Chlorinated hydrocarbons in pelagic forage fishes and squid of the Southern California Bight, USA

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Abstract

Large quantities of dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyls (PCB) have been historically discharged to the southern California Bight (SCB). While these contaminants have bioaccumulated in sediment-associated fishes, little data exists on concentrations of these compounds in pelagic forage species that are the likely food source to larger predatory mammals and birds. The goal of the present study was to assess the extent and magnitude of DDT and PCB bioaccumulation in the four major pelagic species of the SCB: Pacific sardine (*Sardinops sagax*), Pacific chub mackerel (*Scomber japonicus*), northern anchovy (*Engraulis mordax*), and California market squid (*Loligo opalescens*). A total of 99 composite samples were collected from commercial landing docks along the southern California coast from July 2003 to February 2004. Whole fish were homogenized and analyzed for total DDT (*ortho*- and *para*-isomers of DDT and its degradation products) and 41 PCB congeners. Virtually all of the samples of Pacific sardine, northern anchovy, and Pacific chub mackerel had detectable levels of total DDT. Only 50% of the California market squid samples had detectable total DDT. Northern anchovy had the highest total DDT concentrations (60 ±38 µg/kg wet wt), followed by Pacific chub mackerel (41 ±40 µg/kg wet wt), Pacific sardine (34 ±29 µg/kg wet wt), and California market squid (0.8 ±1.2 µg/kg wet wt). In general, concentrations were highest in the central SCB. An estimated 99% of northern anchovy, 83% of Pacific sardine, 33% of Pacific chub mackerel, and 0% of California market squid landings exceeded wildlife risk screening values for total DDT. Virtually none of the landings were estimated to exceed wildlife risk screening values for PCBs.

Introduction

Large quantities of the chlorinated hydrocarbons dichlorodiphenyltrichloroethane (DDTs) and polychlorinated biphenyls (PCBs) have been historically discharged to the SCB. An estimated 41.5 metric tonnes of DDTs and 55.5 metric tonnes of PCBs have been discharged to the SCB since 1971 (Schiff *et al.* 2001, Raco-Rands and Steinberger 2001). As much as 20 times this amount was discharged prior to 1971. Most of these chlorinated hydrocarbons emanated from the Montrose Chemical Corporation (Torrance, CA), formerly the worlds largest manufacturer of DDT, and was discharged through the sanitary sewer system ocean outfall (Stull 1995). Since the early 1970s when domestic use of DDT was banned and Montrose's discharge to the sanitary sewer system was halted, inputs from the ocean outfalls in the SCB have dramatically decreased and chlorinated hydrocarbon emissions are presently nondetectable. However, the legacy of this contamination is still observed in the SCB. The highest sediment concentrations are found near Palos Verdes on the Los Angeles margin and an estimated 70 metric tonnes may still reside in these marine sediments (Lee and Wiborg 2002). However, DDT and PCB contamination is widespread; approximately 82% of the surface area on the continental shelf in the SCB has sediments that contain measurable DDTs and/or PCBs (Schiff 2000).

The historical inputs of DDTs and PCBs have resulted in exposure and impacts to biota. Similar to sediments, widespread contamination of biological organisms has been observed. Marine bivalves had detectable concentrations of DDTs along the entire 350 km coastline of the SCB (Mearns *et al.* 1991). An estimated 96% of the Pacific sanddab (*Citharichthys sordidus*) population, the most common flatfish on the shelf, is contaminated with DDTs

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and/or PCBs (Schiff and Allen 2000) and 99% of the sanddab guild (the most widespread foraging guild on the shelf) had detectable levels of DDT in 1998 (Allen *et al.* 2002, Allen *et al.* 2004). Reproductive impairment due to DDT and/or PCB was observed in white croaker (*Genyonemus lineatus*) in the 1980s (Cross and Hose 1988, Hose *et al.* 1989). Health-risk advisories to warn anglers still exist along many kilometers of the southern California coastline for several species, including white croaker (Office of Environmental Health Hazard Assessment. Sacramento, CA; http://www.oehha.org/fish/so_cal/index.html). Historically, reproductive success was suggested to be impaired in pinnipeds such as the California sea lion (*Zalophus californianus*) that suffered from premature pupping (Delong *et al.* 1973) or seabirds such as the brown pelican (*Pelecanus occidentalis*) that suffered from eggshell thinning (Gress 1994). While these reproductive failures have reversed themselves, other high level predators continue to struggle. For instance, transplanted bald eagles (*Haliaeetus leucocephalus*) hatched their first two chicks on the California Channel Islands in more than 30 years (D. Witting, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southwest Regional Office, Long Beach, CA, personal communication, May 13, 2006). Concentrations of DDTs and PCBs still average 150 mg/kg wet weight in the blubber of marine mammals such as California sea lions in 2000 (Kannan *et al.* 2004).

While contaminant pathways to sediment-associated biota have been the focus of many investigators, contaminant pathways to higher-level predators have been studied much less intensively. For example, tissue concentrations of flatfish are highest near Palos Verdes where sediment concentrations maxima are located (Mearns *et al.* 1991, Allen *et al.* 2002, Allen *et al.* 2004). Bight-wide relationships between sediment contaminant concentrations and flatfish tissue concentrations were highly correlated for both DDTs and PCBs (Schiff and Allen 2000, Allen *et al.* 2002, Allen *et al.* 2004, Allen *et al.* 2002). Moreover, different flatfish species of the same foraging guild and have similar lifestyles accumulated similar quantities of DDTs and PCBs (Allen *et al.* 2002). In contrast, little data exists on pelagic forage fishes and squid that might serve as pathways to mammals and seabirds. Both northern anchovy and California market squid are primary prey items for the California sea lion in the SCB (Lowry and Carretta 1999, Lowry *et al.* 1991). The Brown pelican was reported to feed consistently on northern anchovy and SCB breeding status has been strongly linked to anchovy abundance and availability (Anderson *et al.* 1980). Additional wildlife predators of pelagic forage species such as northern anchovy, California market squid, Pacific sardine, and Pacific chub mackerel include larger pelagic fishes of the SCB such as Pacific barracuda (*Sphyraena argentea*), Pacific bonito (*Sarda chiliensis*), tunas (*Thunnus* spp.), and yellowtail jack (*Seriolis lalandi*; Pauly *et al.* 1998).

The primary objective of the present study was to assess the extent and magnitude of total DDT and total PCB contamination in pelagic forage fishes within the SCB. This goal will be addressed by answering two basic questions. What percent of the pelagic forage fish biomass exceeds wildlife risk screening values? Are there geographic patterns in the concentration of total DDT, total PCB, or the percentage of biomass that exceeds thresholds of concern? These data can then be used for determining potential pathways to higher predators such as marine mammals and birds.

METHODS

Sample Collection

Pelagic forage fish and squid were collected between July 2003 and Feb 2004 at local commercial fishing ports along the southern California coast from Ventura to San Diego. Both commercial landing markets and bait receivers were randomly targeted for sampling. Commercial landing markets received fish directly from purse-seine fishing vessels, while bait receivers received fish directly from commercial purse-seine fishing vessels to sell to recreational fishers as live bait. Fish collected at commercial landing markets were sampled at random throughout the entire catch during offload. Fish collected at bait receivers were selected at random from the sea pen. Fishing location was determined from landing receipts or directly from the fishing captain or bait receiver tenders. Fishing location was typically provided as California Department of Fish and Game (CDFG) fishing block, a number identifying a 16 x 16 km (10 x 10 mi) block encompassing a 256 km^2 (100 mi^2) area within the SCB. Block numbers were designated for fishing location when only a geographic landmark was provided.

Species selection was based on two criteria including species comprising the greatest biomass in the SCB and favored prey items by either marine birds or mammals. The species selected for contaminant analysis were northern anchovy, Pacific sardine, Pacific chub mackerel, and California market squid. Individuals were sampled from fish bins throughout an entire fishing vessel load during the offloading process. Individuals were rinsed with deionized water, wrapped in clean foil, labeled, and frozen until sample processing.

The sampling design included stratifying the SCB into four geographic regions including: (1) north coast; (2) central coast; (3) south coast; and (4) offshore islands (Figure 1). Ten composite samples per species per region were targeted, except for Pacific chub mackerel (three samples per region), for a total of 160 sample composites. Samples were distributed as evenly as possible over summer and non-summer months of the sampling period.

Sample Processing and Analysis

Composite samples consisted of 10 individuals for northern anchovy, 6 for Pacific sardine and California market squid, and 3 for Pacific chub mackerel based on total sample biomass. After thawing, individual fish in a composite was measured (cm standard length for fish; cm mantle length for squid) and weighed; individual weights were summed to give a composite weight in grams. Composite samples were homogenized in a blender with 1.0 L glass containers with ceramic-coated stainless steel blades, Buna rubber gaskets, and aluminum foil-lined lids. The composite fish and an equal weight of deionized water (to facilitate blending) were combined and blended for 2 to 5 minutes to obtain a smooth homogenate. Two equal-sized aliquots of homogenate were used to fill two wide-mouthed glass jars with Teflon®-lined lids (and external labels) to three-fourths full or less and kept at -20°C (±2°C) for up to 8 months. Blenders were washed with nonionic soap and water, rinsed several times with deionized water, dried, and then rinsed with appropriate solvents (e.g., methanol, ethanol, acetone) and dried before processing the next sample.

Prior to analysis, sample aliquots were thawed and thoroughly mixed to ensure a uniform homogenate and then subsequently solvent extracted. Extraction methods included accelerated solvent extraction or homogenization solvent extraction. The extracts were dried using anhydrous sodium sulfate, sulfur was removed with either copper or mercury, and cleaned up using Florisil (J.T. Baker, Phillipsburgh, NJ) and/or alumina-packed columns (Schiff and Allen 2000) and analyzed by gas chro-

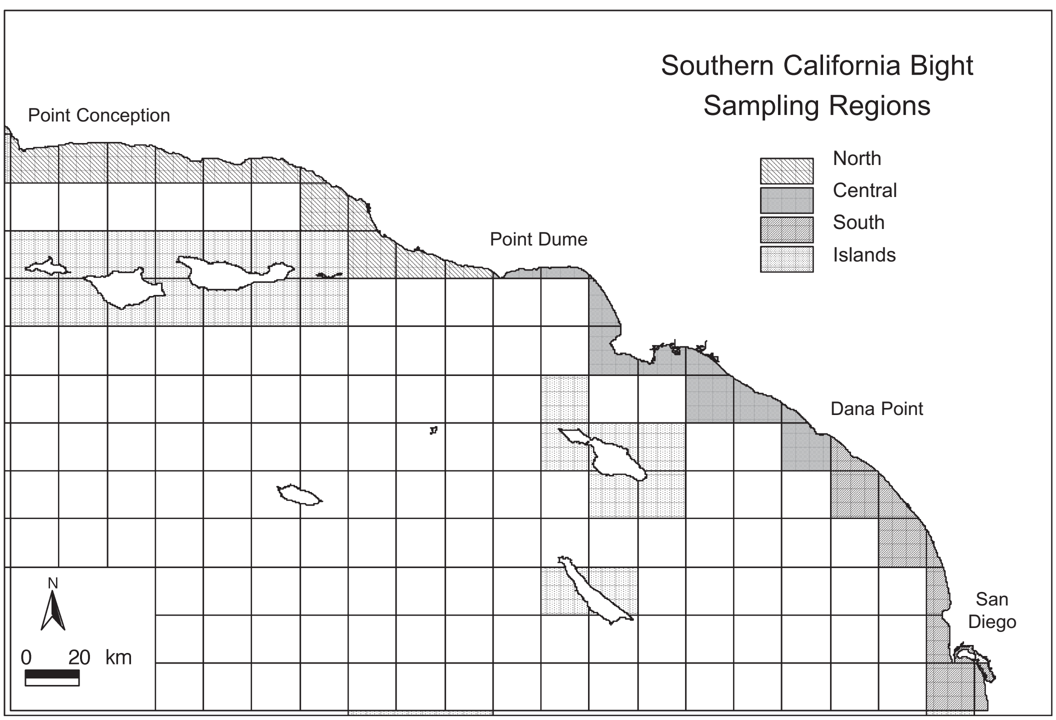

Figure 1. Southern California, USA north, central, and southern coastal plus island strata sampled from July 2003 to February 2004 for pelagic forage fish and squid. Squares represent California Department of Fish and Game 256 km² fishing blocks.

matography - electron capture detection or gas chromatography - mass spectrometry. Target analytes included total DDT (*ortho*- and *para*- isomers of DDT and its degradation products DDE and DDD) and total PCB (41 congeners: 18, 28, 37, 44, 49, 52, 66, 70, 74, 77, 81, 87, 99, 101, 105, 110, 114, 118, 119, 123, 126, 128, 138, 149, 151, 153, 156, 157, 158, 167, 168, 169, 170, 177, 180, 183, 187, 189, 194, 201, 206). Following analysis, the measured concentration was doubled to correct for the equal weight of water added to the sample during homogenization.

Analytical performance was monitored through the use of method blanks, certified reference materials (CRMs), and sample duplicate analyses. All method blanks were nondetectable. The CRM was CARP-1 (National Research Council, Canada). All CRM analyses met the predetermined performance criteria of being within 40% of the certified value for 80% of the target analytes. All duplicate analysis met the predetermined performance criteria of being within 30% reproducible percent difference.

Data Analysis

To address the objectives of the present study, five different types of data analysis were performed. The first type of data analysis determined the representativeness of the samples collected. To address representativeness, commercial landings of coastal pelagic species were obtained from CDFG by species, CDFG block, and month during our sampling campaign. All landings were assigned into one of the four strata within the SCB according to block location, then total landings by species were summed by stratum-month. Next, each sample collected was assigned a similar stratum-month by species in a similar fashion. It was assumed that all fish within the same species stratum-month contained similar concentrations. Thus, the proportion of landings with representative samples was calculated by summing the sampled landing biomass by total landing biomass for each matching stratum-month for each species. Bait receiver samples were not accounted for in this calculation because the fishing location of bait landings was not always reported. Therefore, the estimate of representativeness for northern anchovy and Pacific sardine was likely an underestimate.

The second type of data analysis examined the extent and magnitude of tissue contamination in pelagic forage fishes and squid in the SCB. Concentrations were examined in three fashions including percent of samples with detectable levels of total DDT or total PCB, the range of total DDT or total PCB concentrations, and biomass weighted mean (±95% confidence intervals [CI]) concentrations of total DDT or total PCB. The observed concentrations during the present study were then compared by species and strata. Composites with non-detectable contaminant concentrations were treated as zero for this analysis.

The third type of data analysis examined the potential factors that may influence bioaccumulation examined in the present study. A multiple linear regression model (SAS® Ver 9.1, SAS Institute, Inc., Cary, NC) was used to test whether species, season, geographic region, and lipid content were predictors of the total DDT and total PCB concentrations found in pelagic forage fishes and squid within the SCB. Composites with non-detectable contaminant concentrations were removed prior to this analysis.

The fourth type of data analysis estimated the relative risk of total DDT and total PCB in pelagic forage species within the SCB. To accomplish this, the biomass weighted mean concentration of total DDT or total PCB for each stratum-month was compared to wildlife risk screening thresholds according to the following equation:

$$P_a = \left(\frac{\sum l_{i,a}}{\sum L_{i,a}} \right) \bullet 100$$

where, P_a = Percent of landings in region *i* that exceed wildlife risk threshold in species *a*; $l_{i,a}$ = Landings in region *i* for species *a* that exceed a wildlife risk threshold; and $L_{i,a}$ = Total landings in region *i* for species *a*.

The wildlife risk screening values were for aquatic and/or marine wildlife and from the National Academy of Science (National Academy of Science 1974) and Environment Canada (Environment Canada 1998, Ridgway *et al.* 2000). These guidelines address several avian and marine mammal predators, including those found in the SCB such as bald eagles, seals, and seal lions. The screening value for total DDT was 14.0 µg/kg wet weight (Ridgway *et al.* 2000) and that for PCB was 0.79 ng toxicity equivalent quotient (TEQ)/kg wet weight (Environment Canada 1998). The TEQ is the sum of the product of individual PCB congeners and their toxicity equivalency factors (TEFs). These TEFs were used to estimate the relative toxicity of PCBs based on their similarity to dioxin. Specifically, the

TEFs are assigned to the congeners based on their ability to produce a response in the cytochrome system relative to the most potent inducer, 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD; Environment Canada 1998). Thus, the TEQ is the total TCDD toxic equivalents concentration and is calculated as follows:

$$TEQ = \sum(PCB_i \bullet TEF_i)$$

where, PCB_i = Individual PCB congener, and TEF_i = Toxicity of PCB congener relative to TCCD dioxin. The TEFs used in the present study were those recommended by the World Health Organization (Van den Berg *et al.* 1998). The TEFs were available for 12 PCB congeners found in the present study, with TEFs differing for mammals and birds.

The fifth type of data analysis estimated the mass of total DDT and total PCB within the pelagic forage fish and squid of the SCB. Total contaminant mass was calculated as follows:

$$X_a = \sum ([\bar{x}]_i \bullet L_i)$$

where, X_a = Total mass of constituent x in species a; $[\bar{x}]_i$ = Mean concentration of constituent x in region i; and L_i= Total landings in region i. Finally, the value of each X_a was summed across all species.

Results

A total of 99 composite samples, representing 1,460 individual fish or squid were collected for organic contaminant analysis (Table 1). Samples of the four target species were collected from each of the four regions identified. Sample sizes ranged from 34 composites for Pacific sardine to 13 composites for Pacific chub mackerel. Bait and landing composites were treated equally throughout the data analysis process. Concentrations of total DDT and total PCB in bait receiver and commercial landing composites for both northern anchovy and Pacific sardine were not significantly different (p >0.05). Despite combining composites from commercial landings and bait receivers, not all of the sampling targets were achieved during the sampling campaign. For example, only 70% of the target samples were collected for northern anchovy.

California market squid (34 x 10^3 metric tonnes) and Pacific sardine (14 x 10^3 metric tonnes) comprised over 90% of the total biomass landed in the SCB during the present study. These two species were sampled with the greatest success in the survey. Pacific chub mackerel (4 x 10^3 metric tonnes), the species that was sampled with intermediate success, comprised 6% of the total biomass landed during the study period. Northern anchovy (2 x 10^3 metric tonnes), the species sampled with the least success, comprised less than 3% of the total biomass landed during the study. Jack mackerel, which was not sampled, comprised only 1% of the total biomass landed during the study period.

While target sample sizes were not achieved for all species and strata, the sampling effort was representative of the appropriate geographic distributions of pelagic forage fishes and squid that were commercially landed in southern California (Figure 2). For example, 71% of all Pacific sardines were landed in the central stratum and the present study representatively sampled 92% of these landings. Similarly, representative samples were collected for the majority of landings of California market squid. A very

Table 1. Sampling success of southern California, USA pelagic forage species targeted for whole fish composite contaminant analysis between July 2003 and February 2004.

Species	Mainland Coast			Islands	Total	Target
	North	Central	South			
Northern anchovy	10	10	2	2	24	40
Pacific sardine	9	10	5	10	34	40
California market squid	10	8	0	10	28	40
Pacific chub mackerel	3	4	1	5	13	20
Total	32	32	8	27	99	140

small proportion of the landings from the Islands stratum offset the lack of sampling success in the southern SCB. We were unable to representatively sample the majority of northern anchovy landings, which were dominated by fisheries in the northern SCB. Approximately 50% of the Pacific chub mackerel were representatively sampled.

Tissue concentrations differed among species (Figure 3). Northern anchovy had the highest biomass-weighted average concentrations of total DDT (61 ±38 µg/kg wet wt). All but one of the northern anchovy samples had detectable quantities of total DDT and these concentrations ranged from 3 to 135 µg/kg wet weight. California market squid had the lowest biomass-weighted average concentration of total DDT (0.8 ±1.2 µg/kg wet wt). Fifty percent of California market squid samples had nondetectable concentrations. Pacific sardine and Pacific chub mackerel had intermediate biomass-weighted average concentrations of total DDT (34 ±29 and 41 ±40 µg/kg wet wt, respectively). Both species also ranged in total DDT concentration from 3 to >100 µg/kg wet weight with only a single nondetectable sample (for Pacific sardine). Pacific chub mackerel had the highest total DDT concentration of all three species (141 µg/kg wet wt). The distribution of total PCB concentrations between species mimicked total DDT concentrations, but was lower by approximately one order of magnitude (Figure 4). For example, the biomass weighted average total PCB concentration in northern anchovy was 3 ±5 µg/kg wet weight.

In general, the central stratum had the highest mean concentrations of detectable total DDT and total PCB (Table 2). Detectable concentrations of

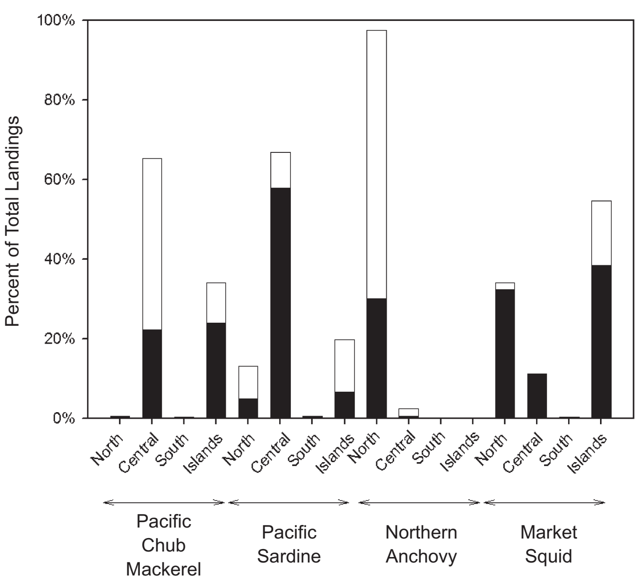

Figure 2. Representative samples by species and geographic stratum. White bars denote the relative percentage of total landings by species for each stratum. Black bars denote the fraction of total landings with a representative sample.

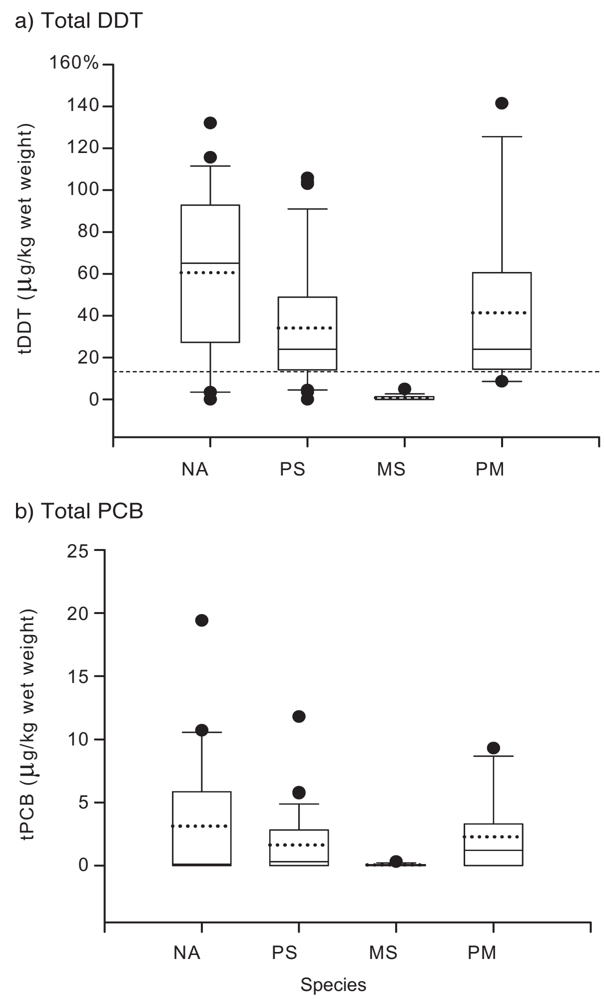

Figure 3. Box plots of total dichlorodiphenyltrichloroethane (tDDT; (a)) and total polychlorinated biphenyls (tPCBs; (b)) in whole fish composites of pelagic forage species sampled from southern California, USA commercial fish markets and bait receivers from July 2003 – February 2004. NA = northern anchovy (*n* = 24); PS = Pacific sardine (*n* = 34); MS = California market squid (*n* = 28); and PM = Pacific chub mackerel (*n* = 13)). The dashed line in the upper panel represents the wildlife-risk screening value for tDDT (14 µg/kg wet wt). Box hinges represent the 25th, 50th, and 75th percentiles of the data distribution. Whiskers represent the 10th and 90th percentiles of the data distribution. Dots represent individual data points beyond the whiskers. Dotted line represents the mean.

total DDT were highest in the Central stratum for three of the four species, but were not statistically significant (p >0.05) due, in part, to large within-stratum variability. Interestingly, the Islands contained the highest average total DDT concentration for the remaining species (northern anchovy). Similarly, there were no statistically significant different concentrations (p >0.05) of detectable total PCB between strata for each species, largely due to within-stratum variability. However, the highest average total PCB concentrations were observed from the Central stratum for three of the four species. Only the Southern stratum had greater detectable total PCB concentrations than the central stratum, and this was in Pacific chub mackerel.

Regardless of species, season, or stratum, concentrations of total DDT appeared to be a function of lipid content (Figure 3). Lipid content and total DDT concentration were significantly correlated in three of the four species (p <0.05); market squid lacked a relationship mostly due to the large number of nondetectable quantities. Lipid content explained 43% of the variability in total DDT concentrations for Pacific sardine (r^2 = 0.43), the species with the greatest number of detectable samples. Percent lipid content was highest in Pacific sardine (5.0% ±5.3 Standard deviation or SD), followed by northern anchovy (4.1% ±3.8 SD) and Pacific chub mackerel (2.9% ±1.2 SD). California market squid had the lowest percent lipid content (1.1% ±0.8 SD). Similar to the regressions using bulk tissue total DDT concentrations, no significant differences in contaminant levels between season, regional strata, or species was observed after lipid normalization of total DDT concentrations. There was no significant relationship between lipid content and total PCB concentration although total PCB regressions were hampered by small sample size resulting from non-detectable quantities.

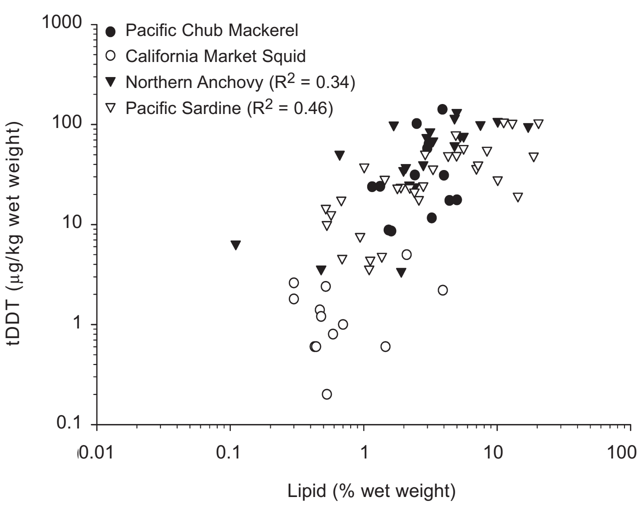

Figure 4. Relationship between lipid content and total dichlordiphenyltrichloroethane (tDDT) wet weight concentrations in whole fish composites (n = 80) of pelagic forage fishes and squid sampled from southern California, USA commercial fish markets and/or bait receivers from July 2003 to February 2004.

Approximately 99% of all commercial landings of northern anchovy in the SCB exceeded wildlife-risk screening values for total DDT during the present study (Figure 5). Approximately 86% of the Pacific sardine and 33% of the Pacific chub mackerel commercial landings also exceeded the total DDT screening values during the present study. None of the California market squid landings exceeded the wildlife risk screening value for total DDT. The extent of total PCB exceedence of wildlife risk screening values (as TEQs) was much less. Less than 1% of the commercial landings for Pacific chub mackerel exceeded wildlife-risk screening values for birds during the present study. None of the other species exceeded the PCB risk screening values for either birds or mammals.

Based on the total biomass of commercial landings, an estimated 1.3 kg (±95% CI = 0.6 kg) of total DDT was contained within the four pelagic fish species examined during the present study. In a similar fashion, 0.06 kg (±95% CI = 0.06 kg) of total PCB was contained within the four pelagic fish species examined during the present study. Most of the total DDT (71%) resided within the landings for Pacific sardine. Pacific sardine had the second highest average concentrations of total DDT and it was the species that had the second highest biomass. In contrast, California market squid contained less than 2% of the total DDT mass found in pelagic fish tissues. While California market squid had the highest amount of landing biomass, it also had extremely low levels of total DDT. Like the total DDT mass estimates, Pacific sardines had the greatest quantity of total PCB of all species examined (83%).

Discussion

Despite the reduction in the discharge of total DDT and total PCB in the SCB over the last 35 years (Schiff *et al.* 2001, Raco-Rands and Steinberger 2001), a large fraction of pelagic bio-

Table 2. Summary of lipid, total dichlorodiphenyltrichloroethane (DDT) and polychlorinated biphenyl (PCB) µg/kg wet wt concentrations in whole-fish composites of pelagic forage species by region within the Southern California Bight, USA, 2003 to 2004.

Species/ Region		Lipid (%)			Total DDT (µg/kg wet wt)						Total PCB (µg/kg wet wt)					
	n	% ND	Mean	SD	%ND	Median	Mean	95%CI	Min	Max	%ND	Median	Mean	95%CI	Min	Max
Pacific chub mackerel																
North	3	0	2.5	2.2	0	23.8	21.8	4.1	17.6	24.0	33	2.3	1.5	1.5	0.0	2.3
Central	4	0	2.8	1.0	0	56.7	65.9	65.0	8.8	141.4	25	0.9	2.8	4.3	0.0	9.3
South	1	0	2.4	--	0	31.2	31.2	--	31.2	31.2	0	4.3	4.3	--	4.3	4.3
Islands	5	0	3.2	1.1	0	31.0	35.6	21.3	8.6	57.4	60	0.0	1.9	2.9	1.8	7.7
California market squid																
North	10		1.2	0.7	50	0.3	0.7	0.6	0.0	2.6	70	0.0	0.0	0.0	0.0	0.2
Central	8		1.2	1.2	38	1.8	1.7	1.2	0.0	5.0	68	0.0	0.1	0.1	0.0	0.3
South	0		--	--	--	--	--	--	--	--	--	--	--	--	--	--
Islands	10		1.0	0.7	60	0.0	0.3	0.2	0.0	1.0	90	0.0	0.0	0.0	0.0	0.1
Northern anchovy																
North	10	0	5.5	4.4	0	75.2	71.5	20.4	24.8	132.0	70	0.0	2.1	2.4	0.0	9.6
Central	10	0	2.0	1.8	10	65.0	56.8	25.6	0.0	115.6	40	0.4	4.8	4.2	0.0	19.4
South	2	0	2.2	0.4	0	13.6	13.6	20.0	3.4	23.8	0	2.1	2.1	3.6	0.2	3.9
Islands	2	0	6.1	5.7	0	72.3	72.3	68.8	37.2	107.4	50	1.2	1.2	2.3	0.0	2.3
Pacific sardine																
North	9	0	3.2	2.3	0	23.2	33.6	18.9	14.6	105.7	33	1.3	1.3	0.8	0.0	3.3
Central	10	0	8.6	7.0	0	43.1	52.8	20.1	12.6	103.8	50	1.2	2.6	2.3	0.0	11.8
South	5	0	2.2	0.4	0	10.0	13.1	7.0	4.8	23.6	40	0.5	1.0	1.2	0.0	3.3
Islands	10	0	4.7	4.1	10	27.6	26.4	13.9	0.0	57.6	50	0.1	1.3	1.3	0.0	5.8

CI: confidence interval; SD: standard deviation; ND: not detected.

mass appears to be affected by total DDT. The extent of bioaccumulation examined herein was widespread with multiple species; sardines, anchovies, and mackerel accumulated measurable total DDT and total PCB throughout virtually all of the landings in the SCB. Moreover, the accumulation of total DDT, based upon wildlife risk screening values (Ridgway *et al.* 2000), was at levels that represented a potential risk to higher order predators such as marine birds and mammals.

At least three factors could possibly control the bioaccumulation of total DDT and total PCB in pelagic forage species of the SCB. One factor could be equilibrium partitioning between the concentrations in the water column and lipid reservoirs in the fish. A strong correlation was observed between tissue concentrations and fish lipid content during this the present study. Species with the greatest lipid content, such as Northern anchovy, also contained the highest contaminant concentrations. Species with the lowest lipid content, such as California market squid, also contained the lowest contaminant concentrations. However, the geographic patterns also appear to play a role. Tissue total DDT concentrations from the present study mirrored geographic patterns in total DDT concentrations observed in both sediment (Schiff 2000) and the water column (Zeng *et al.* 2005) of the SCB. All three studies found the greatest concentrations of total DDT in the central region of the SCB.

A second factor that could control tissue concentrations of pelagic forage fishes of the SCB is life history strategy including diet and age. California market squid, the species with the lowest contaminant concentrations, forages primarily on crustacean zooplankton (Yaremko 2001) and has a relatively short life span of approximately six to nine months (Zeidberg *et al.* 2006). The low total DDT concentrations found in California market squid in the present study could be due, in part, to its short life span and lower trophic level diet. Northern anchovy generally live to approximately three to four years and

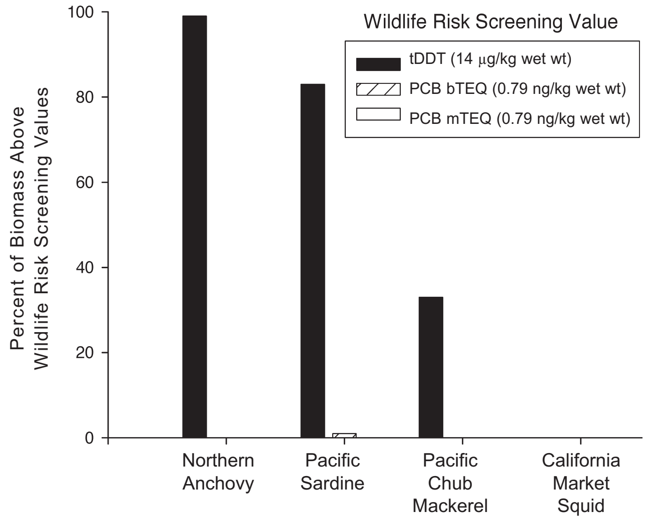

Figure 5. Percentage of pelagic forage fish and squid landings in the Southern California Bight, USA estimated as having contaminant levels above wildlife-risk screening values. tDDT = total dichlorodiphenyltrichloroethane; PCB bTEQ = polychlorinated biphenyl toxicity equivalent quotient for birds; and PCB mTEQ = PCB TEQ for mammals.

feed by filtering or engulfing crustacean zooplankton and ichthyoplankton (Bergen and Jacobson 2001). Most Pacific sardine live to three to seven years and feed by filtering crustacean zooplankton and ichthyoplankton (Wolf *et al.* 2001). Northern anchovy and Pacific sardine had greater tissue contaminant concentrations, perhaps due to their longer life span and amended diet. Pacific chub mackerel feed primarily on small fishes, ichthyoplankton, squid, and crustacean zooplankton; most that are caught in the commercial fishery are less than four years (Konno and Wolf 2001). The average tissue contaminant concentrations in Pacific chub mackerel were higher than squid, but less than anchovy and sardine. While these factors may partially explain differences in tissue concentrations among species, this assumption was not specifically tested during the present study.

A third factor that could control tissue concentrations of pelagic forage fishes is fish mobility that, in turn, would affect exposure. The central subpopulation of Northern anchovy in the SCB is known to migrate southward and offshore for winter spawning (Mais 1974). Pacific chub mackerel subadults and adults move northward along the coast during the summer and also exhibit inshore-offshore migration off California, moving inshore from July through November and offshore from December through May (Konno and Wolf 2001, Mais 1974). Although affected by oceanographic factors, Pacific sardine migrations typically are northward during the early summer and southward beginning in the fall (Wolf *et al.* 2001, Mais 1974). Despite population mobility, average concentrations of total DDT and total PCB in the present study were generally higher from the central coastal region of the SCB.

The assessment of widespread risk to wildlife in the present study is derived from the use of wildlife risk screening values. While a number of human health risk screening values exist for human consumers of fish (USEPA 2000), no widely accepted screening thresholds for wildlife consumption are available. Environment Canada has published values specifically for marine birds and mammals, some of which are found in the SCB (Environment Canada 1998, Van den Berg *et al.* 1998, Roe *et al.* 2000). To assess potential bias associated with different screening values, other unpublished screening values used in California were examined. Regardless of the screening value, little change in the assessment of widespread risk given here was observed. Screening values and guidelines usually focus on effects to the most sensitive species examined. As actual risk to consumers is a function of prey selection, prey concentration, predator consumption rates, physiological target organs, and genetic predisposition of a species, it may vary by species or individuals within a species. Hence these screening values may provide only a general warning, which may result in further studies to determine whether species or populations of concern are actually at risk. Typically, this is manifested through ecological risk modeling (Cullon *et al.* 2005). Secondarily, many managers may be concerned about harm to the pelagic fish that were the focus of the present study. However, deriving individual or population effects thresholds for whole body residues is difficult and fraught with complications (Beckvar *et al.* 2005). Impacts to individual fish, especially sublethal effects such as reproduction or growth, are best evaluated by examining specific organs (i.e., gonads) or early life history stages (Cross and Hose 1988, Hose *et al.* 1989).

Four factors could have influenced estimates of contaminant extent and magnitude in pelagic forage fishes of the SCB. The first factor was sampling success and subsequent representativeness for extrapolation to landed biomass. A large proportion of Pacific sardine and California market squid were representatively sampled, but sampling success appeared limited for northern anchovy and Pacific chub mackerel since sampling targets were not achieved. This perceived limitation, however, was not a function of sampling failures. Rather, it was a function of fishing effort. Sampling success was relatively low for these two species because relatively low quantities of biomass were landed for northern anchovy and Pacific chub mackerel. Cumulatively, northern anchovy and Pacific chub mackerel constituted less than 9% of the total biomass landed during the present study period.

The second factor that could influence estimates of contaminant extent and magnitude in pelagic forage fishes was extrapolation to various geographic regions of the SCB. While extrapolating data collected from commercial landings are well-grounded in fisheries assessments, landings data are prone to inaccurate and imprecise spatial representation. For example, catch in CDFG fishing blocks (270 km^2) are self-reported by the fishermen, and there is no mechanism for ground-truthing reported fishing locations. Perhaps a more important concern, however, was bias associated with unequal sample size among regional strata of the SCB used in the present study. Once again, this bias was minimized by the low quantity of biomass landed in these regions. Small sample sizes were due to regional differences in catch and not poor sampling. For example, the smallest sample sizes routinely occurred in the southern SCB, but only 1% of the commercial landings occurred in the southern SCB for all four species.

The third factor that could influence estimates of contaminant extent and magnitude in pelagic forage fishes of the SCB was temporal variability. Sample design minimized intra-annual variability by sampling across seasons. However, inter-annual variability could still play a role. Assuming that landings were largely a function of abundance, annual landing data for our target species were compiled from CDFG between 1983 and 2004 (Figure 6). Three of the four species were relatively abundant during the study year; northern anchovy, Pacific sardine, and California market squid exceeded the 20-year median of their respective annual landings. In contrast, Pacific chub mackerel had one of its poorest years declining to one-third its 20-year median of landed biomass. These data demonstrate that the extrapolated estimates of biomass provided herein will likely

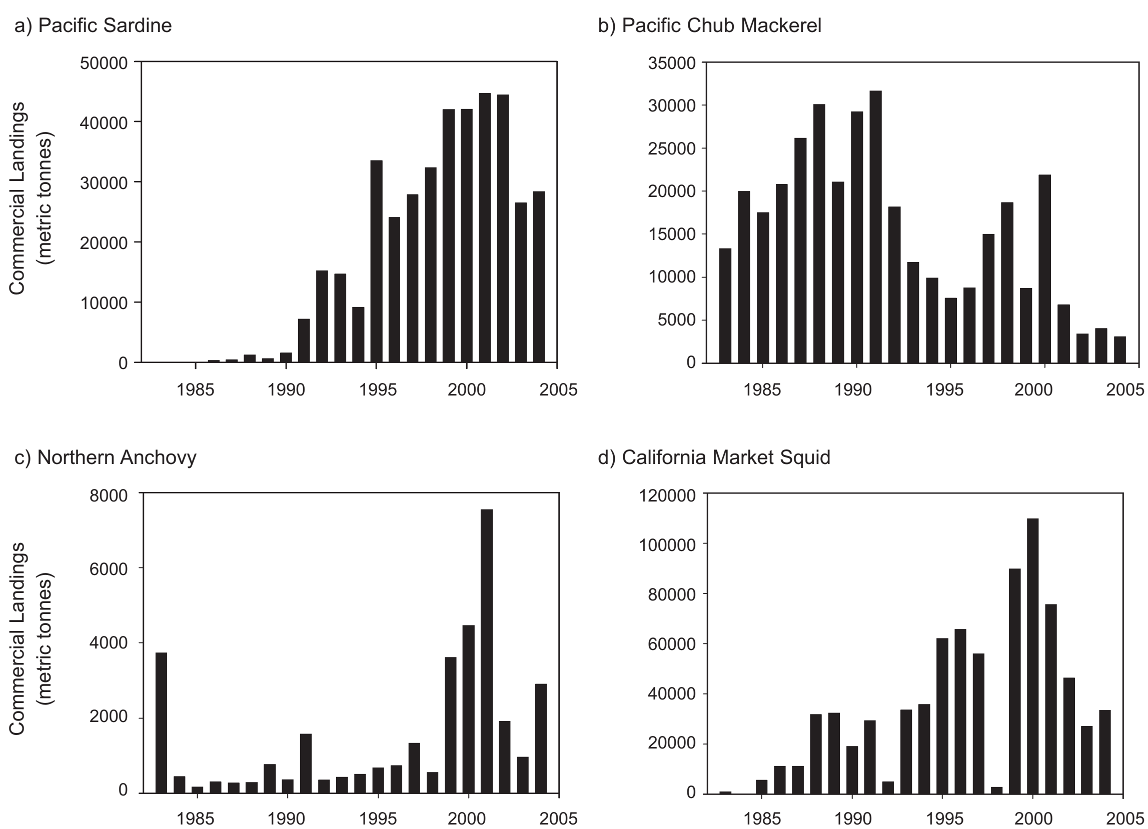

Figure 6. Southern California, USA commercial landings (in metric tons) of Pacific sardine (a), Pacific chub mackerel (b), northern anchovy (c), and California market squid (d) between 1983 and 2004 (California Department of Fish and Game data, unpublished data.

vary over time based on relative abundance. Considering this, overall DDT wildlife risk to consumers of pelagic forage fish and California market squid in the SCB may vary temporally, given that it is likely dependent on the degree of availability and relative preference of birds and mammals for potentially contaminated prey items over time. Fishing and oceanographic cycles can affect the availability of particular prey items for extended periods of time (Jarvis *et al.* 2005), which may in turn increase or decrease exposure to contaminated prey items.

The fourth factor that could influence estimates of contaminant extent and magnitude in pelagic forage fishes of the SCB is the difference associated with commercial landings versus standing stock. Standing stock may be substantially larger than the landed biomass and this would represent an enormous underestimate, particularly for our estimate of total DDT and total PCB mass in pelagic species of the SCB. The Pacific Fishery Management Council sets landings limits for the species examined in this study based upon estimates of stock biomass (California Department of Fish and Game 2004). Based on available estimates of standing stock for Pacific sardine and Pacific chub mackerel for the SCB, the mass of total DDT in pelagic species targeted in the present study would increase from 1.3 to at least 26 kg. While the estimate of total DDT mass in pelagic species increases by an order of magnitude, this quantity is still far short of the 100 metric tonnes estimated to reside in sediments on the Palos Verdes shelf (Lee and Wiborg 2002).

While no previous studies of wildlife risk to consumers of pelagic forage fish have been conducted, total DDT and total PCB levels in edible muscle tissue of pelagic forage fish and California market squid of the SCB were conducted in the early 1980s (Mearns and Young 1980, Gossett *et al.* 1983, Schafer *et al.* 1982). The total DDT muscle tissue values reported in these studies are in general of the same order of magnitude or slightly higher than the whole fish contaminant values reported in the present study (Table 3). While no quantified relationship between edible muscle and whole fish total DDT

Table 3. Comparison of total dichlorodiphenyltrichloroethane (tDDT) and total polychlorinated biphenyls (tPCBs) measured in pelagic forage fishes and squid of the Southern California Bight (SCB), USA in the early 1980s and the present study, 2003 to 2004.

Species/ Location	Year	Composite Type	*n*	Total DDT (µg/kg wet wt)		Total PCBs (µg/kg wet wt)	
				Mean	SD	Mean	SD
California market squid							
Coastal	1980-81[a]	mantle	3	10.0	10.0	10.0	9.0
SCB	2003-04[b]	whole	28	0.8	1.2	0.0	0.1
Northern anchovy							
Coastal	1980-81[a]	muscle	5	47.0	33.0	8.0	9.0
LA/LB Harbor	1980[c]	muscle	5	121.0	31.0	98.0	21.0
SCB	2003-04[b]	whole	24	60.6	38.3	3.1	5.1
Pacific chub mackerel							
Coastal	1980-81[a]	muscle	6	130.0	145.0	26.0	22.0
Santa Monica Bay	1981[d]	muscle	5	57.0	37.0	15.0	7.0
Palos Verdes	1981[d]	muscle	5	44.0	--	12.0	12.0
Laguna Beach	1981[d]	muscle	1	129.0	86.0	34.0	22.0
SCB	2003-04[b]	whole	13	41.4	40.2	2.3	3.1
Pacific sardine							
Coastal	1980-81[a]	muscle	5	484.0	112.0	105.0	40.0
SCB	2003-04[b]	whole	34	34.1	28.7	1.6	2.5

[a]Schafer *et al* . 1982
[b]The present study
[c]Mearns and Young 1980
[d]Gossett *et al* . 1983

SD: standard deviation; LA/LB: Los Angeles/Long Beach Harbor concentrations in these species exists, whole fish tissue concentrations of total DDT in other fishes are generally an order of magnitude greater than muscle tissue concentrations. Assuming this relationship holds true for pelagic forage species, total DDT concentrations in pelagic forage fishes and squid in the SCB have decreased over the past 25 years. Similarly, total PCB concentrations have also decreased for the species examined herein. For both total DDT and total PCB, Pacific sardine showed the most dramatic difference between muscle tissue concentration in the early 1980s (484 µg total DDT/kg wet wt; Mearns and Young 1980) and whole fish concentrations in 2003 to 2004 (34 µg total DDT/kg wet wt, the present study).

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