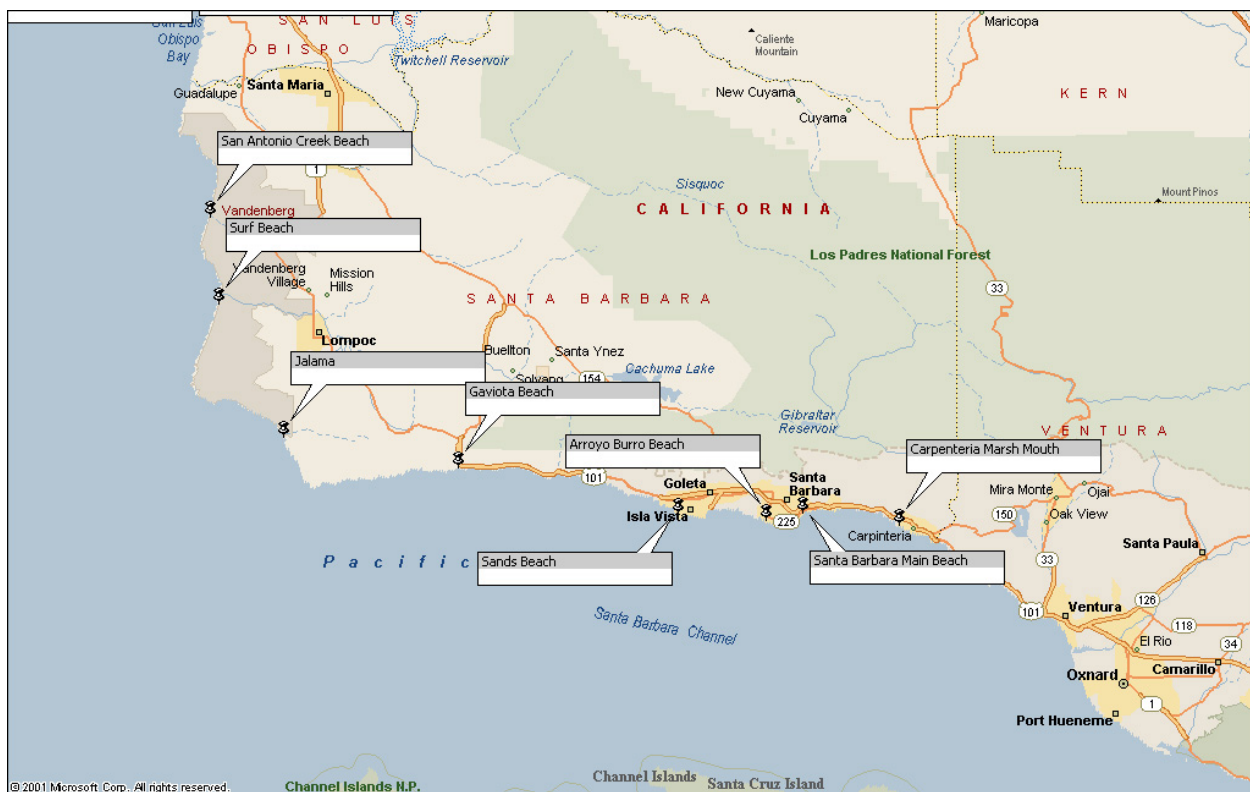Figure 1c. Locations of sampling sites for sand crabs in San Luis Obispo County

Figure 1d. Locations of sampling sites for sand crabs in Santa Barbara County.

Port San Luis Harbor Beach and Sands Beach). Samples of crabs were collected along a spatial gradient away from the potential sources at distances ranging from 10 to 900 meters. Where possible, samples were collected at a range of distances in opposite longshore directions of potential sources/discharge areas, such as river mouths.

In general, two replicates were collected at each sample site. Individuals of *Emerita analoga* were collected using cleaned stainless steel shovels and gloved hands. Latitude and longitude were measured at each sampling location with a GPS. All crabs collected and determined to be of the appropriate size and/or age class were placed in methanol rinsed aluminum foil and then into pre-labeled ziplock^{TM} bags. Bags were placed in ice chests with dry ice and kept frozen until analysis. Both of the replicates collected were analyzed for polynuclear aromatic hydrocarbons (PAHs). One of the replicates was additionally analyzed for pesticides and trace elements.

For the purpose of investigating spatial variation in contaminant burdens in *Emerita analoga*, the samples were collected at the majority of sites listed in Table 1 during the summer (July/August) of 2000.   To investigate possible seasonal variability in uptake of contaminants by *E. analoga*, samples were collected during the spring (May 2000), summer (July/August 2000), and winter (February 2001) at Avila Beach and Guadalupe Beach. To investigate contaminant levels present in different life stages of this species, megalopa of *E. analoga* were collected during the spring months (May) and compared to overwintered crabs.

Sample handling and analysis

Sample Handling
A chain-of-custody form was completed and accompanied every sample. The chain-of-custody record contained the following information, as appropriate: project name, sample identification number (unique for each sample), name and signature of field recorder, signatures of persons involved in the chain of possession, inclusive dates and times of possession and sample shipping date and mode. Each shipping container containing samples was accompanied by its own chain of custody record.

Chemical analysis
Each replicate was analyzed for polynuclear aromatic hydrocarbons (PAHs). One of the replicates was additionally analyzed for pesticides and trace elements. Analytical methodologies conformed to the State Mussel Watch protocols and quality assurance requirements for PAHs, pesticides, and trace metals. Samples were prepared for pesticide, PCB and PAH analysis using pressurized fluid extraction (Dionex ASE 200) followed by gel permeation chromatography and column chromatography cleanup and fractionation. Sample extracts were analyzed for pesticides and PCBs using Agilent 6890 gas chromatographs each equipped with dual electron capture detectors and dual 60 meter DB5 and DB17 columns (J&W Scientific). Sample extracts were analyzed for PAHs using an Agilent 6890/5973 GC-MSD equipped with a 30 meter DB5MS column (J&W Scientific). In addition, the petroleum products were analyzed for a variety of biomarkers such as terpane, sterane and monoaromatic and triaromatic sterane families. The pesticide and PCB extraction and analysis followed Fish and Game SOP "SO_Tissue". The

PAH extraction followed Fish and Game SOP "PAH Extraction and Cleanup" and PAH quantification followed the Fish and Game protocol #FG-Polycyclic Aromatic Hydrocarbons.

Quality assurance
Data was collected according to quality assurance measures specified in the State Mussel Watch Program Quality Assurance Program Plan. During the sampling, sample duplicates, trip blanks, and field equipment blanks were collected. Duplicate samples were collected using the same procedures as those used to collect primary samples. Duplicate samples were analyzed for PAH quantification as above. Two trip blanks consisting of a pre-cleaned aluminum foil accompanied each of the sample teams into the field. The two trip blanks were opened for five minutes at a randomly selected sampling site and evaluated for possible incorporation of airborne contaminants. Equipment blanks were prepared by pouring deionized laboratory reagent water over sampling shovels after decontamination following sample collections. The rinse water was collected and analyzed for PAHs with the rest of the samples as described above.

Data analysis
Sample results at sites associated with oil contamination, urban development, river mouth discharge and reference areas were compared. Samples of different age classes and seasons from Guadalupe and Avila were compared statistically using ANOVA. Regression analyses were used to investigate possible spatial trends in tissue burdens of contaminants.

Laboratory results in electronic format including minimum detection limits, probable quantification limits, and QA/QC results were produced for the samples analyzed. These results were delivered in an Excel data format provided by CCAMP to the RWQCB.

RESULTS

A total of 164 samples of sand crabs were collected at 19 sites characterized as having different land use or potential contamination sources as identified in Table 1. We collected sand crab samples at 3 urban beaches, 5 beaches adjacent to agricultural runoff, 7 beaches adjacent to potential oil sources including sites of chronic petroleum spills at Avila and Guadalupe, sites of a recent oil spill on Vandenberg Air Force Base, sites adjacent to areas of natural petroleum seeps, and 4 potential reference beaches (Table 1, Figure 1a-d)). Samples were arrayed spatially from 10 to 1000 meters distance along the shoreline from potential sources of terrestrial runoff such as river, slough or creek mouths, or a nearby landmark such as a pier or jetty (Table 1).   At Avila and Guadalupe Beaches, additional samples of sand crabs were collected in May 2000 and February 2001 for use in comparisons of lifestages and evaluation of seasonal variation.

Petroleum Hydrocarbons

Polycyclic aromatic hydrocarbons or PAHs are ubiquitous in the environment. These contaminants form when organic matter is exposed to high temperatures or burned. For example, a forest fire is a major source of PAHs. PAHs are present in crude oil and are also formed when gasoline and other petroleum products are combusted. PAHs include a great diversity of compounds and two major classes are recognized in contaminant studies. The

Table 1. Locations, dates, numbers and types of samples of sand crabs, *Emerita analoga,* collected for contaminant analyses.
(o= areas of oil production, spills, and natural seeps, a= agricultural land use, u = urban land use, r = reference sites)

County/Beach Name	Lat. N Dec. Deg.	Long. W Dec. Deg	Sample date(s)	n	SamplesDistances (m) and landmark	Life Stage/ Reprod. state
Santa Cruz County						
Scott Creek Beach r	37.040	122.239	September 1, 2000	4	325S, 425S (river)	Adult
Santa Cruz Main Beach u	36.961	122.025	September 1, 2000	4	100S, 100N (pier)	Adult (small)
Monterey County						
Elkhorn Slough Mouth a	36.810	121.792	August 11, 2000	5	105S, 246N (jetty)	Adult
			October 12, 13, 2000	4	263S, 131N (jetty)	Adult
Salinas River Mouth a	36.754	121.806	August 19, 2000	9	0, 100S, 200S, 300S (Monterey Dunes Colony)	Adult
Carmel Beach r	36.554	121.940	September 15, 2000	4	0, 100S (main access)	Adult
San Luis Obispo County						
Port San Luis Harbor o	35.171	120.849	August 8, 2000	4	332S, 10 N (pier)	Adult
Avila Beach o	35.178	120.735	May 25, 2000	9	0, 30E, 530E, 250W (pier)	Megalopa
			May 25, 2000	8	0, 30E, 530E, 250W (pier)	Adult
			August 9, 2000	9	25E,100E,10W,100W (pier)	Adult (small)
			February 16, 2001	8	25E, 100E, 10W,100W (pier)	Adult
Shell Beach r	35.148	120.656	August 9, 2000	1	300S (point)	Adult (small)
Pismo Beach u	35.138	120.652	August 9, 2000	4	110S, 10 N (pier)	Adult (2 small)
Guadalupe Beach o/a	34.972	120.627	May 25, 2000	8	20S, 500S, 134N, 634N (river)	Megalopa
			May 25, 2000	8	20S, 500S, 134N, 634N (river)	Adult
			August 7, 2000	12	150N,300N, 450N,750N, 900N (river)	Adult
			February 16, 2001	10	195S, 335S, 200N, 300N (river)	Adult
Santa Maria River Beach o/a	34.970	120.567	August 7, 2000	8	150S, 300S, 450S, 600S (river)	Adult
Santa Barbara County						
San Antonio Creek Beach o	34.795	120.625	August 12, 2000	7	150S, 300S, 150N, 300N (river)	Adult (ovig.)
Surf Beach o	34.690	120.611	August 11, 2000	9	250S, 150N, (river)	Adult (ovig.)
					0, 275S (Surf Station)	Adult (ovig.)
Jalama Beach r	34.512	120.507	August 10, 2000	4	150S, 150N (Trestle)	Adult (ovig.)
Gaviota State Beach r	34.471	120.236	August 10, 2000	4	20E, 150E (pier)	Adult (ovig.)
Sands Beach o	34.410	119.893	August 30, 2000	4	150E, 50W (slough mouth)	Adult (ovig.)
Arroyo Burro Beach o	34.402	119.747	August 29, 2000	7	150E, 300E, 150W, 320W (creek)	Adult (ovig.)
Santa Barbara Main Beachu	34.414	119.696	August 9, 2000	4	280E, 1000E (pier)	Adult (ovig.)
Carpinteria Marsh Mouth a	34.396	119.535	August 9, 2000	6	150E, 300E, 300W (mouth)	Adult (ovig.)
Totals 19 sites	2.6 degrees	2.7 degrees	14 dates	164 samples		2 age classes

pyrogenic PAHs are formed by the burning of organic matter and the combustion of both crude and refined petroleum products. These can reach the intertidal through direct wet or dry deposition from the atmosphere and via runoff from street and parking lot surfaces. The pyrogenic PAHs have a wide range of characteristics, but generally are made up of 4- to 7- benzene rings and are higher in molecular weight. These heavier PAHs are less water soluble, less volatile, less readily metabolized and more persistent and they are dominated by parent species of PAHs. The petrogenic PAHs reach the intertidal via leaks and spills of crude and refined petroleum products. These PAHs generally have 2- to 3- ring structure and are lower in molecular weight. The petrogenic PAHs are more water soluble, more volatile, more readily metabolized and less persistent and are dominated by alkylated or substituted species. Ratios of parent to substituted PAHs can be used to help evaluate potential sources of petroleum contamination.

PAHs were detected in every sample of sand crabs at every beach we sampled (Figures 2, 3). Concentrations of total PAHs in sand crab tissues varied nearly 2 orders of magnitude among sand crab samples collected in August-September 2000, ranging from 20 to 2061 ng/g dry weight and 148 to 14419 ng/g ppb lipid weight.   Concentrations of total substituted PAHs in sand crab tissues also varied over an order of magnitude among samples, ranging from 34 to 2141 ng/g dry weight and 254 to 14526 ug/g lipid weight (Figures 2, 3).

The highest concentrations of petroleum hydrocarbons found in sand crab tissues occurred at beaches adjacent to oil sources including locations of chronic oil leaks and spills, and natural hydrocarbon seep areas in the study region (Figures 2, 3). The greatest concentrations of total PAHs in sand crabs were found in the vicinity of the Santa Maria River (Guadalupe and Santa Maria River) where values for individual samples collected in August ranged from 310 to 2117 ng/g dry weight and 2167 to 14419 ng/g lipid weight. Mean concentrations of total PAHs in samples from the Santa Maria River site located south of the river exceeded 940 ng/g dry weight and 6500 ng/g lipid weight. Mean concentrations of total PAHs exceeding 500 ng/g dry weight and 3400 ng/g lipid weight were also found in samples of sand crabs collected from beaches at Avila, Port San Luis, Sands, and in the single sample from Shell Beach (Figures 2, 3). The mean concentration of total PAHs in sand crabs was 488 ng/g dry weight for the four samples from Pismo Beach but varied over 15 fold among samples.   Sand crabs from the beach at Arroyo Burro also had relatively high tissue concentrations of PAHs (297 ng/g dry weight) (Figures 2, 3). Both Sands and Arroyo Burro beaches are located in close proximity to offshore natural petroleum seeps. Large quantities of freshly deposited tarballs and oil were observed on these two beaches during sample collections in August 2000. It is possible that natural petroleum seeps could affect tissue concentrations of petroleum hydrocarbons in sand crabs on several of the other study beaches, however large quantities of fresh tarballs and oil were not observed on other beaches during our field sampling.

Low concentrations of PAHs were present in sand crab samples from beaches on Vandenberg Air Force Base that were affected by the 1997 Torch oil spill (San Antonio Creek, Surf) (Figures 2,3). It is expected that the overwintered adult sand crabs collected in summer of 2000 settled on those beaches in spring of 1999, long after the September 1997 oil spill.

For some sites, the variance in PAH concentrations in sand crab tissues was high (coefficient of variation > 1) among samples collected within a few hundred meters (e.g. Salinas River, Pismo, and Avila, see Figures 2, 3, 8). This result could be associated with a variety of factors, including different exposure histories, variation in lipid content, molt stage, and reproductive
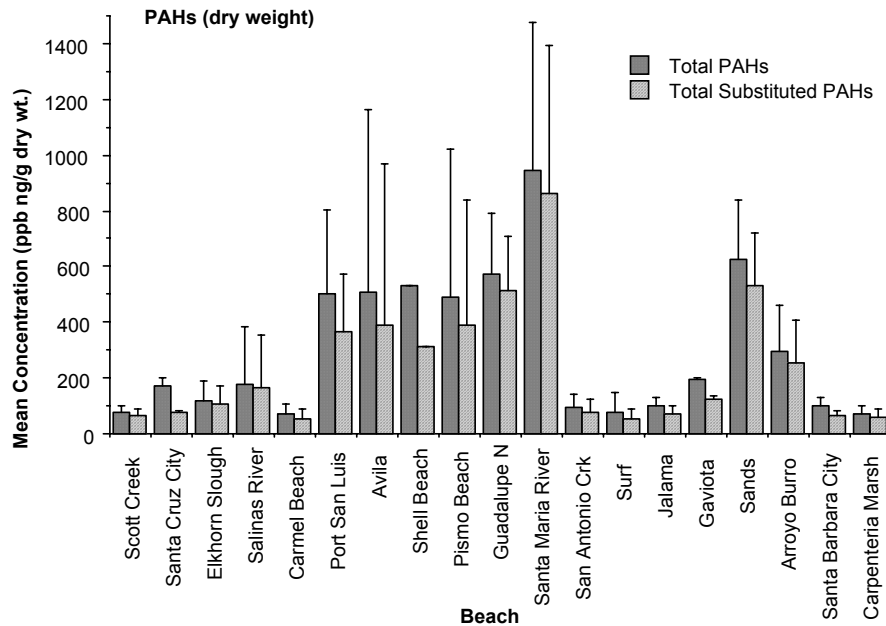

Figure 2. Mean dry wt. concentrations ng/g (+ 1 std. deviation) of total PAHs and total substituted PAHs in tissues of adult sand crabs collected at 19 beaches in August- September 2000.

Figure 3. Mean lipid wt. concentrations ng/g (+ 1 std. deviation) of total PAHs and total substituted PAHs in tissues of sand crabs collected at 19 beaches in August- September 2000.

state, mortality of highly contaminated crabs, and the metabolism of PAHs in sand crabs. It is not possible to resolve this issue with the present sampling design and the limited understanding of PAH metabolism in sand crabs. This is a high priority area for further study and is critical to the interpretation of results on tissue concentrations of PAHs in this species.

When the proportion of substituted PAHs to total PAHs was plotted (Figure 4), it was evident that the majority of PAHs (70% or more) found in sand crab tissues were substituted PAHs at most of the beaches we sampled. The only beach where substituted PAHs made up less than 50% of the PAHs was Santa Cruz City. Sand crabs in the single sample from Shell Beach also had a relatively low level (<60%) of substituted PAHs.

Figure 4. Proportion of substituted PAHs in tissues of adult sand crabs collected at 19 beaches in August-September 2000

The concentration of total PAHs did not vary significantly among age classes of sand crabs at Guadalupe (1 way ANOVA, F= 1.342, p = 0.266, df = 7) or at Avila (1 way ANOVA, F= 0.070, p = 0.795, df = 7) in May 2000 (Figure 5). This result suggests that crabs are exposed to and accumulate PAHs within a month of settling in the intertidal zone following their planktonic larval life and that sources of PAHs are present and available to intertidal crabs at both of these sites on a more chronic temporal scale than that of winter runoff events or river/stream discharge. This result also points to the need to better understand the metabolism of PAHs in sand crabs.
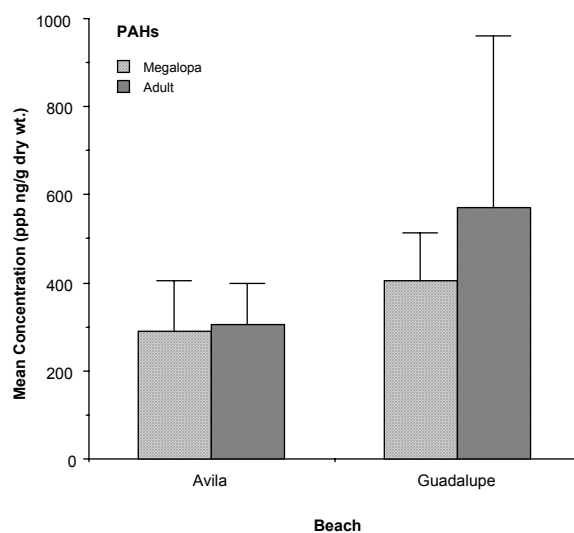
Figure 5. Mean dry wt. concentrations ng/g (+ 1 std. deviation) of total PAHs in newly settled megalopa and overwintered adult sand crabs at Avila and Guadalupe in May 2000.

Using data from Guadalupe and the Santa Maria River mouth where the highest concentrations of PAHs were present in sand crab tissues, we examined the hypothesis that the concentration of total PAHs in sand crabs varied with distance from the river mouth, a potential source of oil contamination. Since concentrations of total PAHs did not vary with age, both age classes of crabs were included in the regression analyses at Guadalupe for May 2000. We found no relationship between the concentrations of total or substituted PAHs in sand crab tissues and the distance from the river mouth for combined data from May and August 2000, and February 2001 (Figures 6, 7). In addition, no significant relationships between total PAHs in sand crabs and distance from the river were present in the regressions of the individual data from May and August 2000 and February 2001. This result suggests that exposure of sand crabs to PAHs at Guadalupe does not vary with distance from the river, a potential source (note: the river mouth location moves along the coastline). A combination of factors including nonpoint sources of petroleum, coastal processes, and the movement of sand crabs along the shoreline may contribute to a lack of spatial patterns in tissue loadings of PAHs. These results suggest that although exposure of sand crabs to PAHs was high in the vicinity of the Santa Maria River, the local source may be relatively widespread and is likely associated with the Guadalupe Oil Field.

At Avila, no spatial gradients in total or substituted PAHs were found (Figures 8,9). The high porosity of sandy beaches and coastal dunes means that a constant exchange of water and potentially dissolved contaminants can occur in the dynamic shallow intertidal aquifer and porewater (e.g. Horn 2002) present in the intertidal zone of the beach. This aquifer may be connected to upland sources of groundwater or it may be relatively isolated from them in the dry season of the year. Sand crabs typically inhabit the intertidal zone at the level where the pore or interstitial water in this shallow aquifer reaches the surface and drains across the beach face into the ocean. This microhabitat preference means that porewater is a likely source of contaminants in sand crabs at Guadalupe, Avila and other beaches.
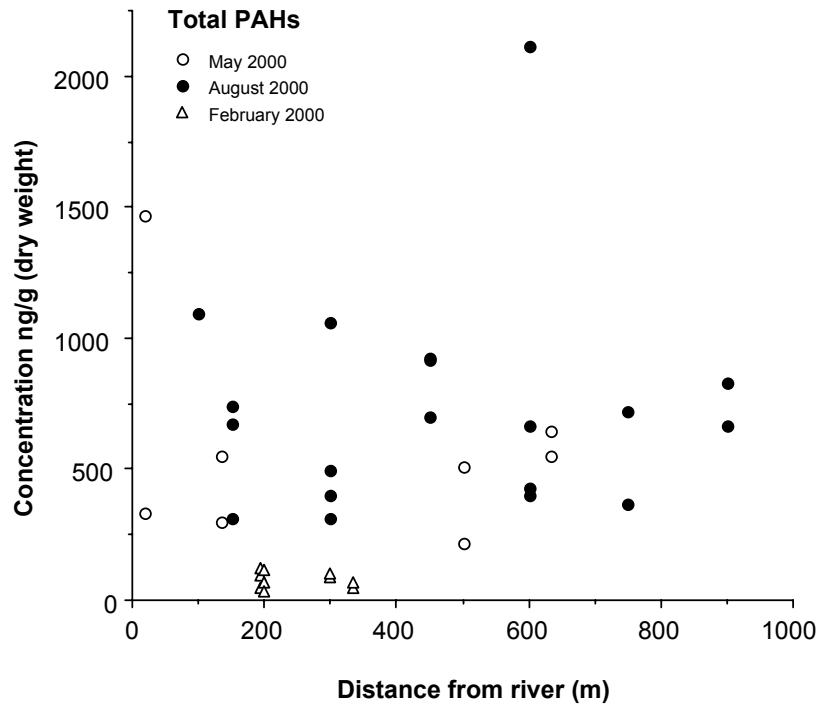
Figure 6. Dry wt. concentrations of total PAHs ng/g in adult sand crabs as a function of distance from the Santa Maria River mouth for samples collected at the Guadalupe/Santa Maria River sites on three dates.
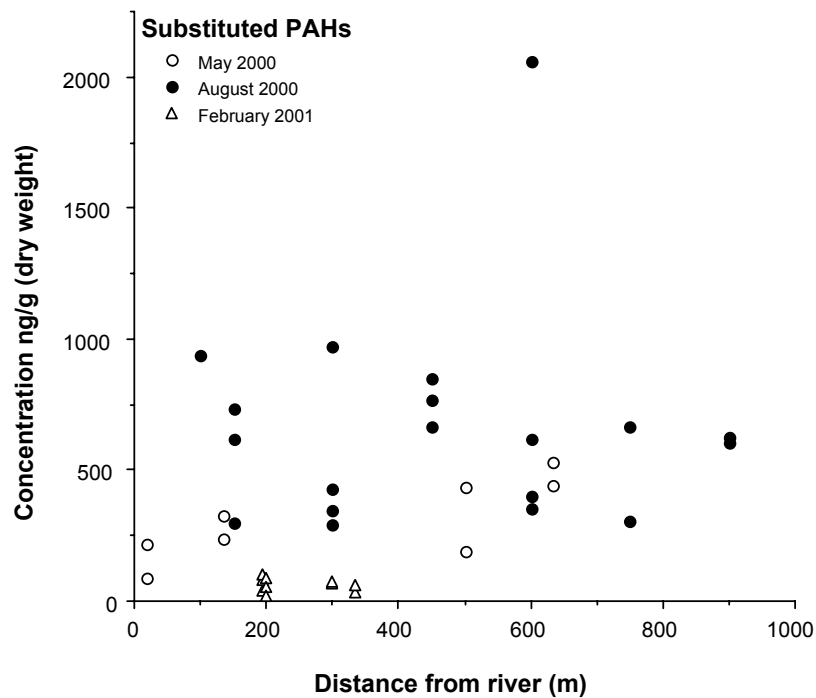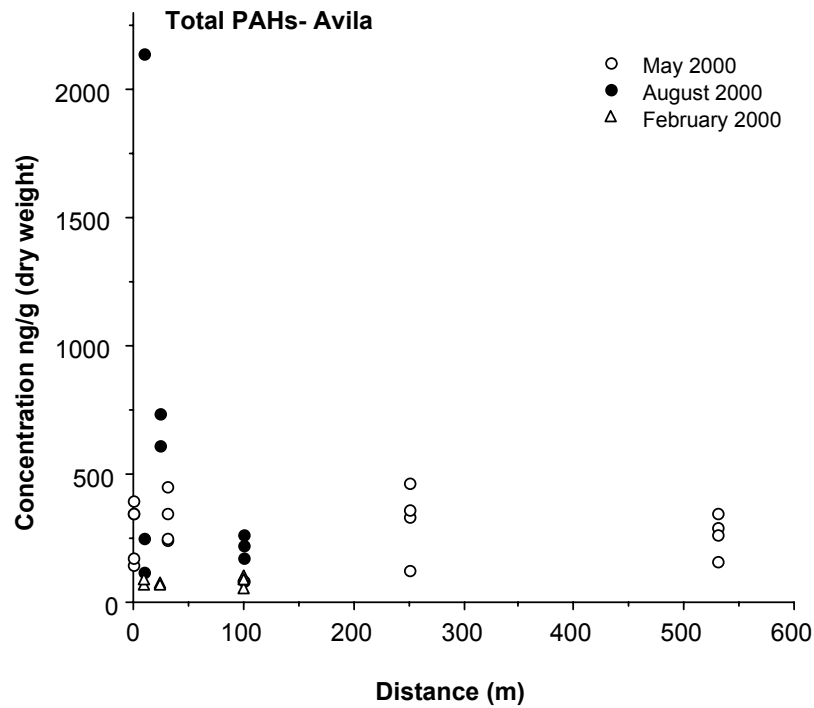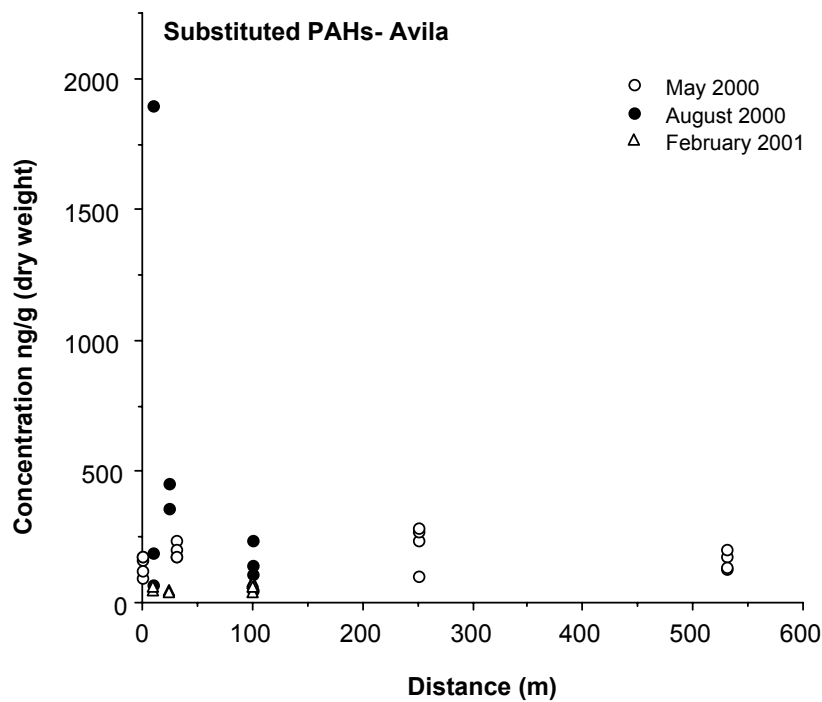

Figure 7.   Dry wt. concentrations of substituted PAHs ng/g in adult sand crabs as a function of distance from the Santa Maria River mouth for samples collected at the Guadalupe/Santa Maria River mouth sites on three dates.

Figure 8. Dry wt. concentrations of total PAHs ng/g in adult sand crabs as a function of distance from the Avila pier for samples collected on three dates.

Figure 9. Dry wt. concentrations of substituted PAHs ng/g in adult sand crabs as a function of distance from the Avila pier for samples collected on three dates.

Significant temporal variation in the concentrations of PAHs in sand crab tissues was evident in comparisons of samples from May and August 2000 and February 2001 at Avila and the Guadalupe/Santa Maria River mouth sites (1 way ANOVA, F= 3.04, 13.38, p <0.05, 0.001, respectively). Lower concentrations were present in the spring (May 2000) and winter (February 2001) samples than in the summer for total and substituted PAHs (Figures 10, 11).   Factors associated with this variation may include: dilution by runoff, reduced reproduction and metabolic rates, and variation in molt stage and lipid content of crabs. The lower proportion of substituted PAHs present in the May 2000 samples are consistent with runoff of pyrogenic PAHs from the watersheds and urban areas.
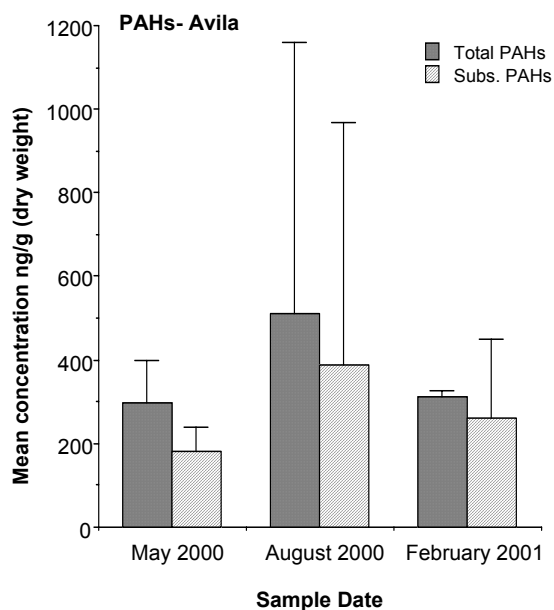

Figure 10. Temporal variation in mean dry wt. concentrations ng/g (+ 1 std. deviation)of PAHs in sand crabs at Avila.
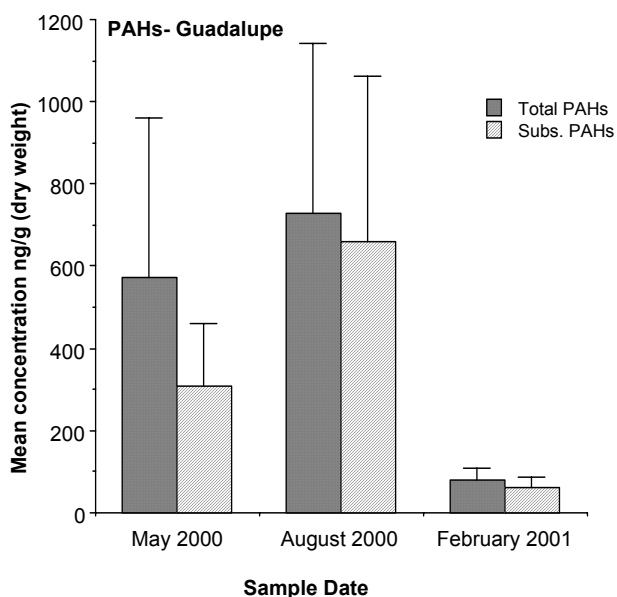

Figure 11. Temporal variation in mean dry wt. concentrations ng/g (+ 1 std. deviation) of PAHs in sand crabs at the Guadalupe/Santa Maria River sites.

Pesticides

The highest concentrations of pesticides found in sand crab tissues appear to be linked to past and present agricultural land uses in the study region (Figure 12). Pesticides that have been characterized as pollutants since the 1960's and 1970's are often referred to as legacy pesticides. These include pesticides such as DDTs, Chlordanes and Toxaphene. Sand crabs accumulated both legacy pesticides and current use pesticides. The most widespread group of pesticides detected in tissues of sand crabs was the DDTs, a pesticide that has been banned for use in the USA since 1970 but was manufactured here until much later. This group of pesticides was detected in every sample of sand crabs at every beach we sampled (Figure 12). Concentrations of total DDT's in sand crab tissues varied over an order of magnitude among samples, ranging from 14.7 to 556 ng/g dry weight and 179 to 6488 ng/g lipid weight. The highest concentrations of total DDTs in sand crabs were found in the vicinity of the Santa Maria River (Guadalupe and Santa Maria River sites) where agricultural land use predominates in the watershed. Concentrations of total DDTs exceeding 100 ng/g dry weight and 1700 ug/g lipid weight were also found in sand crabs from beaches near the mouth of Elkhorn Slough. The concentrations of DDTs we found in sand crabs from these two areas in the summer of 2000 are quite similar to those reported by Burnett (1971) for samples collected in these locations in November 1970 and February 1971. This result suggests that comparable amounts of DDT persist and are biologically available 30 years after the use of this pesticide was banned in the USA.
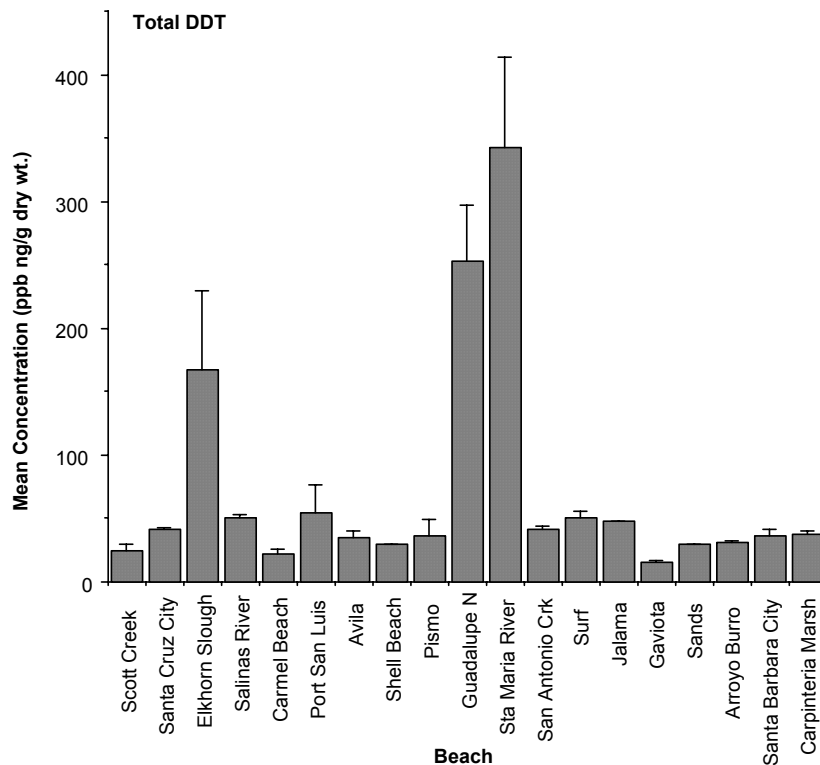

Figure 12. Mean dry wt. concentrations ng/g (+ 1 std. deviation) of total DDTs (DDD, DDE & DDT) in tissues of sand crabs collected at 19 beaches in August-September 2000.

DDT and its derivatives are persistent contaminants with high bioaccumulation potential. The ratio of DDE to DDT can be used to estimate the relative age of DDT contaminants. Fresh samples of DDT-derived contaminants are expected to have a lower DDE to DDT ratios than older samples. In older more weathered samples, DDE is the more prevalent form of this pesticide. In our study, DDE/DDT ratios at sites with greater concentrations of DDT ranged from 3-8, suggesting sand crabs were generally exposed to and accumulating derivatives of this pesticide from older sources. Ratios of DDE/DDT ranged from <1 to >85 in Burnett's study (Burnett 1971) and he reported DDE/DDT ratios of ~2.5 for Monterey Bay, and ~ 7.1 for the Santa Maria River area.

Although adult crabs had higher mean concentrations of total DDT, concentrations of total DDTs did not vary significantly among age classes of sand crabs at Guadalupe in May 2000 (1 way ANOVA, distance as a covariate, F= 0.449, p= 0.532, df = 5) (Figure 13). This result suggests a fairly constant source of DDTs exists for sand crabs in the vicinity of the Santa Maria River and that surf zone resuspension of sediments containing DDT may contribute to the tissue levels observed. At Avila, low mean concentrations of DDT occurred in both megalopa and adult crabs in May 2000.
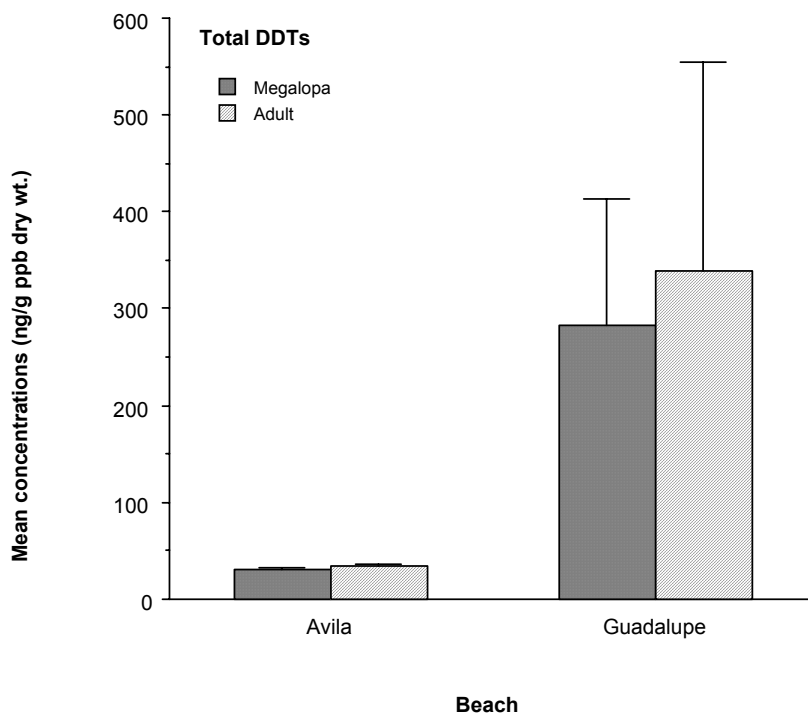

Figure 13. Mean dry wt. concentrations ng/g (+ 1 standard deviation) of total DDT's in tissues of newly settled megalopa and overwintered adult sand crabs at Avila and Guadalupe in May 2000 (all stations combined).
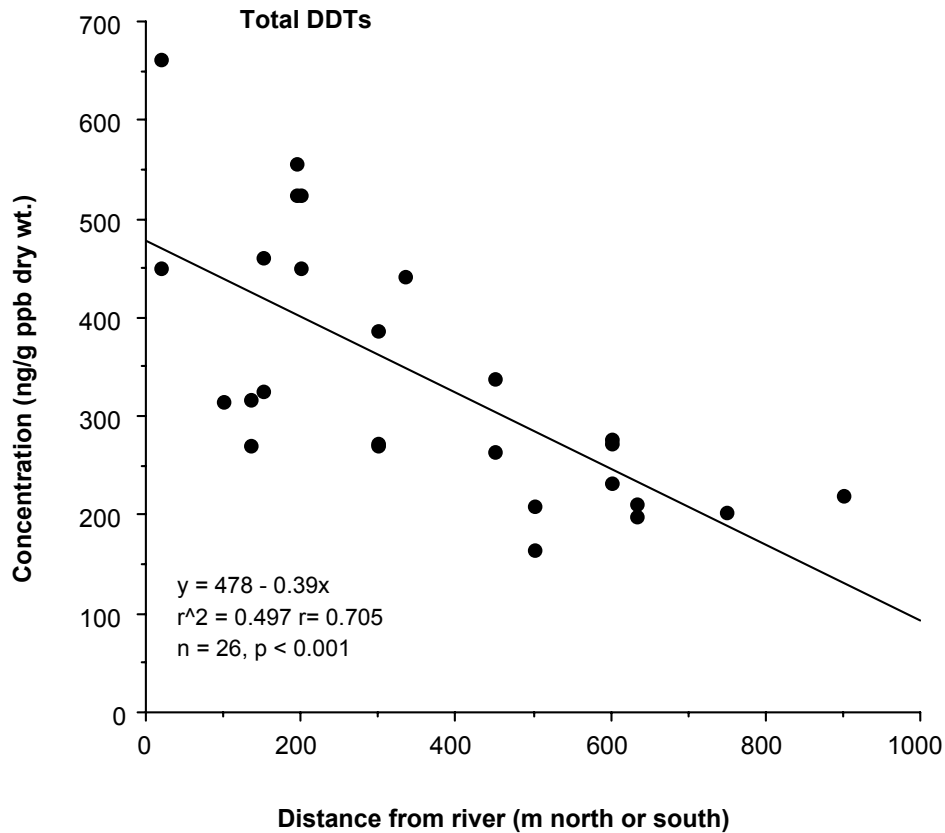
Figure 14. Dry wt. concentrations ng/g of total DDTs in tissues of sand crabs as a function of distance from the Santa Maria River mouth for sand crabs collected from the Guadalupe and the Santa Maria River sites from May and August 2000, and February 2001.

Using data from Guadalupe and the Santa Maria River mouth, we examined the hypothesis that the concentration of total DDTs in sand crab tissues varies with distance from the river mouth (20 – 900 m) using ordinary least squares regression analyses. Based on the preceding results for life stage above, both age classes of crabs were included in the regression analyses. We found a strong and significant negative relationship between the concentration of total DDTs in sand crab tissues and the distance from the river mouth for combined data from May and August 2000, and February 2001 (Figure 14). Statistically significant negative relationships with distance from the river were also present in the data from May and August 2000 ($p< 0.02$ and $p< 0.01$ respectively) and a marginally nonsignificant negative relationship was found for data from February 2001. These results suggest a relatively persistent gradient of exposure to DDTs exists for sand crabs in the vicinity of the Santa Maria River which drains major agricultural areas. This gradient in tissue concentrations of DDTs may reflect the nearshore transport and resuspension of sediments contaminated with DDTs originating from the Santa Maria River watershed.

At Elkhorn Slough, where concentrations of DDT in tissue of sand crabs were also high (100 ng/g dry weight and 1700 ug/g lipid weight), samples of crabs were collected at only two distances from the slough mouth (~100 and ~300 m) on both sampling dates making it impossible to statistically evaluate these results for spatial gradients. No spatial gradient in total DDT concentrations in sand crabs tissues was evident for samples collected at 4 distances from the Salinas River (0-300 m scale). However, total DDT concentrations were relatively low (~50 ppb dry weight) in sand crabs from in this area.

Pesticides of several other types were present in sand crab tissues (Table 2). After total DDTs, the most widespread pesticide detected in sand crab tissues was HCB, which occurred in low (1.1 to 26.2 ng/g) but detectable concentrations in sand crabs at 12 sites. Highest concentrations of this pesticide were detected in sand crabs from the Santa Barbara City beach.   The legacy pesticide, Oxychlordane, was also fairly widespread but detected in low concentrations (4.0 to 10.1 ng/g dry weight) in samples from five sites. Highest levels of this pesticide were detected in sand crabs from the beach at the mouth of Elkhorn Slough. The use of chlordane on crops has been restricted since 1974 and its use as a termiticide has been severely restricted since 1988.

Table 2. Pesticides, other than DDTs, detected in tissues of *Emerita analoga* in this study (* denotes currently applied pesticides).

Pesticide	Site	Date(s)	Max. Concentration (ng/g) dry wt.
Oxychlordane	Elkhorn Slough Mouth	Aug/Oct 2000	10.1
	Santa Cruz City Beach	Aug 2000	4.3
	Carmel	Aug 2000	4.0
	Avila Beach	Feb 2001	4.1
	Santa Barbara City Beach	Aug 2000	7.9
Diazinon*	Avila (megalopa only)	May 2000	649.0
	Guadalupe (adult only)	May 2000	364.0
Dieldrin	Guadalupe	May 2000	13.8
		Feb 2001	8.5
	Santa Maria River Mouth	Aug 2000	10.3
HCB	Scott Creek Beach	Aug 2000	1.1
	Santa Cruz City Beach	Aug 2000	2.6
	Elkhorn Slough Mouth	Aug/Oct 2000	1.7
	Port San Luis Harbor	Aug 2000	2.0
	Shell Beach	Aug 2000	6.5
	Pismo Beach	Aug 2000	12.2
	Avila	May 2000	1.0
		Aug 2000	4.2
		Feb 2001	1.9
	Guadalupe	May 2000	1.2
		Aug 2000	1.4
	Santa Maria River Mouth	Aug 2000	1.5
	Sands Beach	Aug 2000	1.1
	Arroyo Burro Beach	Aug 2000	1.7
	Santa Barbara City Beach	Aug 2000	26.2
	Carpinteria Marsh Mouth	Aug 2000	3.3
Toxaphene	Guadalupe	May 2000	90.3
		Feb 2001	95.0
	Santa Maria River	Aug 2000	104.0

High levels of two other pesticides were found in sand crabs from beaches near the Santa Maria River, again suggesting a link to agricultural land uses (Table 2). Moderately high levels (up to 364 ng/g dry weight) of a currently applied pesticide, diazinon, were detected in sand crabs from beaches near the Santa Maria River mouth (Guadalupe) in the spring. This pesticide was only detected in overwintered adult crabs at this site and date suggesting a link to runoff associated with winter rainfall. High levels of diazinon (629 ng/g dry weight) were also found in one sample of megalopa from Avila in May. Toxaphene (up to 104 ng/g dry weight) was detected in a number of sand crab samples (including megalopa) collected from beaches in the vicinity of the Santa Maria River on all sampling dates (May and August 2000 and February 2001). This result suggests that a fairly constant supply of this legacy pesticide may be available on beaches near the Santa Maria River.

PCBs

The presence of PCBs (polychlorinated biphenyls as a total of the congeners) in an intertidal animal is indicative of runoff from industrial land uses and from some agriculture pesticides. PCBs are considered priority organic chemicals. Although use of PCBs began to be phased out in 1971 and a ban on new devices was initiated in 1976, PCBs are still in use as dielectric fluids in many factories. Total PCBs were widespread in sand crab tissues in this study and were detected in every sample of sand crabs from the 19 sites (Figure 15). The concentrations of PCBs in tissues of sand crabs varied among sites by over an order of magnitude, ranging from 3.3 to 223 ng/g dry weight and 22.0 to 2247 ng/g lipid weight. The highest concentrations of PCBs were found in sand crabs from beaches near the mouth of Elkhorn Slough (up to 223 ng/g dry weight). Variance was high among samples from that location with nearly 2 fold and up to 8 fold higher concentrations in the samples from south of the slough mouth in August and October 2000 respectively. Although PCBs were not detected in sediment samples collected for the
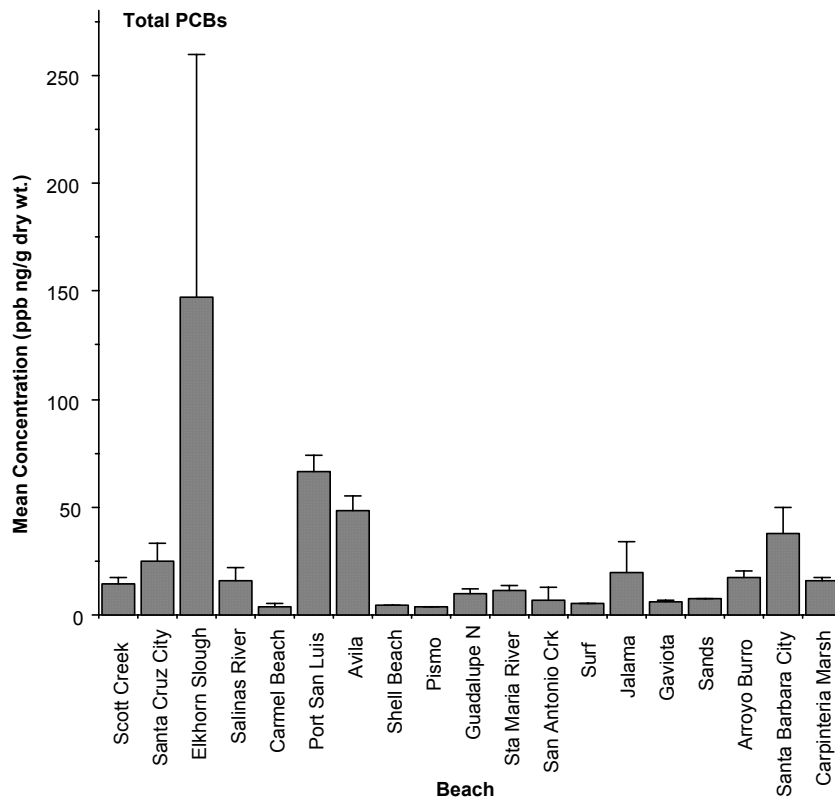

Figure 15. Mean dry wt. concentrations of total PCBs ng/g (+ 1 standard deviation) in tissues of adult sand crabs at 19 beaches in August of 2000.

Avila Pier petroleum hydrocarbon contamination assessment study, concentrations of PCBs exceeded 50 ng/g dry weight in sand crabs from beaches at Port San Luis Harbor and Avila Beach. San Luis Obispo Creek, which drains into the bay at Avila has been listed as impaired by priority organic chemicals, specifically PCBs. The site with the highest concentrations of PCBs detected in sand crab tissues, Elkhorn Slough, is listed as impaired for "pesticides" many of
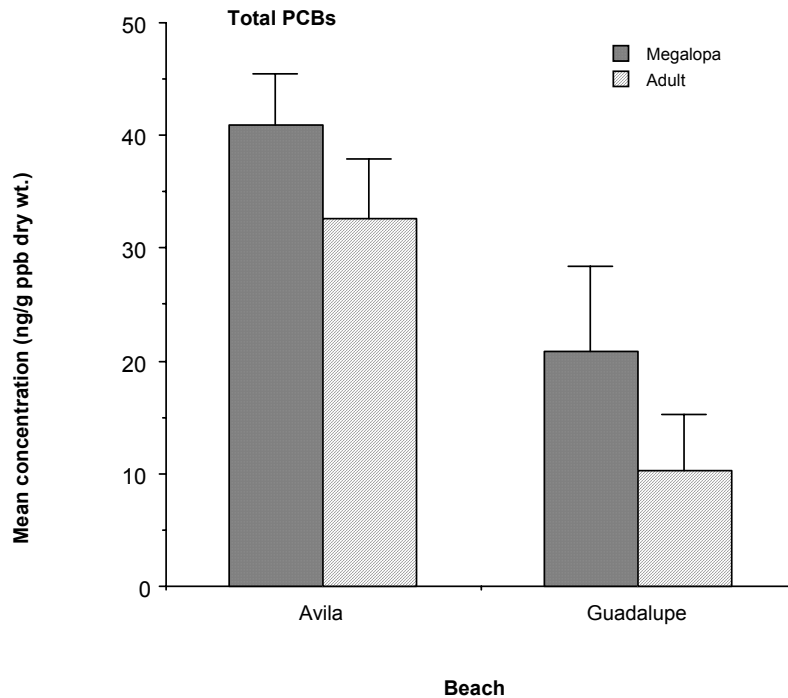
Figure 16. Mean dry wt. concentrations ng/g (+ 1 standard deviation) of total PCBs in newly settled megalopa and overwintered adult sand crabs at Avila and Guadalupe in May 2000 .

included PCBs as a chemical component. Tissue concentrations of DDT were also relatively high in samples of sand crabs from beaches near the mouth of Elkhorn Slough. The result of elevated concentrations of PCBs in sand crab tissues at sites known to be affected by PCB contamination suggest that this species may be a useful biological indicator for this chemical.

Concentrations of PCBs varied significantly among different life stages of sand crabs (Figure 16). At Avila, where PCB concentrations were higher, statistically significant differences in PCB concentrations were detected between life stages of sand crabs on both a dry and a lipid weight basis (1 way ANOVA, $F = 7.150$, df = 8, $p < 0.03$ and $F = 16.830$, df = 8, $p < 0.005$ respectively). At Guadalupe, dry weight-based concentrations of PCBs were nearly significantly different ($p = 0.07$) among life stages of crabs and lipid weight-based concentrations of PCBs were significantly higher in young of the year than in older sand crabs (1 way ANOVA, $F = 14.47$, df = 6, $p < 0.01$). This result did not appear to be related to a higher lipid content in young of the year crabs. It could potentially be related to the higher intertidal zone occupied by young of the year sand crabs but it is not possible to resolve this question with our results. We were not able to statistically evaluate spatial gradients in PCB concentrations in sand crabs at Elkhorn Slough or Port San Luis because samples were collected at only two distances. However, this would be of interest if additional sampling and analyses are conducted.

Trace metals

Trace metals in the tissues of sand crabs could be linked to a variety of land uses and the natural or enhanced erosion of different geologic formations, such as serpentine outcrops and selenium rich rocks and soils. A total of 12 trace metals (silver, aluminum, arsenic, cadmium, chromium, copper, lead, manganese, nickel, selenium, zinc, and mercury) were detected in sand crab tissues. Mercury was only detected in 2 of the samples. Results on the concentrations of the other 11 metals detected in sand crab tissues at each beach are presented in Figure 17 a-k. The majority of the metals we detected were present in relatively low concentrations in sand crab tissues. Aluminum was detected in the highest concentrations in sand crab tissues, reaching 2000 ppm dry weight (Figure 17 b). Aluminum is known to be strongly associated with sediments for bivalve studies and high concentrations may be characteristic of suspension feeder in a sandy habitat. Strong site-specific patterns were present in only a few metals (aluminum, chromium and nickel, Figure 17 b, e, and h) and are likely linked to erosion of local geologic formations, such as serpentine and other rocks. High levels of chromium and nickel reported for coastal sediments from Point Conception, CA to the Hood Canal, WA are believed to be associated with the geologic composition of bedrock formations rather than human activities (Daskalakis. and O'Connor 1994, see http://ccma.nos.noaa.gov/cit/assessments/ac_spec_trends.html). No geographic patterns were evident for arsenic, copper, selenium and zinc (Figure 17 c, f, j, and k).

Mercury was detected in sand crab tissues in a single sample at each of two beaches, Santa Cruz City beach (0.142 ppm dry weight) and Pismo Beach (0.185 ppm dry weight). Other hippid crab species, including *Emerita brasiliensis*, *E. portoricensis* and *Hippa cubensis* (Perez 1999) from beaches in Golfo Triste, Venezuela have been reported to contain levels of mercury ranging from 2 to 1449 ppb. This suggests that although sand crabs did not have detectable levels of mercury at most sites in the present study, this species has the potential to accumulate this metal.
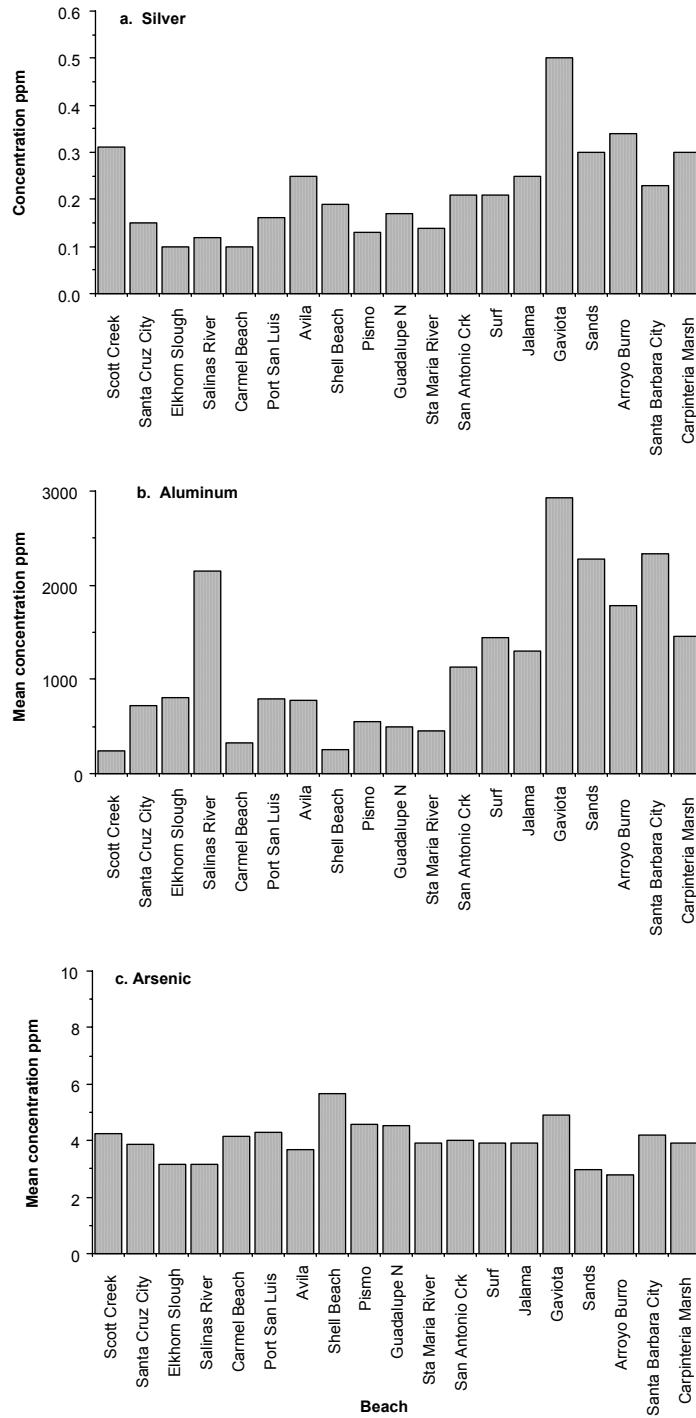
Figure 17 a-c. Mean dry wt. concentrations ppm of trace metals in tissues of adult sand crabs collected at 19 beaches a) silver, b) aluminum, and c) arsenic.
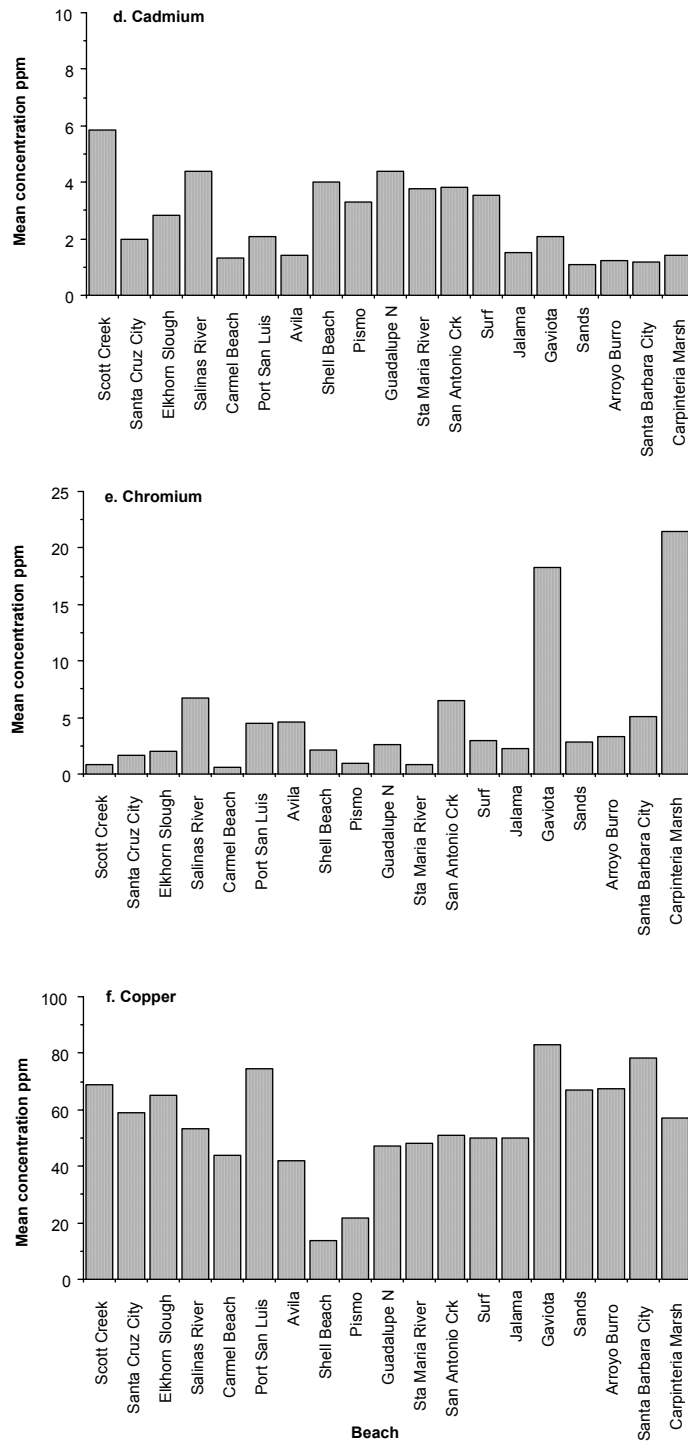
Figure 17 d-f. Mean dry wt. concentrations ppm of trace metals in tissues of adult sand crabs collected at 19 beaches in August/September 2000 d) cadmium, e) chromium, and f) copper.
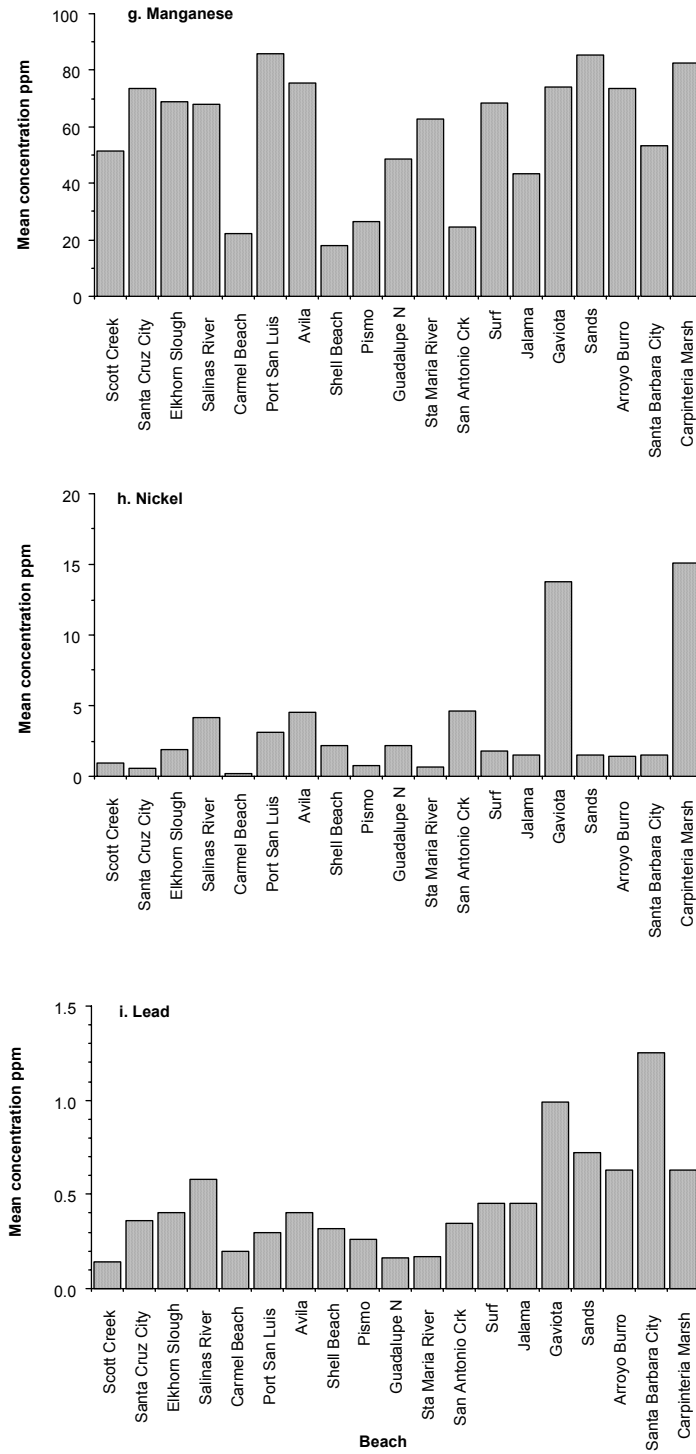
Figure 17 g-i. Mean dry wt. concentrations ppm of trace metals in tissues of adult sand crabs collected at 19 beaches in August/September 2000 g) manganese, h) nickel, and i) lead.
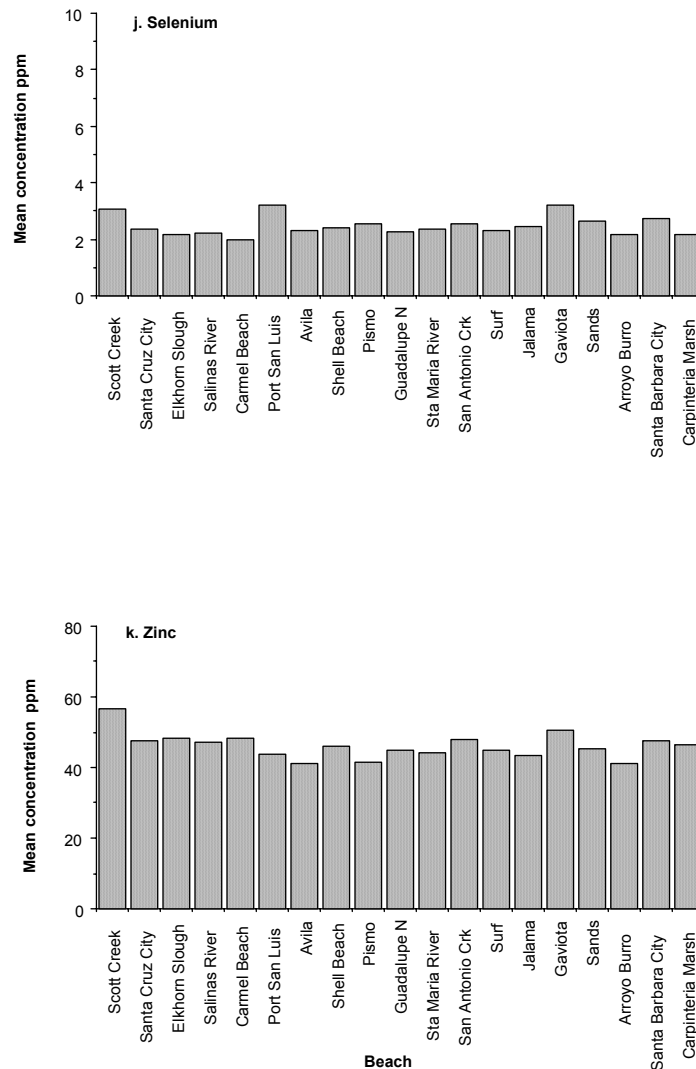
Figure 17 j-k. Mean dry wt. concentrations ppm of trace metals in tissues of adult sand crabs collected at 19 beaches in August/September 2000 j) selenium and k) zinc.

For samples from Guadalupe and Avila, the age class of sand crab appeared to influence the concentrations of chromium and nickel most strongly (Figure 18 a-b). For those two metals, concentrations in older adult crabs were much higher than in tissues of newly settled megalopa (Figure 18 a-b). This result also suggests that intertidal organisms may be exposed to these metals primarily through winter runoff and the erosion of rock formations rich in these trace metals. The concentration of aluminum was also consistently higher in adult crabs than in megalopa which could be related to the difference in length of time the two age classes have been associated with sediments (1 month or less for megalopa and 1+ years for older adult crabs)
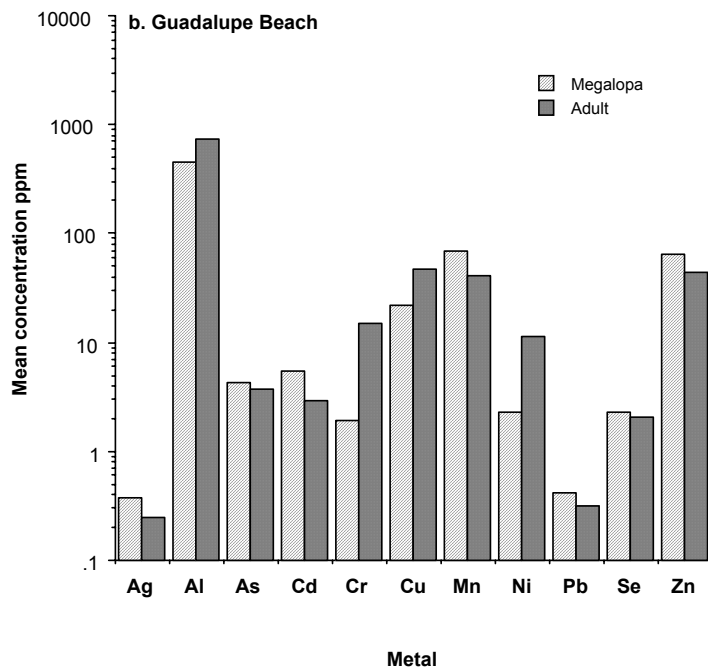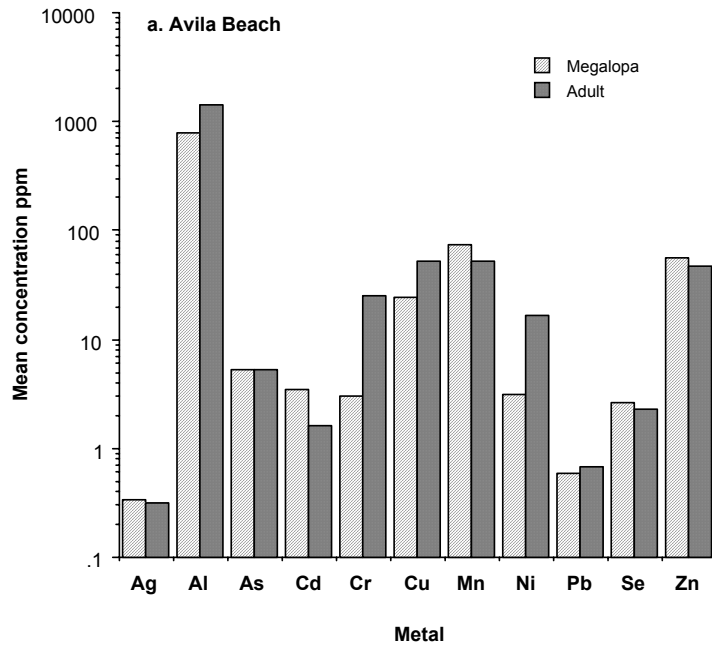
Figure 18 a-b. Mean dry wt. concentrations ppm of 11 trace metals in tissues of newly settled megalopa and overwintered adult sand crabs collected at a) Avila and b) Guadalupe in May 2000.

Concentrations of chromium and nickel in sand crab tissues also showed the greatest variation among sampling dates at Avila and Guadalupe (Figure 19 a-b). This is also consistent with a link between runoff and the presence of these metals in sand crab tissues.
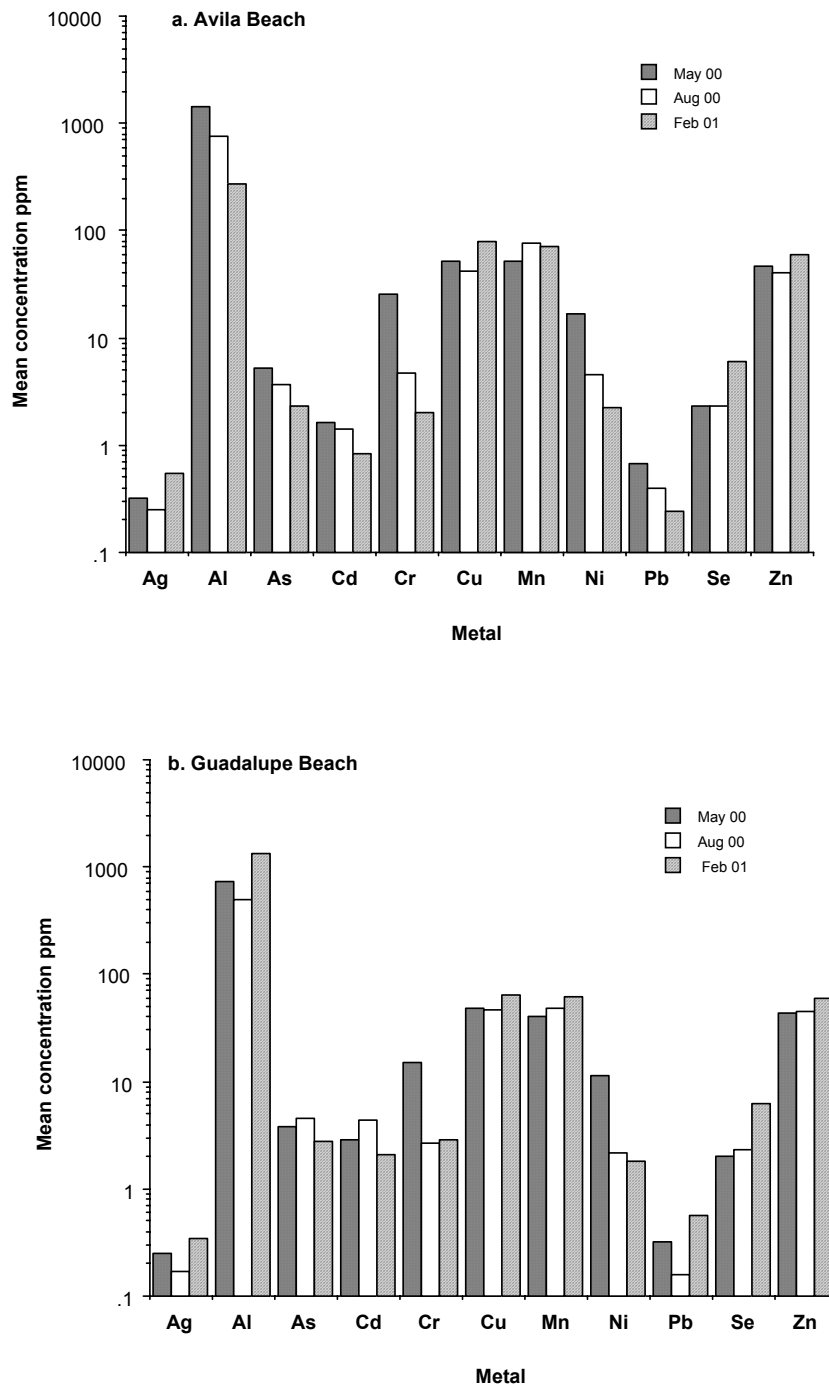

Figure 19 a-b. Mean dry wt. concentrations ppm of 11 trace metals in tissues of adult sand crabs collected at a) Avila and b) Guadalupe for samples collected in May 2000, August 2000 and February 2001.

SUMMARY AND RECOMMENDATIONS:

The results of this study support the concept of using sand crabs as a biological indicator for use in long term ambient monitoring of pollutants on the California coast. Tissues of sand crabs collected from 19 coastal beaches spanning a range of land use types contained detectable concentrations of contaminants including petroleum hydrocarbons, chlorinated hydrocarbons (a number of pesticides and polychlorinated biphenyls (PCBs)), and 12 different trace metals. Concentrations of several types of contaminants (PAHs, DDTs, PCBs) in sand crab tissues varied over an order of magnitude among the sampling sites. In some cases, concentrations of contaminants in sand crab tissues varied significantly with distance from potential sources, the time of year and/or the age class of the crabs.

Sand crabs are a major prey resource for many vertebrate predators, including shorebirds and fishes. The detection of pollutants in sand crabs described in this study thus may also have implications for species conservation and human health. For example, beaches at the Santa Maria River, Guadalupe and Sands, where elevated levels of PAHs were found in sand crab tissues, are designated as critical habitat for a threatened shorebird species, the Western Snowy Plover. Recreational fishing of surfperch and other coastal fishes for human consumption is also common at these beaches.

Elevated tissue burdens of petroleum hydrocarbons (PAHs) were most evident in sand crabs collected from sites near known oil sources including the Santa Maria River and Guadalupe sites, the Avila and Port San Luis sites, Sands Beach and Arroyo Burro. Sand crabs from reference, agricultural, and urban sites generally had considerably lower average tissue burdens of PAHs (< 200 ppb dry wt.) than observed at the preceding beaches. The exceptions to this pattern were the single sample from Shell Beach (originally categorized as a reference site) and four samples from Pismo Beach (urban site) where average concentrations of PAHs in sand crab tissues exceeded 485 ppb dry wt.. The source or sources of hydrocarbons to these two sites are unknown but may be associated with natural petroleum seeps.

Our results for petroleum hydrocarbons (PAHs) in sand crabs from the Santa Maria River and Guadalupe sites indicate that the Guadalupe oil field area still represents a significant source of petroleum hydrocarbons to intertidal biota and the coastal zone. We suggest that sand crabs in this area should be monitored over a sufficient time span (years) to determine if the oil contamination continues to reach the intertidal zone.

The results for PAHs in sand crabs at Avila and Port San Luis also suggest that petroleum hydrocarbon contamination is present in the area. However, the source or sources of these hydrocarbons can not be determined based on our results. Nonetheless, further monitoring of tissue burdens of PAHs in sand crabs is warranted to evaluate if the buried petroleum hydrocarbon contamination (e.g. outlier plume) under the Avila Pier and/or other sources continue to release petroleum hydrocarbons to the marine environment in this area.

Our results suggest that sand crabs may be quite useful as biological indicators of petroleum hydrocarbon contamination in coastal habitats. However, additional research in several areas would be of significant benefit in the interpretation of coastal monitoring data for petroleum

hydrocarbons based on sand crabs. Further studies are needed on the processes and factors associated with the high variation observed in PAH concentrations among samples of sand crab tissues at several individual sites and at Avila and Guadalupe. It is notable that high variability in tissue loadings of PAHs was primarily observed in older sand crabs from sites where high concentrations of PAHs occurred in crab tissues. Samples of sand crabs from sites where overall concentrations of PAHs in tissues were low generally did not exhibit the high variability in tissue loadings. This result suggests that sand crabs exposed to high levels of PAHs may be experiencing differential mortality or exhibiting metabolic responses to exposure to this contaminant. It is clear from these results that we need to learn more about the metabolism of PAHs in this species and investigate the effects of life history factors such as reproductive state, molt stage, lipid content, nutritional state and age on tissue burdens and metabolism of PAHs. It is also important to assess the potential mortality of different life stages of this species associated with high tissue loadings of PAHs.

Temporal variation in PAH concentrations in sand crab tissues was apparent among samples collected at three times of year for Avila and Guadalupe. This result strongly suggests the need to investigate how the animals interact with potential sources of PAHs such as runoff, beach porewater and ocean sources. Monitoring crabs of specific reproductive or age types on a finer temporal scale (6 times /year) along appropriate spatial gradients at sites known to be contaminated, such as Avila and Guadalupe, during years with different rainfall patterns would increase our understanding of these issues.

For pesticides, PCBs, and metals, the low variability within beaches and the significant patial gradients in tissue concentrations from potential source areas, such as river mouths, found in our results suggest that the use of sand crabs as biological indicators for these contaminants in monitoring programs for coastal habitats would be valuable and cost effective. Monitoring of sand crab tissues for these contaminants will likely yield results that can be readily interpreted and useful to regulatory agencies. Analysis of sand crabs collected along appropriate spatial gradients can potentially be used to investigate sources of these contaminants as shown by our results from Guadalupe and the Santa Maria River mouth for DDTs. We suggest that this type of gradient sampling and analysis should be employed particularly at sites where levels of PCBs and/or pesticides were high in sand crabs, such as the Elkhorn Slough mouth, in the present study.

For most of the contaminants of interest, collection of samples in the summer (August) appeared to provide a reasonable basis for comparisons among sites. At Avila and Guadalupe, where three collections were made (May, August and February) we found little difference among samples collected at three times of year for many of the contaminants analyzed. Variation in precipitation among years could have contributed to low levels of some runoff-associated contaminants in February 2001 relative to the preceding May (2000). Resolving relationships between tissue burdens of contaminants in sand crabs, precipitation and runoff will require a considerably longer time series of data collection than was possible in the present study. We suggest that initiating a long term time series of sample collection and analyses at several sites would be helpful in resolving these relationships.

For many of the contaminants analyzed at Avila and Guadalupe, including DDT and PAHs, tissue concentrations of contaminants did not vary significantly between the age classes of sand crabs (overwintered female crabs and megalopa) we analyzed. Megalopa have generally inhabited the sandy intertidal beach habitat for 1 month or less while overwintered animals have been there for a year or more. This result suggests that these contaminants are readily available in the sandy coastal habitat of sand crabs. However, the number of comparisons was relatively small for this analysis and could be a topic of additional research. In addition, megalopa are not consistently available for collection throughout the year. For this reason in particular, we recommend that collections of sand crab samples for monitoring of ambient pollutants focus on older overwintered female crabs which are available more consistently through the year. A part of a monitoring program, the crabs selected for sampling and analyses should ideally be similar in reproductive state (preferably ovigerous), sex, size, and age class (individually measured and recorded prior to analyses) with the goal of achieving consistency for all spatial and temporal comparisons of tissue burdens of ambient pollutants.

ACKNOWLEDGEMENTS

LITERATURE CITED

Alexander, R. R., R. J. Stanton Jr., and J. R. Dodd 1993. Influence of sediment grain size on the burrowing of bivalves - correlation with distribution and stratigraphic persistence of selected neogene clams. Palaios 8, 289-303.

Barron M. G., R. S. Podrabsky, R. S. Ogle, J. E. Dugan, and R. W. Flicker 1999. Sensitivity of the sand crab, *Emerita analoga,* to a weathered oil. Bull. Environ. Contam. Toxicol. 62: 469-271.

Bascom, W. 1980. Waves and Beaches. Anchor Press/Doubleday, New York. 366 pp.

Beckwitt, R. 1985. Population genetics of the sand crab, *Emerita analoga* Stimpson, in southern California. J. Exp. Mar. Biol. Ecol. 91 (1-2):45-52

Boolootian R.A., A. C. Geise., A. Farmanfarmaian, and J. Tucker 1959. Reproductive cycles of five west coast crabs. Physiol. Zool. 32: 213-220.

Burnett R. 1971. DDT residues: Distribution of concentration in *Emerita analoga* (Stimpson) along the coast of California. Science 174: 606-608.

Cubit J. 1969. Behavior and physical factors causing migration and aggregation of the sand crab, *Emerita analoga* (Stimpson). Ecology 50: 118-123.

Daskalakis, K.D. and T.P. O'Connor. 1994. Inventory of chemical concentrations in coastal and estuarine sediments. NOAA Technical Memorandum 76. NOS/ORCA. Silver Spring , MD 47pp + appendices.

Diaz, H., J. E. Conde and M. Bevilacqua 1983. A volumetric method for estimating fecundity in Decapoda. Mar. Ecol. Prog. Ser. 10: 203-206.

Dillery, D. G. and L. V. Knapp 1970. Longshore movements of the sand crab, *Emerita analoga* (Decapoda, Hippidae). Crustaceana 18: 233-240.

Dugan, J. E. 1990. Geographic and temporal variation in the life history, growth, and reproductive biology of the sand crab, *Emerita analoga* (Stimpson). Ph.D. dissertation. University of California, Santa Barbara. 329 pp.

Dugan, J. E., A. M. Wenner and D. M. Hubbard. 1991. Geographic variation in the reproductive biology of the sand crab, *Emerita analoga* (Stimpson), on the California coast. J. Exp. Mar. Biol. Ecol. 150: 63-81.

Dugan, J. E., D. M. Hubbard and A. M. Wenner. 1994. Geographic variation in life history in populations of the sand crab, *Emerita analoga* Stimpson, on the California coast: relationships to environmental variables. J. Exp. Mar. Biol. Ecol. 181: 255-278.

Dugan, J. E., D. M. Hubbard and H. M. Page. 1995. Scaling population density to body size: tests in two soft sediment intertidal communities. J. Coast. Res. 11(3): 849-857.

Dugan, J. E., and D. M. Hubbard 1996. Local variation in populations of the sand crab, *Emerita analoga* (Stimpson) on sandy beaches in southern California. Rev. Chil. Hist. Natural. 69, 579-588.

Dugan, J. E., D. M. Hubbard and A. M. Wenner. 1998. A catalog of the sandy beaches of San Luis Obispo and Santa Barbara Counties. Report prepared for POSCR, MMS, US. Dept. of the Interior, Camarillo, CA. 20 pages .

Dugan, J. E., D. M. Hubbard, J. M. Engle, D.L. Martin, D. M. Richards, G. E. Davis, K. D. Lafferty, and R. F. Ambrose 2000a. Macrofauna communities of exposed sandy beaches on the Southern California mainland and Channel Islands. Fifth California Islands Symposium, OCS Study, MMS 99-0038: 339-346.

Dugan J.E., D. M. Hubbard, and M. Lastra 2000b. Burrowing abilities and swash behavior of three crabs, *Emerita analoga* Stimpson, *Blepharipoda occidentalis* Randall and *Lepidopa californica* Efford (Anomura, Hippoidea), of exposed sandy beaches. J. Exp. Mar. Biol. Ecol. 255**:** 229-245.

Dugan J.E., D. M. Hubbard, M. McCrary, and M. Pierson 2003. The response of macroinfauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California. Est Coastl Shelf Sci 58S:133-148.

Efford, I. 1966. Feeding in the sand crab, *Emerita analoga* (Stimpson) (Decapoda, Anomura). Crustaceana 10, 167-182.

Efford, I. 1967. Neoteny in sand crabs of the genus *Emerita* (Anomura, Hippidae). Crustaceana 13: 81-93.

Efford, I. 1970. Recruitment to sedentary marine populations as exemplified by the sand crab, *Emerita analoga* (Decapoda, Hippidae). Crustaceana 18: 293-308.

Efford, I. 1976. Distribution of the sand crabs in the genus *Emerita* (Decapoda, Hippidae). Crustaceana 30, 169-183.

Entrix Inc. 1996. Guadalupe Remediation Project Beach Excavation, Post-construction sand crab (*Emerita analoga*) tissue report. Report to Unocal Corporation.

Farrington, J.H., E. D. Goldberg, R.W. Risebrough, J. H. Martin, and V. T. Bowen 1983. U.S. Mussel Watch 1976-1978: an overview of the trace metal, DDE, PCB, hydrocarbon and artificial radionnuclide data. Environ. Sci. Tech. 17, 490-496.

Fusaro, C. 1978. Growth rate of the sand crab, *Emerita analoga* (Hippidae) in two different environments. Fish. Bull. 76(2): 369-375.

Fusaro C 1980. Diel distribution differences in the sand crab, *Emerita analoga* (Stimpson) (Decapoda, Hippoidea). Crustaceana 39: 287-300.

Goldberg, E.D., V. T. Bowen, J. W. Farrington, G. Harvey, J. H. Martin, P.L Parker, R. W. Risebrough, E. Robertson, E. Scheider, and E. Gamble 1978. The Mussel Watch. Environ. Conserv. 5, 101-125.

Haley, S. R. 1982. Zonation by size of the Pacific mole crab, *Hippa pacifica* Dana (Crustacea: Anomura: Hippidae), in Hawaii. J. Exp. Mar. Biol. Ecol. 58, 221-231.

Horn, D. P. 2002. Beach groundwater dynamics. Geomorphology 48: 121-146.

Jaramillo E., and A. McLachlan 1993. Community and population responses of the macroinfauna to physical factors over a range of exposed sandy beaches in south-central Chile. Est. Coast. Shelf Sci. 37, 615-624.

Jaramillo, E., J. Dugan, and H. Contreras 2000. Abundance, population structure, tidal movement and burrowing rate of *Emerita analoga* (Stimpson 1857) (Anomura, Hippidae) at a dissipative and a reflective beach in south central Chile. Mar. Ecol. Napoli.21(2): 113-127.

Lastra, M., J. E. Dugan and D. M. Hubbard. 2002. Burrowing and swash behavior of the Pacific mole crab, *Hippa pacifica* (Anomura, Hippidae) on tropical sandy beaches. J. Crust. Biol., 22: 53-58.

Leatherman, S. P. 1997. Beach rating: A methodological approach. J. Coastal Res. 13(1):253-258

Martin, M., M. D. Stephenson, D. R. Smith, E. A.Gutierrz-Galindo and G. Flores-Munoz 1988. Use of silver in mussels as a tracer of domestic wastewater discharge. Mar. Poll. Bull. 19, 512-520.

NOAA 1988. National status and trends program for marine environmental quality progress report: a summary of data on tissue contamination from the first three years (1986-1988) of the Mussel Watch project. National Oceanic and Atmospheric Administration. Technical Memo NOS OMA 49. NOAA/NOS/Coastal and Estuarine Assessment Branch, Rockville, MD.

Osorio, C., N. Bahamonde, and M. T. López 1967. El limanche (*Emerita analoga* Stimpson) en Chile. Bol. Mus. Hist. Nat. 29: 61-116.

Perez, D. 1999. Mercury levels in mole crabs, *Hippa cubensis*, *Emerita brasiliensis*, *E. portoricensis* and *Lepidopa richmondi* (Crustacea: Decapoda: Hippidae) from a sandy beach in Venezuela. Bull. Environ. Contam. Toxicol. 63: 320-326.

Phillips, D.J.H. 1980. Quantitative Aquatic Biological Indicators. Applied Science Publishers, Ltd. London.

Rossi S.S., G. W. Rommel, and A.A. Benson. 1978. Hydrocarbons in sand crabs (*Emerita analoga*) from southern California (U.S.A.) Chemosphere 2: 131-141.

Seapy, , R. R. and M. M. Littler. 1980. Biogeography of rocky intertidal invertebrates of the southern California Islands. pp. 307-323. In: The California Islands: Proceedings of a Multidisciplinary Symposium. D. M. Power (ed.). Santa Barbara Museum of Natural History, Santa Barbara, CA.

Siegel, P.R. and A. M. Wenner. 1984. Field and laboratory studies of sand crab growth. In: A. M. Wenner (ed.) Crustacean Growth, Crustacean Issues, Vol II. Balkema Press, Rotterdam.

Smith, E. J. , D. H. Fry, H. W. Fry, J. Speth, A. Rutch and L. Fisk 1976. Coastal county fish and wildlife resources and their utilization. Calif. Dept. Fish and Game, Sacramento, CA.

Straughan, D. 1982. Inventory of the natural resources of sandy beaches in southern California. Technical Report, Alan Hancock Foundation, 6.

Straughan, D. 1983. Ecological characteristics of sandy beaches in the Southern California Bight. Pp. 441-447 in A. McLachlan and T. Erasmus (eds). Sandy beaches as ecosystems. Developments in hydrobiology. 19. Dr. W. Junk Publishers, The Hague. 757pp.

Trueman, E. R. 1970. The mechanism of burrowing of the mole crab, *Emerita*. J. Exp. Biol. 53, 701-710.

Trueman, E. R., and A. D. Ansell 1969. The mechanisms of burrowing into soft substrata by marine animals. Oceanogr. Mar. Biol. Ann. Rev. 7: 315-366.

Wenner, A. M. 1988. Crustaceans and other invertebrates as indicators of beach pollution. In: Soule, D. F. and G. S. Kleppel (eds.) Marine Organisms as Indicators, pp. 199-229. Springer-Verlag, New York.

Wenner, A. M., D. M. Hubbard, J. E. Dugan, J. Shoffner, and K. Jellison. 1987. Egg production of the sand crab, *Emerita analoga* Stimpson, as a function of size and age. Biol. Bull. 172: 225-235.

Wenner, A. M., J. E. Dugan and H. Wells. 1991. Estimating egg production in multibrooding populations. pp. 333-355 In: A. Wenner and A. Kuris (eds.) Egg Production, Crustacean Issues Vol. 7, Balkema, Netherlands.

Wenner, A. M., J. E. Dugan and D. Hubbard. 1993. Sand crab population biology on the California Islands and mainland. pp 335-348 In: F. G. Hochberg (ed.), Third California Islands Symposium, Recent Advances in Research on the California Islands. Santa Barbara Museum of Natural History, Santa Barbara, CA. 661 pp.