# Mercury in Birds of the San Francisco Bay-Delta:
## Trophic Pathways, Bioaccumulation, and Ecotoxicological Risk to Avian Reproduction

*2006 Annual Administrative Report*

Josh Ackerman[1], Collin Eagles-Smith[2], Gary Heinz[3], Susan Wainwright-De La Cruz[1], John Takekawa[1], Terry Adelsbach[2], Keith Miles[1], Dave Hoffman[3], Steve Schwarzbach[1], Tom Suchanek[1], and Tom Maurer[2]

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CALFED BAY-DELTA PROGRAM

U.S. FISH & WILDLIFE SERVICE
DEPARTMENT OF THE INTERIOR

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U.S. DEPARTMENT OF THE INTERIOR
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## A. MERCURY IN BIRDS OF THE SAN FRANCISCO BAY-DELTA: TROPHIC PATHWAYS, BIOACCUMULATION, AND ECOTOXICOLOGICAL RISK TO AVIAN REPRODUCTION

**By Josh Ackerman, Collin Eagles-Smith, Gary Heinz, Susan Wainwright-De La Cruz, John Takekawa, Terry Adelsbach, Keith Miles, Dave Hoffman, Steve Schwarzbach, Tom Suchanek, and Tom Maurer**

## B. INTRODUCTION TO THE PROJECT

**Background:** The Bay-Delta watershed has a legacy of mercury (Hg) contamination that threatens human and wildlife health, as well as ecosystem function. Hg bioavailability within the Bay-Delta may be increased by wetland restoration and complicates restoration goals of CALFED. The Mercury Strategy Document cited the need for information on methylmercury (MeHg) effects in birds as a requirement for adaptive restoration of the Bay-Delta ecosystem and recognized the sensitivity of avian reproduction to MeHg (Wiener et al. 2003). The ecotoxicological risk of Hg to birds is unclear because we do not understand MeHg exposure among different foraging guilds of birds and MeHg's effect on avian reproduction.

**The Guild Approach:** Estuarine waterbirds form distinct foraging guilds that are distinguished by their feeding method, diet preferences, and habitat use. These guilds include: 1) surface-feeding recurvirostrids (American avocets and black-necked stilts), 2) diving benthivores (surf scoters), and 3) obligate piscivores (Forster's terns and Caspian terns). Each guild represents a unique foraging pathway within the Bay-Delta ecosystem for Hg bioaccumulation.

**Project Goals:** Our goal is to integrate a field assessment of Hg exposure and effects with a laboratory assessment of the sensitivity of avian embryos to MeHg to quantify the risks of Hg to aquatic birds. Our field approach will evaluate the hazard of Hg to 3 foraging guilds of birds with different potential risks. Our complementary lab approach will improve interpretation of our field data, assess variation in Hg sensitivity among species, and establish and refine MeHg dose-response relationships and threshold concentrations associated with avian embryo toxicity. In sum, we will follow Hg through avian prey, into adult birds, maternal transfer of Hg into eggs, and then evaluate how Hg influences egg hatchability and chick survival (Fig. 1).

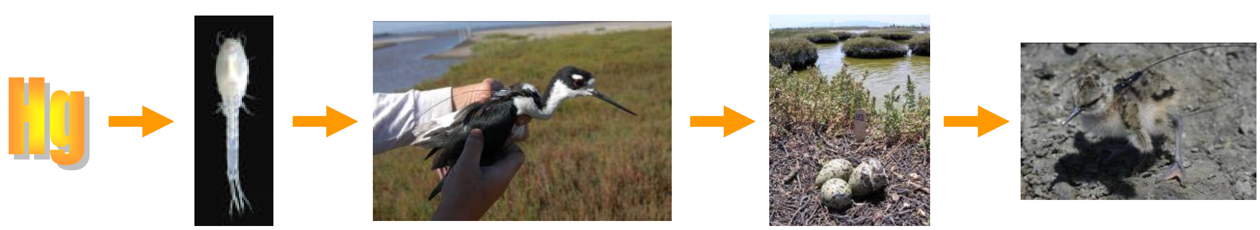



***Fig. 1.*** *Project overview depicting Hg bioaccumulation, maternal transfer, and effects on egg hatchability and chick survival.*

**Hypotheses:** Our research program has 3 main objectives, each consisting of a suite of hypotheses. Please see Appendix 1 for a detailed list of hypotheses.
*<u>Objective I</u>*: Determine avian Hg exposure and bioaccumulation in each foraging guild.
*<u>Objective II</u>*: Determine effects of Hg bioaccumulation on avian reproduction.
*<u>Objective III</u>*: Determine the differential sensitivity of avian taxa to Hg and toxic threshold concentrations using egg injections and controlled feeding experiments.

## C. PROJECT TIMETABLE AND PROGRESS

CBDA approved the project for funding in December 2003, with funding received by July 2004. Currently, we are entering the third and final field season of our project and expect to be finished with field work by September 2007. We have already produced many products including 6 scientific journal articles, 5 general articles, and 77 presentations (Appendix 2). We anticipate that the final report will be submitted in July 2008.

We are currently on schedule to complete all project objectives and have met all project milestones as detailed in Section D. However, we have modified a few tasks based on early data analyses and logistics. *Objective I*: We found sample sizes and access insufficient for telemetry on two guilds in the North Bay (Task I.1, I.2). Instead, we increased sample size in other study areas. Also, we were issued a restricted federal permit on Caspian terns, precluding several aspects of the project. Thus, we increased efforts on the other species in the fish-eating guild, Forster's terns. *Objective II*: We found sample sizes insufficient for full breeding studies in the North Bay (Task II.1, II.2). Instead, we increased breeding samples in other areas. The restricted federal permit precluded Caspian tern breeding studies, so we focused more on Forster's terns and recurvirostrids. *Objective III*: The timing for the egg injection study was delayed because in 2005 we had poor hatching success of artificially incubated recurvirostrid eggs, but we completed this objective in 2006.

## D. PROJECT HIGHLIGHTS AND RESULTS

### Objective I. Determine Avian Mercury Exposure and Bioaccumulation in Three Guilds

Using diet analysis, stable isotope techniques, Hg analysis of prey, and radio telemetry, we are identifying species differences in trophic pathways of MeHg exposure in 3 guilds of aquatic birds. Our general approach was to capture, radio-mark, and track birds to determine sites of dietary Hg uptake. Once an individual bird's space use was quantified, we then calculated the core use area within its home range, and randomly sampled telemetry locations within the core use area for their invertebrate prey (avocets, stilts, and scoters) or fish prey (terns). In general, adult avocets had the lowest blood total Hg (THg) concentrations (geometric mean±SE [$\mu g\ g^{-1}$ ww]: 0.30±0.06), followed by scoters (0.41±0.03), stilts (1.00±0.21), Caspian terns (1.36±0.31), and Forster's terns (1.49±0.29; Fig. 2). THg concentrations were highest in South Bay (1.35±0.09), followed by North Bay (0.79±0.07), and Central Bay (0.52±0.06). See Appendix 3 and 4 for maps of study area. Below we briefly present our main results to date by task.

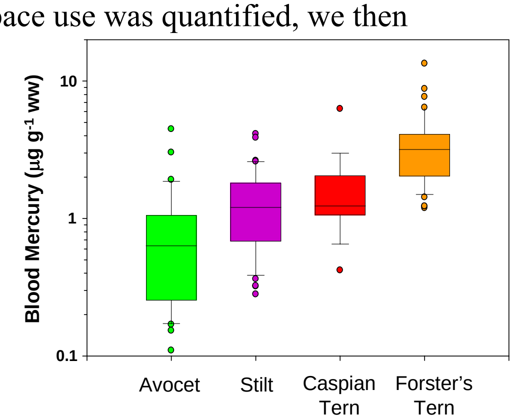



***Fig. 2.*** *Blood THg concentrations in breeding waterbirds approached and surpassed toxic levels in San Francisco Bay, especially for terns.*

**Task I.1**- *Identify trophic pathways of MeHg exposure in surface feeding avocets and stilts.*

<u>Telemetry</u>---During 2005 and 2006, we captured, radio-marked, and tracked 115 avocets and 94 stilts and obtained 2,393 and 1,928 telemetry locations, respectively, during the pre-breeding seasons (February-April) when birds aquired resources for egg laying. Radio-marked birds showed high site fidelity and remained near their capture site (e.g., Figs. 3 and 4; enlarged in Appendix 5). Avocets used salt ponds and tidal flats more often than stilts, whereas stilts used marshes more often than avocets. Within the same sites, avocets used more open water and

mudflat habitats whereas stilts used more vegetated areas.

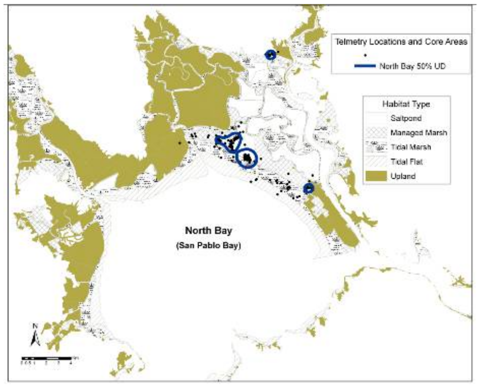



***Fig. 3.*** *Radiotelemetry locations and core use home ranges of stilts in North Bay (2005).*

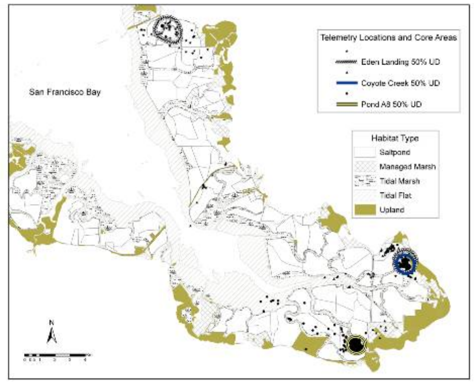



***Fig. 4.*** *Radiotelemetry locations and core use home ranges of avocets in South Bay (2005).*

Diet & Stable Isotopes---We analyzed tissues for stable isotopes and collected stomach contents to estimate site-specific diet. Stilt $\delta^{15}N$ values did not differ from those of avocets in the South Bay (ANOVA: $F_{1,52}=0.06$, $P=0.81$), whereas they were significantly lower in both North and Central Bay regions (North Bay, ANOVA: $F_{1,23}=8.96$, $P=0.01$; Central Bay ANOVA: $F_{1,17}=8.93$, $P=0.01$; Fig. 5). These data suggest that avocets either foraged at a higher trophic position than stilts, or foraged in a different habitat with distinct basal $\delta^{15}N$ ratios. Carbon isotope ratios ($\delta^{13}C$), which provide an index of foraging habitat, indicated that stilts and avocets obtained energy from different basal sources in all 3 regions. $\delta^{13}C$ ratios were significantly depleted (lower) in stilts compared with avocets (ANOVA: $F_{1,131}=28.32$, $P<0.0001$), perhaps indicating greater reliance by stilts on marsh plain food sources relative to those of open water and slough habitats (Fig. 6).

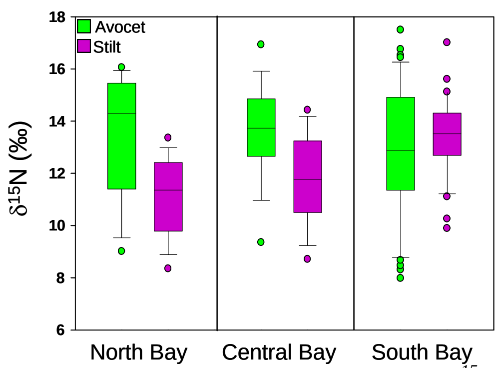



***Fig. 5.*** *Stable nitrogen isotope ratios ($\delta^{15}N$) in avocet and stilt muscle tissue.*

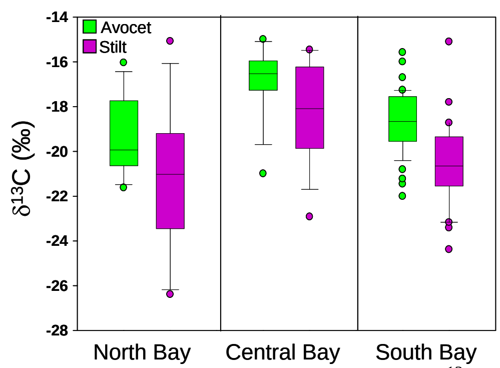



***Fig. 6.*** *Stable carbon isotope ratios ($\delta^{13}C$) in avocet and stilt muscle tissue.*

Mercury in Prey---We sampled invertebrates at 9 sites in 2005 and 2006 during pre- and post-breeding seasons. Of 13 taxa, only Corixidae (water boatman) were found at all 9 sites. We therefore used Corixidae to assess MeHg differences among sites, seasons, and years. MeHg concentrations differed among sites ($F_{8,136}=26.65$, $P<0.0001$) and between pre- and post-breeding seasons ($F_{1,136}=43.85$, $P<0.0001$), but not between years ($F_{1,136}=0.99$, $P=0.32$). Geometric mean MeHg concentrations (µg $g^{-1}$ dw) were highest in the South Bay at Rectangle Marsh (1.75) and pond A8 (0.77); intermediate at pond A16 (South Bay: 0.45), pond 1 (North Bay: 0.42), and New Chicago Marsh (South Bay: 0.30); and lowest at Mare Island (North Bay: 0.20), Coyote Creek Lagoon (South Bay: 0.19), Eden Landing (Central Bay: 0.16), and Newark (Central Bay: 0.05;

Fig. 7). Corixidae MeHg concentrations were near or exceeded reported dietary effects levels (0.50 µg $g^{-1}$ dw) for birds at 4 of 9 sites. Time series analysis at pond A8 and New Chicago Marsh indicated that MeHg concentrations decreased throughout the bird breeding season (Fig. 8). In general, MeHg concentrations were higher in Corixidae than in all other taxa, possibly because they are predators and eat other invertebrates.

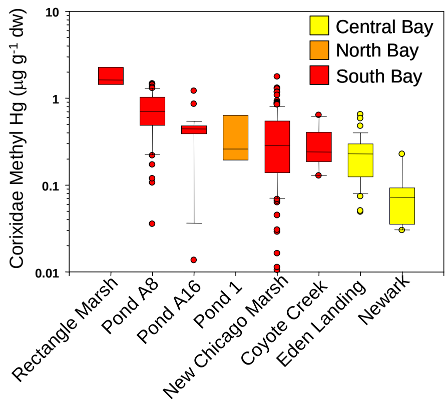



***Fig. 7.*** *MeHg concentrations in Corixidae collected at sites throughout the San Francisco Bay.*

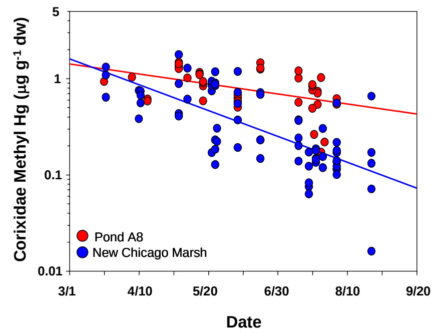



***Fig. 8.*** *Corixidae MeHg concentrations over time in New Chicago Marsh and pond A8 (2006).*

<u>Mercury in Pre-breeding Adults</u>---We captured or collected 373 avocets and 157 stilts during the pre-breeding seasons in 2005 and 2006. THg concentrations in bird blood was highly correlated with THg and MeHg concentrations in liver, kidney, and muscle (Appendix 6); therefore we will present only blood THg concentrations to reduce redundancy. To determine which factors influenced THg concentrations in avocets and stilts, we tested the effects of species, site, sex, year, and date. Using AIC model selection procedures (Appendix 7), capture site was the most important factor influencing THg concentrations in birds (Fig. 9), followed by species and sex (ANCOVA: site: $F_{7,518}=53.85$, $P<0.0001$; species: $F_{1,518}=168.31$, $P<0.0001$; sex: $F_{1,518}=20.69$, $P<0.0001$; year: $F_{1,518}=0.52$, $P=0.47$; date: $F_{1,518}=0.52$, $P=0.47$). THg concentrations were higher in stilts (geometric mean: 1.09 µg $g^{-1}$ ww) than in avocets (0.25 µg $g^{-1}$ ww) and males (stilts: 1.32 µg $g^{-1}$ ww; avocets: 0.32 µg $g^{-1}$ ww) had higher levels than females (stilts: 1.15 µg $g^{-1}$ ww; avocets: 0.21 µg $g^{-1}$ ww). THg concentrations were highest for both species in the South Bay, especially in salt pond A8 (stilts: 3.31 µg $g^{-1}$ ww; avocets: 0.58 µg $g^{-1}$ ww). When viewed in light of our telemetry and stable isotope results, our data suggest that variation in blood THg concentrations among sites was largely attributed to differences in foraging areas, and species differences in microhabitat use and foraging strategies increased Hg exposure in stilts more than avocets.

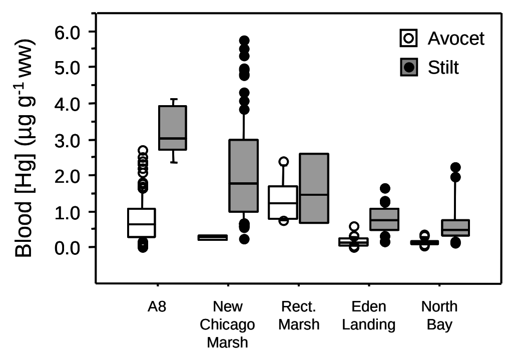



***Fig. 9.*** *Blood THg concentrations (µg $g^{-1}$ ww) in pre-breeding avocets and stilts.*

<u>Mercury in Breeding Adults</u>---We captured or collected 38 female avocets and 46 female stilts on their nests during the breeding seasons in 2005 and 2006. Similar to the pre-breeding season, blood THg concentrations were higher in breeding stilts (geometric mean: 1.10 µg $g^{-1}$ ww) than in breeding avocets (0.56 µg $g^{-1}$ ww). Interestingly, blood THg concentrations were nearly 3-times higher in breeding than pre-breeding avocets (Fig. 10), whereas there was no difference in THg concentrations between these time periods in stilts (ANOVA: $F_{1,89}=2.02$,

P=0.16; Fig. 11). Unlike pre-breeding birds, there was no difference in THg concentrations among capture sites for breeding avocets (ANOVA: $F_{5,25}$=1.90, P=0.13), but THg concentrations differed among sites for stilts (ANOVA: $F_{5,35}$=8.51, P<0.0001).

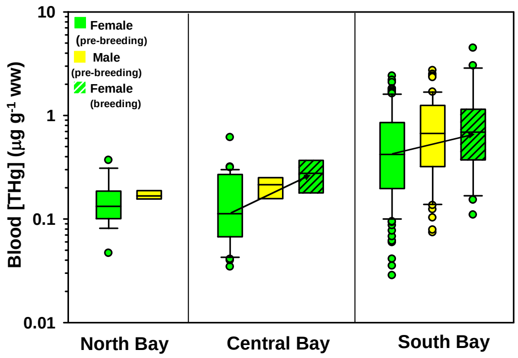



***Fig 10.*** *Blood THg concentrations (µg g$^{-1}$ ww) in pre-breeding and breeding avocets.*

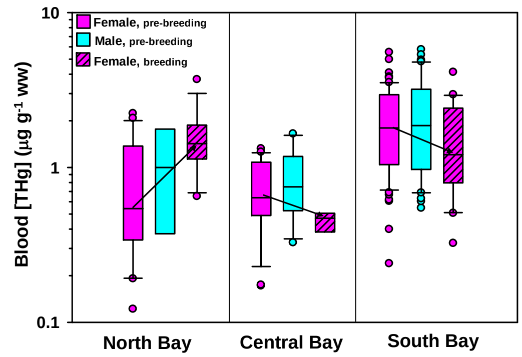



***Fig 11.*** *Blood THg concentrations (µg g$^{-1}$ ww) in pre-breeding and breeding stilts.*

**Task I.2** - *Identify trophic pathways of MeHg exposure in terns.*

Telemetry----During 2005 and 2006, we captured, radio-marked, and tracked 72 Forster's terns and obtained 1,012 telemetry locations during the pre-breeding seasons (March-May) to determine sites of Hg uptake. Radio-marked terns generally remained within the area where they were captured (e.g., Figs. 12 and 13; enlarged in Appendix 8), although they ranged further than avocets and stilts (previous Figs. 3 and 4). Terns mainly foraged within salt ponds, managed and tidal marshes, and tidal flats, and were relatively absent from bays, sloughs, and lagoons.

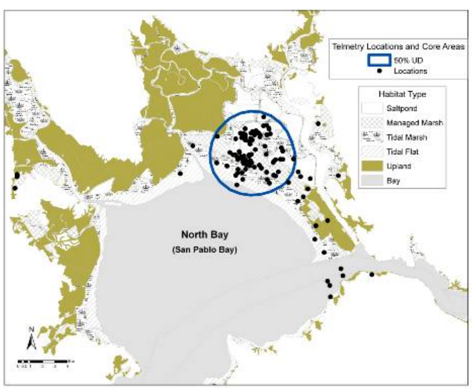



***Fig. 12.*** *Radiotelemetry locations and core use home ranges of Forster's terns in North Bay (2005).*

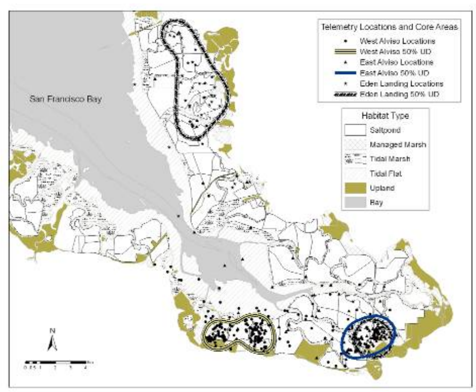



***Fig. 13.*** *Radiotelemetry locations and core use home ranges of Forster's terns in South Bay (2005).*

Diet & Stable Isotopes---Nitrogen isotope ratios ($\delta^{15}N$) were consistently elevated in Forster's terns and Caspian terns over stilts and avocets across all regions, indicating that terns forage at a higher trophic position than avocets and stilts (ANOVA: $F_{3,149}$=42.45, P<0.0001; Fig. 14). We estimated diets of Forster's terns at 7 breeding colonies throughout the Bay using >1,100 fish that terns returned to colonies to feed their mates and offspring (Fig. 15). Diet varied substantially among colonies, with top prey items including yellowfin gobies (Pond A1), three-spined sticklebacks (A7 and Newark), topsmelt (Eden Landing, A8, and A16), and Mississippi silversides (North Bay). There was considerable partitioning of fish resources within colonies, and a single fish species accounted for >50% of the diet at only 3 of 7 colonies.

Mercury in Prey---We sampled Forster's tern fish prey in 2005 and 2006 from actual (randomly chosen) telemetry locations within the pre-breeding core use areas of individually

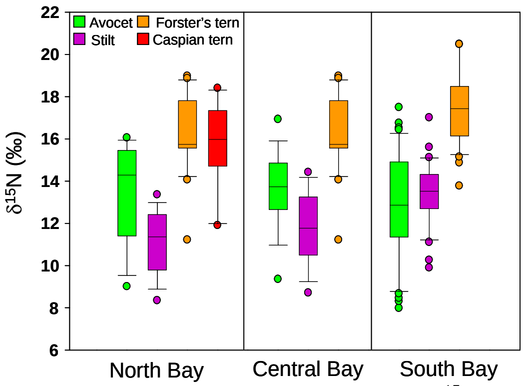



***Fig. 14.*** *Stable nitrogen isotope ratios ($\delta^{15}N$) in avocets, stilts, Forster's terns, and Caspian terns.*

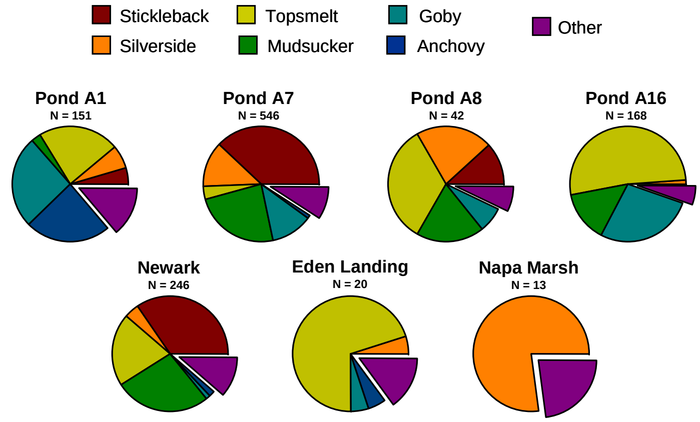



***Fig. 15.*** *Diet composition of Forster's terns at seven colonies.*

radio-marked terns. Additionally, to examine temporal patterns in fish THg concentrations, we established time-series stations at 12 sites within 4 ponds and sampled them bi-weekly (April-August 2006). Controlling for site and fish length, THg concentrations varied among species and sites (ANCOVA: Species: $F_{9,250}$=21.33, P<0.0001; Site: $F_{3,250}$=52.17, P<0.0001; Appendix 9). THg concentrations (least-square means±SE; µg $g^{-1}$ dw) were highest in rainwater killifish (1.58±1.22) and silversides (1.17±0.24); intermediate in sculpin (0.49±0.08), three-spined sticklebacks (0.48±0.46), and topsmelt (0.45±0.07); and lowest in yellowfin gobies (0.32±0.05) and long-jawed mudsuckers (0.31±0.04). THg concentrations also varied among sites, being most elevated in ponds and marshes in East Alviso (0.91±0.16), followed by West Alviso (0.71±0.14), the open South Bay (0.40±0.08), and the Napa-Sonoma Marsh ponds and sloughs (0.35±0.06). However, the relative concentrations between species differed among sites as indicated by the significant site by species interaction (ANCOVA: $F_{27,239}$=2.67, P=0.003).

Mercury in Pre-breeding Adults---We captured or collected 122 Forster's terns and 30 Caspian terns during the pre-breeding seasons in 2005 and 2006. Using AIC model selection procedures (Appendix 7), capture site and capture date were the most important factors explaining variation in blood THg concentrations in Forster's terns, followed by sex and year (ANCOVA: site: $F_{3,115}$=5.15, P=0.002; date: $F_{1,115}$=9.38, P=0.003; sex: $F_{1,115}$=4.19, P=0.04; year: $F_{1,115}$=3.29, P=0.07). THg concentrations in Forster's tern blood were highest in the extreme South San Francisco Bay at East Alviso (1.66±0.22 µg $g^{-1}$ ww), followed by North Bay (0.97±0.17 µg $g^{-1}$ ww), South Bay at West Alviso (0.91±0.12 µg $g^{-1}$ ww), and South-Central Bay at Eden Landing Ecological Reserve (0.77±0.14 µg $g^{-1}$ ww; Fig. 16). Importantly, blood THg concentrations more than tripled during the 45-day pre-breeding time period from when Forster's terns arrived in San Francisco Bay to when they began initiating nests (Fig. 17). Male terns (1.20±0.13 µg $g^{-1}$ ww) had higher THg concentrations than females (0.88±0.10 µg $g^{-1}$ ww) and

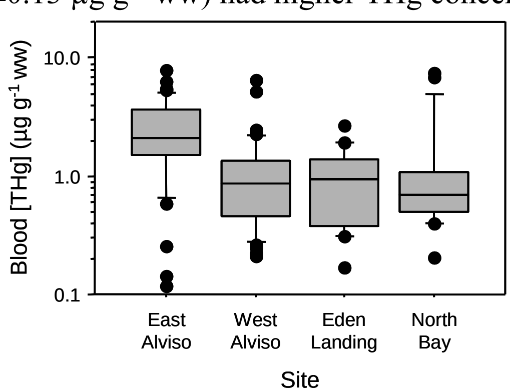



***Fig. 16.*** *Blood THg concentrations (µg $g^{-1}$ ww) in Forster's terns (2005-2006).*

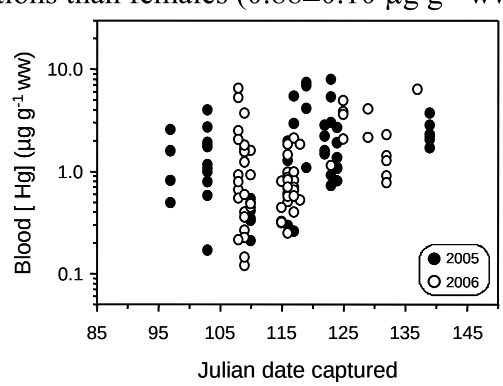



***Fig. 17.*** *Blood THg concentrations (µg $g^{-1}$ ww) in Forster's terns increased with capture date (2005-2006).*

concentrations in 2005 (1.18±0.13 μg $g^{-1}$ ww) were generally higher than in 2006 (0.90±0.10 μg $g^{-1}$ ww). In contrast to blood data, capture site and capture date were not important factors explaining variation in feather THg concentrations, probably because Forster's terns grow their feathers at over-wintering sites outside of the Bay several months prior to our sampling. Instead, sex and year were the most important factors explaining THg concentrations in breast feathers (9.57±8.23 μg $g^{-1}$ fw; ANCOVA: sex: $F_{1,114}$=8.70, P=0.004; year: $F_{1,114}$=5.80, P=0.02; site: $F_{3,114}$=0.56, P=0.64; date: $F_{1,114}$=0.04, P=0.84) and sex was the most important factor for head feathers (6.94±7.04 μg $g^{-1}$ fw; ANCOVA: sex: $F_{1,115}$=9.64, P=0.002; year: $F_{1,115}$=0.22, P=0.64; site: $F_{3,115}$=0.75, P=0.53; date: $F_{1,115}$=0.56, P=0.45).

Mercury in Breeding Adults---We captured 50 breeding Forster's terns and 20 Caspian terns on their nests in 2005 and 2006. THg concentrations (geometric means) were higher in Forster's terns (3.02 μg $g^{-1}$) than in Caspian terns (1.37 μg $g^{-1}$; ANOVA: $F_{1,54}$=25.66, P<0.0001). THg concentrations in breeding Forster's tern blood followed a similar spatial pattern to pre-breeding terns, with East Alviso (4.28 μg $g^{-1}$) terns having the highest THg concentrations followed by North Bay (2.60 μg $g^{-1}$), West Alviso (2.45 μg $g^{-1}$), and Central Bay (1.47 μg $g^{-1}$; ANOVA: $F_{3,36}$=5.81, P=0.002). In contrast to the pre-breeding results, we did not observe year effects on blood THg concentrations for Forster's terns (ANOVA: $F_{1,36}$=1.30, P=0.26). Blood THg concentrations in Forster's terns continued to increase over the course of the breeding season as they did during pre-breeding season, and average THg concentrations more than tripled between the pre-breeding and breeding seasons (ANOVA: $F_{1,84}$=62.50, P<0.0001; Fig. 18). Moreover, the increase was proportionally higher in males (307% increase) than females (184% increase), partly reflecting Hg depuration into eggs.

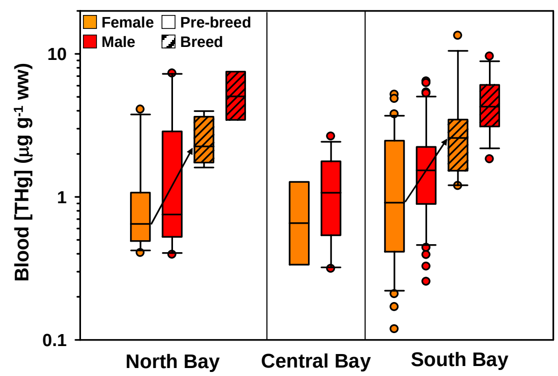



***Fig. 18.*** *Blood THg concentrations (μg $g^{-1}$ ww) in pre-breeding and breeding Forster's terns.*

**Task I.3** - *Identify trophic pathways of MeHg exposure in surf scoters.*

We captured and radio (VHF) or satellite (PTT) marked 209 surf scoters in the North and Central San Francisco Bay in winters from 2004-2006. We tracked returning and new VHF-marked scoters daily and obtained 4,148 locations. Scoters showed site fidelity at a regional scale (Appendix 10); however, some individuals moved among sub-bays. Mean core use home range sizes (±SE) were 40±5.6 $km^2$ (2004), 15.9±3.5 $km^2$ (2005), and 48±65 $km^2$ (2006).

We collected 159 foraging surf scoters and their prey during fall, winter, and spring from Central, North, and Suisun Bays for contaminant, isotope, and condition analyses. We found a strong relationship between THg and MeHg in scoter livers ($R^2$=0.87). Liver THg increased in scoters as they over-wintered in the Bay (ANOVA: $F_{2,154}$=33.70, P<0.001; Fig. 19). Liver THg concentrations were higher in 2005 than in 2004 (ANOVA: $F_{2,154}$=17.53, P<0.001) and THg concentrations were higher in Suisun than in the North or Central Bay (ANOVA: $F_{2,154}$=5.54, P<0.01). Late winter THg concentrations in male scoters appear to have declined since the 1980s. Selenium concentrations

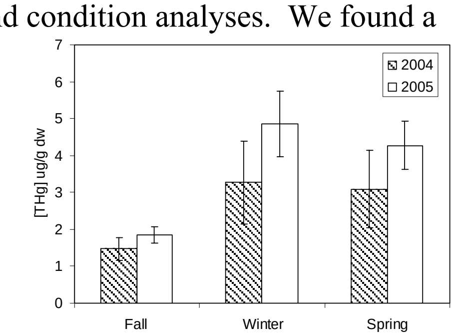



***Fig. 19.*** *THg concentrations in surf scoter livers in fall, winter, and spring (2004-2005).*

in scoter livers ranged from 7.4 to 119 µg $g^{-1}$ dw, and were higher in North and Suisun Bays compared to the Central Bay (ANOVA: $F_{2,154}$=35.18, P<0.001). Selenium data will be used to assess effects on body condition and survival.

**Objective II. Determine Effects of Mercury Bioaccumulation on Avian Reproduction**
**Task II.1 & Task II.2** - *Conduct field studies of reproductive success in avocets, stilts, and Forster's terns to evaluate the fate and effects of Hg on eggs and chicks.*

Nest Success---We monitored 896 avocet, 463 stilt, and 1,141 Forster's tern nests during 2005 and 2006. In general, nest success was variable among sites, years, and species (Appendix 11). Forster's terns had higher nest success than avocets or stilts at sites where they co-occurred, likely due to their habit of nesting colonially on islands which provides refuge from terrestrial predators as well as colonial mobbing of aerial predators to deter predation. The proportion of eggs hatching in a successful nest ranged between 81-85% for avocets, 88% for stilts, and 78-83% for Forster's terns (2005).

Mercury in Eggs---THg concentrations (geometric mean±SE) in randomly collected Forster's tern eggs (6.04±0.48 µg $g^{-1}$ dw) were higher than stilts (2.89±0.32 µg $g^{-1}$ dw) and avocets (1.23±0.11 µg $g^{-1}$ dw; ANOVA: $F_{2,341}$=197.78, P<0.0001; Fig. 20). Similar to our results for THg concentrations in adult birds, THg concentrations in eggs differed among sites (ANOVA: $F_{7,341}$=17.69, P<0.0001; Fig. 20).

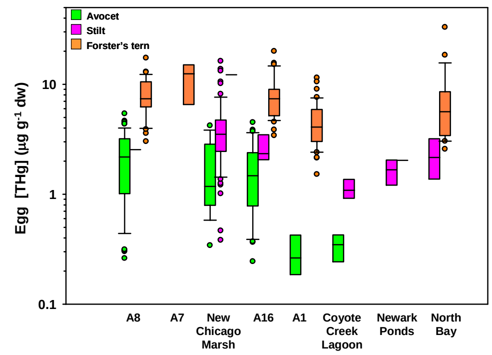



***Fig. 20.*** *Egg THg concentrations (µg $g^{-1}$ dw) in avocets, stilts, and Forster's terns.*

Mercury Effects on Egg Hatchability in the Field---We collected failed-to-hatch, abandoned, and random (viable) eggs to determine whether THg concentrations were higher in failed-to-hatch eggs than in viable eggs. We also collected one egg randomly from clutches at 9-12 days in incubation (avocet N=124, stilt N=88, and Forster's tern N=140), and then the remaining eggs were monitored for hatching success. THg levels in the collected eggs will act as a surrogate for THg levels in the remaining eggs in the same clutch so that we can determine whether THg in eggs influences hatching success in the wild. We also collected entire clutches to examine intra-clutch variation in THg levels to make sure collected eggs are appropriate as surrogates. THg analyses are currently being conducted and results are not yet available.

Mercury in Chicks--- We assessed Hg concentrations in various chick tissues and found that blood was less strongly correlated with internal tissues relative to adults (Appendix 12), and that blood THg concentrations varied among species (ANOVA: $F_{2,182}$=6.83, P=0.001). Whereas the main effect of site was not significant (ANOVA: $F_{1,182}$=0.01, P=0.93), the site by species interaction (ANOVA: $F_{2,182}$=3.72, P=0.03) indicated that THg varied among sites for stilt chicks, but not for avocet or Forster's tern chicks.

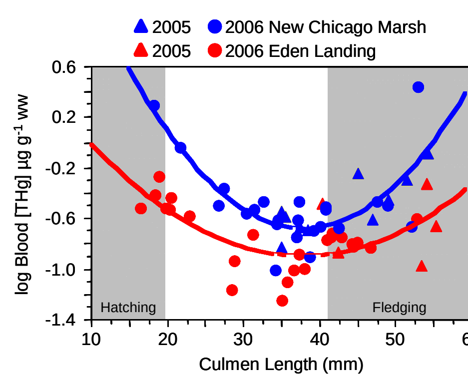



***Fig. 21.*** *Age-specific blood THg concentrations (µg $g^{-1}$ ww) in stilt chicks at New Chicago Marsh and Eden Landing (2006). Lines were fitted with a second-order polynomial.*

However, chick age had substantial effects on blood THg concentrations (Fig. 21). We found that blood THg concentrations were high in newly hatched chicks, due to high *in ovo* THg exposure, and concentrations declined rapidly after hatching as chicks diluted the Hg in their bodies through growth in size and depuration of Hg into growing feathers. Hg concentrations in chicks began to increase rapidly again just before and during fledging (28-days old) when body growth and feather production slowed and chicks continued to acquire Hg through their diets. We observed this pattern of Hg depuration and accumulation in stilt chicks at both a high Hg (New Chicago Marsh: $R^2$=0.63, N=33, P<0.0001; Fig. 21) and low Hg site (Eden Landing Ecological Reserve: $R^2$=0.46, N=29, P=0.001; Fig. 21) as well as in Forster's tern chicks at Newark ($R^2$=0.62, N=75, P<0.0001; Appendix 13).

<u>Mercury Effects on Chick Survival</u>---We evaluated whether Hg influenced survival of avocet and stilt chicks in 2005 and 2006. Using radio telemetry, we radio-marked 158 avocet and 79 stilt chicks at hatching and tracked them daily until their fate was determined. We used THg concentrations in chick down feathers at hatching as our index of *in ovo* Hg exposure. Using AIC model selection procedures (Appendix 7), capture site was the most important variable influencing chick THg concentrations (Fig. 22), followed by year, species, and hatching date (ANCOVA: site: $F_{5,228}$=11.10, P<0.0001; year: $F_{1,228}$=30.60, P<0.0001; species: $F_{1,228}$=19.62, P<0.0001; date: $F_{1,228}$=9.97, P=0.002). We did not find strong support for an influence of *in ovo* Hg exposure on chick survival, despite observing a wide range of THg concentrations in down feathers from 0.40 to 44.31µg $g^{-1}$ fw. We estimated that Hg reduced chick survival rates by ≤3% over the range of observed THg concentrations during the 28-day period from hatching to fledging (Fig. 23).

We also salvaged newly-hatched avocet and stilt chicks that were found dead during routine nest monitoring. In contrast to the telemetry results, we found that THg concentrations in down feathers of dead chicks were higher than those in randomly-sampled live chicks of similar age (ANCOVA: dead or alive: $F_{1,257}$=5.01, P=0.03; site: $F_{5,257}$=13.66, P<0.0001; year: $F_{1,257}$=24.17, P<0.0001; species: $F_{1,257}$=30.18, P<0.0001; date: $F_{1,257}$=7.84, P=0.01; Fig. 24). Our results suggests that Hg exerts its effect on chick survival shortly after hatching (<3 days old) and has a negligible effect on survival between 3-days of age and fledging at 28-days of age. Hg likely has an effect on chick survival shortly after hatching because newly hatched chicks have relatively higher blood THg concentrations due to *in ovo* exposure, whereas older chicks have much lower blood THg concentrations due to 1) rapid body growth and dilution of the body's Hg burden and 2) Hg depuration into growing feathers before fledging (Fig. 21 and Appendix 13).

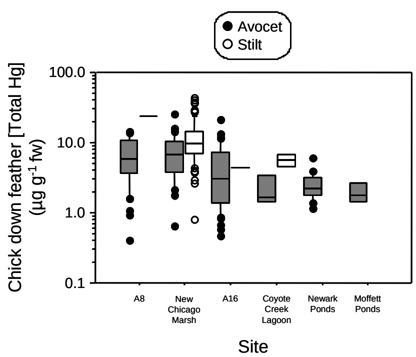



***Fig. 22.*** *THg concentrations in avocet and stilt chick down feathers at hatching (2005-2006).*

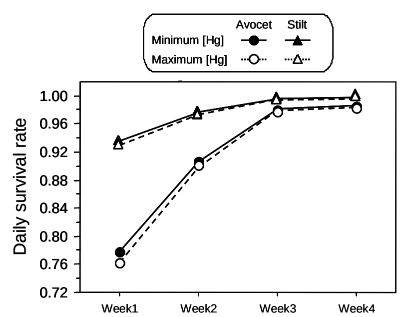



***Fig. 23.*** *Modeled daily survival rates of avocet and stilt chicks at the lowest and highest observed THg concentrations in down feathers at hatching (2005-2006).*

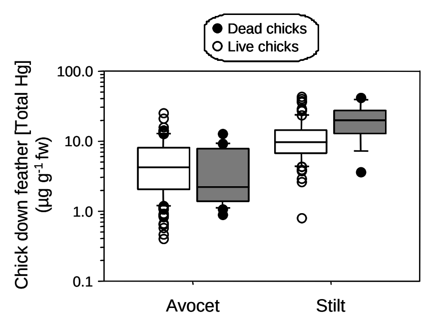



***Fig. 24.*** *THg concentrations in newly-hatched avocet and stilt chicks found dead versus live chicks (2005-2006).*

<u>Mercury Effects on Chick Growth Rates</u>---We used mark-recapture methodology to determine growth rates of Forster's tern chicks in relation to Hg contamination. We individually marked 1,558 Forster's tern chicks in 2005 and 2006, measured and weighed each chick, and

collected downy feathers as an index of *in ovo* Hg concentrations. We also collected breast feathers from recaptured chicks as an indicator of Hg levels post-hatch. We used four indices of chick growth rate: 1) mass, 2) wing, 3) culmen, and 4) tarsus length. In 2005, we found no relationship between wing growth rates and THg concentrations in chick down (N=211, $R^2$=0.01, P=0.97; Fig. 25), but we found a weak negative relationship with wing growth rates and THg concentrations in fully grown chick feathers (N=191, $R^2$=0.04, P=0.01; Fig. 26).

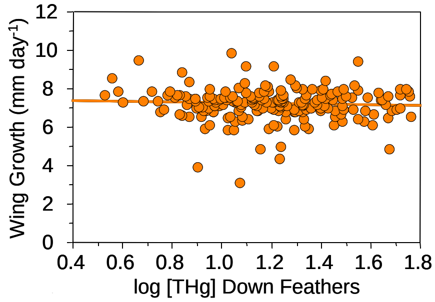



***Fig. 25.*** *Forster's tern chick wing growth rates in relation to THg concentrations (µg $g^{-1}$ fw) in down feathers at hatching (2005).*

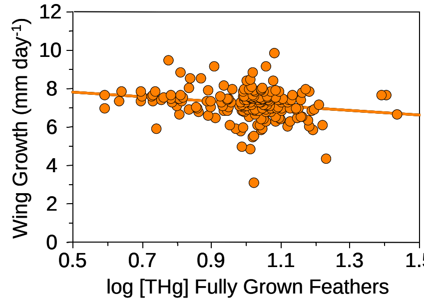



***Fig. 26.*** *Forster's tern chick wing growth rates in relation to THg concentrations (µg $g^{-1}$ fw) in fully grown chick feathers (2005).*

<u>Mercury Effects on Adult and Chick Biochemistry</u>---Glutathione metabolism is the primary physiological pathway for MeHg detoxification (and other metals), and strong patterns were observed between glutathione metabolism and liver THg concentrations (Appendix 14). The ratio of oxidized (GSSG) to reduced (GSH) glutathione (GSSG:GSH) in chicks was positively correlated with THg concentrations (N=16, $R^2$=0.65, P=0.0001; Fig. 27). This relationship was driven by depletion of GSH and subsequent increase in GSSG (GSH: N=16, $R^2$=0.31, P=0.02; GSSG: N=16, $R^2$=0.59, P=0.001). THg in pre-breeding adults also increased with GSSG:GSH, but the relationship was not significant (N=18, $R^2$=0.19, P=0.07; Fig. 27); this was due to a negative correlation between GSH and THg (N=18, $R^2$=0.33, P=0.01) but not between GSSG and THg (N=18, $R^2$=0.02, P=0.54). In breeding adults, we did not find a relationship between glutathione metabolism and liver THg concentrations even though liver THg concentrations were 2-4 times higher than pre-breeding terns. Conversely, the generation of thiobarbituric acid reactive substances (TBARS) (the principal indicator of cellular damage via oxidative stress), was positively correlated with increasing THg concentrations in breeding adults (N=27, $R^2$=0.15, P=0.01); TBARS were only correlated with THg concentrations in breeding females (N=14, $R^2$=0.43, P=0.02, Fig. 28) and not males (N=13, $R^2$=0.0, P=0.99).

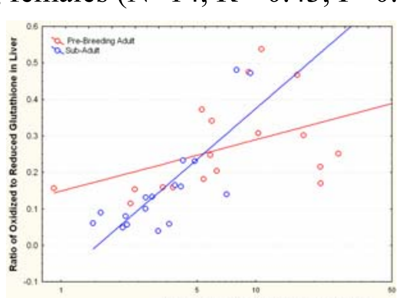



***Fig. 27.*** *Forster's tern GSH:GSSG in relation to liver THg concentrations in chicks (blue) and pre-breeding adults (red).*

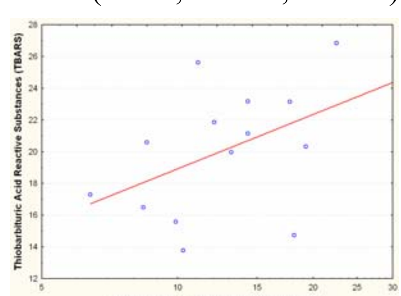



***Fig. 28.*** *Forster's tern TBARS in relation to liver THg concentrations in breeding adults.*

**Task II.3** – *Evaluate reproductive success, adult body condition, and migration of surf scoters.*

We conducted proximate analysis of fat and protein on female scoters collected in 2004 and 2005. Using AIC model selection procedures (Appendix 7), we found that the best model explaining total protein, total fat, and abdominal fat included only year and season, and not THg. The best model for carcass mass included THg (Fig. 29) and year. Fat, protein, and carcass mass declined over winter and increased prior to spring migration; however, spring condition was lower in 2005 (fat: 119±49 g, mass: 830±55 g) than in 2004 (fat: 265±66 g, mass: 996±90 g).

We marked 23 (2005-2006) female scoters with satellite PTT transmitters. Mean±SE departure date from the Bay was April 10±4, and total migration duration was 52±6 days. We found 24 marked scoters on the breeding area and collected fresh eggs from 3 nests. THg in scoter eggs was low (0.53±0.09 µg $g^{-1}$ dw) and no eggs exceeded LOAELs. We are currently analyzing eggs for selenium and organic contaminants.

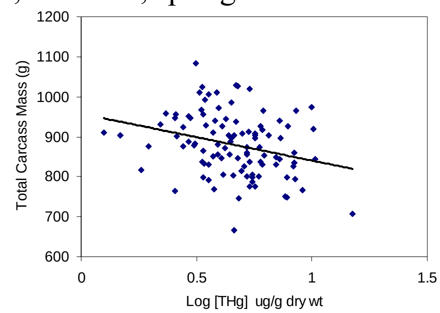



***Fig. 29.*** *Correlation of female surf scoter carcass mass and liver THg (N=139, r=-0.30).*

**Objective III. Determine the Differential Sensitivity of Avian Taxa to Mercury**

**Task III.1** - *Use egg injection techniques to determine sensitivity of avian embryos to MeHg.*

We compared the sensitivities of avian embryos of 26 species to MeHg (Appendix 15) by conducting an egg injection study using procedures in Heinz et al. (2006). Briefly, we collected eggs from the wild and injected them with various doses of MeHg dissolved in corn oil. Injected eggs were placed in an incubator and survival was monitored. For example, tricolored heron and herring gull embryos were more sensitive than were mallard embryos, suggesting that the use of mallard data to establish toxic levels may not be adequate to protect several birds (Fig. 30). For each species, we calculated LOAELs by using Fisher's Exact Probability Test to identify the lowest MeHg treatment with a reduction in survival.

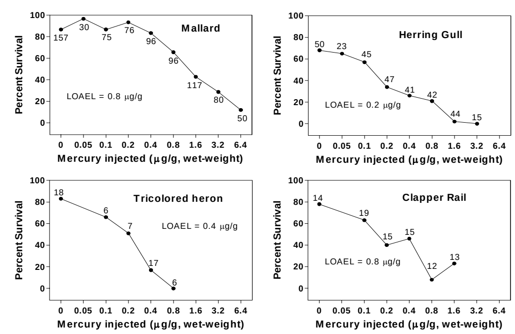



***Fig. 30.*** *Differential sensitivity of avian embryos to MeHg injected into eggs.*

**Task III.2** - *Use egg injection techniques to explore toxic interactions of MeHg and selenium.*

MeHg and selenomethionine can interact in synergistic and antagonistic ways in mallards. We found that adult males were protected from MeHg when selenium was incorporated into the diet, but that embryos from females fed the same combination of MeHg and selenium suffered worse effects than when only MeHg or selenium was fed. Using egg injection techniques, we dosed chicken, mallard, and double-crested cormorant eggs with combinations of MeHg and selenium. Even within the same experiment, we found both synergistic and antagonistic effects. For example, a combination of 0.2 µg $g^{-1}$ MeHg plus 0.1 µg $g^{-1}$ selenium caused a synergistic effect, whereas 1.6 µg $g^{-1}$ MeHg plus 0.2 µg $g^{-1}$ selenium acted antagonistically (Fig. 31). We will explore this relationship further in 2007 with larger sample sizes. If these preliminary findings are supported, more detailed work may be needed to understand why Hg and selenium can have such varied interactive effects, and more importantly,

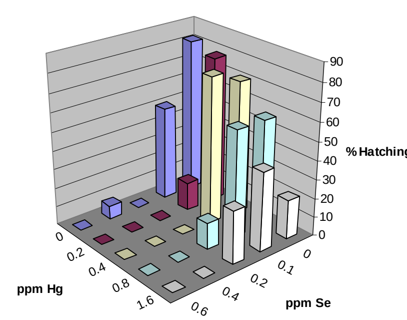



***Fig. 31.*** *Synergistic and antagonistic effects of MeHg and Selenium injected into mallard eggs.*

whether such effects occur in nature.

**Task III.3** - *Conduct a controlled feeding study to establish a dose-response curve and NOAEL.*

Based on a pilot study, we randomized 100 mallard pairs to either a control diet or diets containing 0.5, 1, 2, 4, or 8 µg $g^{-1}$ MeHg in March 2007 and we will follow reproductive success.

## E. POTENTIAL MANAGEMENT IMPLICATIONS OF FINDINGS TO DATE

Mercury Risk to Birds---Hg concentrations in adult birds were high enough to be a cause for concern, especially in the North and South Bays. Overall, we found that 5% of stilts, 6% of avocets, 10% of Caspian terns, and 58% of Forster's terns breeding in San Francisco Bay were at high-risk for Hg toxicity in blood (>3.0 µg $g^{-1}$ ww; Fig. 32). Similarly, 0% of avocet, 10% of stilt, and 46% of Forster's tern eggs had THg concentrations known to reduce hatchability and subsequent chick survival in other species, such as common loons and mallards (>1.3 µg $g^{-1}$ ww; Fig. 33).

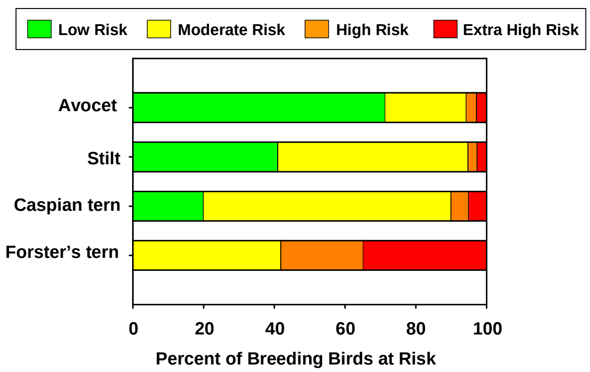



***Fig. 32.*** *The percentage of breeding waterbirds that are at risk to impaired reproduction due to their blood Hg concentrations in San Francisco Bay.*

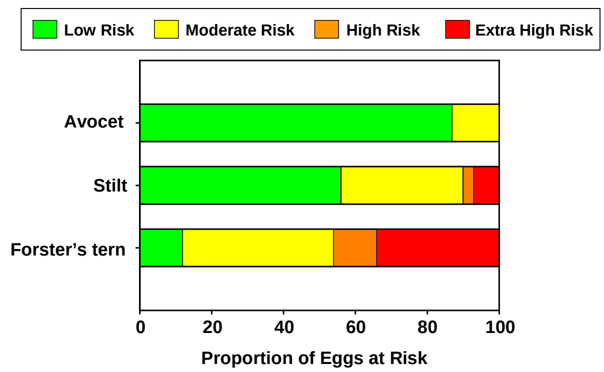



***Fig. 33.*** *The percentage of eggs collected in San Francisco Bay that had Hg concentrations above levels known to reduce hatching success (>1.3 µg $g^{-1}$ ww).*

Mercury Effects on Bird Reproduction---Avian taxa are differentially sensitive to MeHg contamination and several waterbird species are more sensitive to MeHg than mallards. This suggests mallard-based LOAELs may not be applicable to other waterbirds. Furthermore, we found that THg concentrations were higher in newly-hatched stilt chicks found dead than those found still alive. Conversely, we found only limited evidence of reduced chick survival once chicks reached >3-days of age. Our future field analyses will focus on assessing effects of Hg on egg hatchability in avocets, stilts, and Forster's terns, and effects of Hg on Forster's tern chick survival and growth rates.

Bioindicators of Mercury in Wetlands---We assessed whether individual fish species were suitable indicators of Hg contamination in birds. We found very poor relationships between Hg concentrations in individual fish species and tern eggs sampled at the same sites, indicating that individual fish species are not good indicators of Hg concentrations (or risk) in Forster's terns (Appendix 16, A). However, we derived a relationship between egg THg concentrations and fish THg concentrations by using a more sophisticated model which incorporated our site-specific telemetry, bird diet, and fish THg concentrations. We estimated colony-specific diet and space-use weighted THg concentrations in prey and correlated these values with colony-specific egg THg concentrations. We found a relatively strong relationship ($R^2$=0.68) between these estimated prey THg and egg THg concentrations (Appendix 16, B). More work is needed to assess tern sensitivity to Hg to properly assess these results, but they indicate that eggs must be monitored to assess Hg contamination in birds, not just individual prey species such as fish.

***Appendix 1.*** Summary of detailed null hypotheses by task that are being tested to determine the trophic pathways, bioaccumulation, and ecotoxicological risk of Hg to avian reproduction.

**Objective I. Field Studies of Avian Dietary Hg Exposure and Bioaccumulation**

**Task I.1**- *Identify trophic pathways of MeHg exposure in surface feeding avocets and stilts.*

Telemetry---

- Avocets and stilts do not show site fidelity.
- Space use does not differ between avocets and stilts.

Diet & Stable Isotopes---

- Diets do not differ between avocets and stilts.
- Avocet and stilt diets do not vary among locations.
- Trophic position (as indicated by baseline corrected $\delta^{15}N$) does not differ between species.
- Trophic position (as indicated by baseline corrected $\delta^{15}N$) does not differ among sites for either species.
- Habitat-specific energy reliance (as indicated by $\delta^{13}C$ ratios) does not differ between species.
- Habitat-specific energy reliance (as indicated by $\delta^{13}C$ ratios) does not differ among sites for either species.

Mercury in Prey---

- MeHg concentrations in invertebrate bird prey do not differ among taxa.
- MeHg concentrations in invertebrate bird prey do not differ among sites.
- MeHg concentrations in invertebrate bird prey do not differ between years.
- MeHg concentrations in invertebrate bird prey are below avian toxic thresholds.
- MeHg concentrations in invertebrate bird prey do not correlate to those in recurvirostrids.

Mercury in Pre-breeding Adults---

- Hg concentrations in prebreeding avocets and stilts do not vary between species.
- Hg concentrations in prebreeding avocets and stilts do not vary among sites.
- Hg concentrations in prebreeding avocets and stilts do not vary between years.
- Avocet and stilt Hg concentrations are not influenced by diet.
- Hg in pre-breeding avocets and stilts does not vary with date.
- Hg does not differ among sexes in avocets or stilts.

Mercury in Breeding Adults---

- Hg in breeding avocets and stilts does not differ between species.
- Hg in breeding avocets and stilts does not differ among sites.
- Hg in breeding avocets and stilts does not differ between from pre-breeding birds.

**Task I.2** - *Identify trophic pathways of MeHg exposure in terns.*

Telemetry---

- Forster's terns do not show site fidelity.
- Forster's tern space use is no different than that of avocets and stilts.

Diet & Stable Isotopes---

- Forster's tern diets do not differ among colonies.
- Tern trophic position (as indicated by baseline corrected $\delta^{15}N$) does not differ from avocets or stilts.
- Tern trophic position (as indicated by baseline corrected $\delta^{15}N$) does not differ among sites.
- Habitat-specific energy reliance (as indicated by $\delta^{13}C$ ratios) does not differ among sites.

Mercury in Prey---

- Hg in prey fish does not vary between species.
- Hg in prey fish does not vary among sites.
- Hg in prey fish do not vary with date.
- The relative Hg concentrations in different prey species do not differ among sites.

Mercury in Pre-breeding Adults---

- Hg in pre-breeding Forster's terns and Caspian terns do not vary between species.
- Hg in pre-breeding Forster's terns and Caspian terns do not vary among sites.
- Hg in pre-breeding Forster's terns does not vary with date.
- Hg does not differ among sexes in Forster's terns or Caspian terns.

Mercury in Breeding Adults---

- Hg in breeding Forster's terns does not differ between species.
- Hg in breeding Forster's terns does not differ among sites.
- Hg in breeding Forster's terns does not differ from pre-breeding terns.

**Task I.3** - *Identify trophic pathways of MeHg exposure in surf scoters.*

Telemetry---

- Surf scoters do not show winter site fidelity.
- Surf scoters do not preferentially forage at specific sites.

Diet & Stable Isotopes---

- Scoter diets do not vary among locations.
- Scoter diets do not change across winter.
- Scoter trophic position (as indicated by baseline corrected $\delta^{15}N$) does not differ between sites and time periods.
- Habitat-specific energy reliance (as indicated by $\delta^{13}C$ ratios) does not differ between sites and time periods.

Mercury in Prey---

- MeHg concentrations in invertebrate scoter prey do not differ among taxa.
- MeHg concentrations in invertebrate scoter prey do not differ among sites.
- MeHg concentrations in invertebrate scoter prey do not differ between years.
- MeHg concentrations in invertebrate scoter prey are below avian toxic thresholds.
- MeHg concentrations in invertebrate scoter prey do not correlate to those in scoters.

Mercury in Pre-breeding Adults---

- Hg concentrations in scoters do not vary among sites.
- Hg concentrations in scoters do not vary between years.
- Hg concentrations in scoters do not vary across time periods (fall, winter, spring).
- Scoter Hg concentrations are not influenced by diet.
- Scoter Hg concentrations have not changed compared to the 1980s.
- Hg and Se concentrations in pre-breeding adults do not influence breeding propensity.

**Objective II. Field Studies of Hg Effects on Bird Reproduction**

**Task II.1 & Task II.2** - *Conduct field studies of reproductive success in avocets, stilts, and Forster's terns to evaluate the fate and effects of Hg on eggs and chicks.*

Nest Success---

- Nest success does not vary among species.
- Nest success does not vary among sites.
- Nest success does not vary among years.
- Hg does not influence nest success.

Mercury in Eggs---

- Egg Hg concentrations do not vary among species.
- Egg Hg concentrations do not vary among sites.
- Egg Hg concentrations do not vary with date.
- Egg Hg concentrations are not correlated with maternal Hg concentrations.
- Egg Hg concentrations are not related to site-specific prey Hg concentrations.
- Egg Hg concentrations do not vary within clutches.
- Hg is not related to embryo deformities.

Mercury Effects on Egg Hatchability in the Field---

- Egg hatchability does not differ among species.
- Egg hatchability does vary among sites.
- Egg hatchability is not related to egg Hg concentrations.

Mercury in Chicks---

- Chick Hg concentrations do not vary among species.
- Chick Hg concentrations do not vary among sites.
- Chick blood Hg concentrations does not vary with chick age.

Mercury Effects on Chick Survival---

- Chick survival rates do not vary between species (avocets and stilts).
- Chick survival rates do not vary among sites (avocets and stilts).
- Chick survival rates do not vary between years (avocets and stilts).
- Chick survival rate does not vary with date (avocets and stilts).
- Chick survival rates do not vary with chick age (avocets and stilts).
- Chick survival rates are not related to *in ovo* Hg exposure (avocets and stilts).
- Hg concentrations in chicks found dead are no different then Hg concentrations in chicks found alive (avocets, stilts, and Forster's terns).

Mercury Effects on Chick Growth Rates---

- Chick growth rates do not differ among colonies (Forster's terns).
- Chick growth rates do not differ between years (Forster's terns).
- Chick growth rates are not related to *in ovo* Hg exposure (Forster's terns).
- Chick growth rates are not related to post-hatch Hg exposure (Forster's terns).

Mercury Effects on Adult and Chick Biochemistry---

- Oxidative stress biomarkers do not vary with Hg concentrations.
- Oxidative stress biomarkers do not vary with selenium concentrations.
- Oxidative stress biomarkers do not vary with lifestage.
- Oxidative stress biomarkers do not vary with breeding status.
- Organ and tissue health parameters do not vary with Hg concentration.
- Organ and tissue health parameters do not vary with selenium concentrations.
- Cytochrome P450 enzyme response do not vary with polyhalogenated aromatic hydrocarbon concentrations.
- Cytochrome P450 response do not vary with life stage.
- Cytochrome P450 response do not vary with breeding status.
- Cytochrome P450 response do not vary with Hg concentrations.

**Task II.3** - *Evaluate reproductive success, adult body condition, and migration of surf scoters.*

Mercury in Eggs---

- Hg concentrations in San Francisco Bay scoter eggs are not elevated above waterfowl LOAELs.
- Hg in San Francisco Bay scoter eggs is not accumulated in the marine environment .

Mercury Effects on Scoter Survival and Body Condition---

- Scoter survival rates do not vary between years.
- Scoter survival rates are not related to Hg or Se concentrations in blood.
- Scoter survival rates do not vary by sex or age.
- Scoter body condition does not vary by season or year.
- Scoter body condition is not related to Hg or Se.
- Scoters in poor pre-breeding body condition do not have lower breeding propensity.

Migration of SFB scoters---

- Scoter departure dates and migration rates are not related to pre-migration Hg or Se concentrations.
- Scoter departure dates and migration rates are not related to pre-migration body condition.
- Scoter migration duration is not related to Hg concentrations in pre-migratory adults.

**Objective III. Laboratory Studies of Hg Effects on Birds**

**Task III.1** - *Use egg injection techniques to determine sensitivity of avian emryos to MeHg.*

- Avian embryos do not differ in their sensitivity to MeHg.

**Task III.2** - *Use egg injection techniques to explore toxic interactions of MeHg and selenium.*

- There is neither a synergistic nor antagonistic effect between concentrations of MeHg and selenium on egg hatching success.

**Task III.3** - *Conduct a controlled feeding study with mallard ducks to establish a dose response curve and a NOAEL (No Observed Adverse Effects Level).*

- Increasing concentrations of MeHg injected into eggs will not result in reduced egg hatchability.

## *Appendix 2.* PRODUCTS TO DATE

### Journal Articles (6)

Ackerman, JT, CA Eagles-Smith, JY Takekawa, SA Demers, TL Adelsbach, JD Bluso, AK Miles, N Warnock, TH Suchanek, and SE Schwarzbach. 2007. Mercury concentrations and space use of pre-breeding American avocets and black-necked stilts in San Francisco Bay. (submitted)

Ackerman, JT, JY Takekawa, CA Eagles-Smith, and SA Iverson. 2007. Mercury contamination and effects on survival of American avocet and black-necked stilt chicks in San Francisco Bay. (submitted)

Ackerman, JT, CA Eagles-Smith, JY Takekawa, JD Bluso, and TL Adelsbach. 2007. Mercury concentrations in blood and feathers of pre-breeding Forster's terns in relation to space use of San Francisco Bay habitats. (submitted)

Ackerman, JT, JY Takekawa, JD Bluso, JL Yee, and CA Eagles-Smith. 2007. Sex determination of Caspian terns using external morphology and discriminant function analysis. (submitted)

Bluso, JD, JT Ackerman, JY Takekawa, and JL Yee. 2006. Using morphological measurements to sex Forster's terns. Waterbirds, 29(4): 511-516.

Heinz, GH, DJ Hoffman, SL Kondrad, and CA Erwin. 2006. Factors affecting the toxicity of methylmercury injected into eggs. Archives of Environmental Contamination and Toxicology 50:264-279.

### Popular Articles (5)

Ackerman, JT, and CA Eagles-Smith. 2007. Mercury contamination in waterbirds breeding in San Francisco Bay. Tideline, summer.

Ackerman, JT, and CA Eagles-Smith. 2006. A collaborative project to study mercury levels in San Francisco Bay Waterbirds. Bay Bird Review Winter: 4-5.

Ackerman, JT, CM Marn, and JY Takekawa. 2005. Life and death on a salt pond: avocets and stilts survive amidst mercury pollution and invasive gulls. Tideline, Winter 2005, Vol. 25, No. 4: 1–3.

Takekawa, J. Y. 2005. Finding a needle in a big haystack – locating surf scoter nests in the Northern Boreal Forest. Sound Waves 75: 1-2.

Wainwright-De La Cruz, S.E. and J.Y. Takekawa. 2005. Scooping for scoters on San Francisco Bay. Tideline, Spring Issue.

### Reports (2)

Ackerman, JT, CA Eagles-Smith, GH Heinz, SE Wainwright-De La Cruz, JY Takekawa, TL Adelsbach, AK Miles, DJ Hoffman, SE Schwarzbach, TH Suchanek, and TC Maurer. 2007. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation and ecotoxicological risk to avian reproduction. 2006 Annual Administrative Report to CALFED, U. S. Geological Survey, Western Ecological Research Center, and U. S. Fish and Wildlife Service, Environmental Contaminants Division, 41 pp.

Schwarzbach, SE, TH Suchanek, GH Heinz, JT Ackerman, CA Eagles-Smith, TL Adelsbach, JY Takekawa, AK Miles, DJ Hoffman, SE Wainwright-De La Cruz, SE Spring, MA Ricca, and TC Maurer. 2005. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation and ecotoxicological risk to avian reproduction. 2005 Annual

Administrative Report to CALFED, U. S. Geological Survey, Western Ecological Research Center, and U. S. Fish and Wildlife Service, Environmental Contaminants Division, 17pp.

**Presentations (77)**

Ackerman JT, CA Eagles-Smith, JY Takekawa, TL Adelsbach, AK Miles, S Schwarzbach, and T Suchanek. 2007. Mercury risk to waterbird reproduction in San Francisco Bay: implications for the South Bay Salt Pond Restoration Project. South Bay Salt Pond Restoration Group, Oakland, California, March 2. (Oral presentation) Ackerman JT, CA Eagles-Smith, JY Takekawa, TL Adelsbach, AK Miles, S Schwarzbach, and T Suchanek. 2007. Waterbirds' risk to mercury in North San Francisco Bay salt ponds. Napa Sonoma Marsh Restoration Group, Vallejo, California, February 20. (Oral presentation)

Ackerman, JT, and JY Takekawa. 2005. Impacts of gulls: predation on shorebird and tern nests and chicks. South Bay Salt Pond Restoration Project, Bird Workshop 3: Invasive and Nuisance Species, Don Edwards San Francisco Bay National Wildlife Refuge, California, November 18. (Oral presentation and published abstract)

Ackerman, JT, and JY Takekawa. 2006. Gull predation on American avocet and black-necked stilt chicks growing in the South San Francisco Bay. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)

Ackerman, JT, CA Eagles-Smith, and TL Adelsbach. 2006. Mercury accumulation in black-necked stilt chicks in San Francisco Bay. Fish and Wildlife Service Environmental Contaminants Program National Meeting, Colorado Springs, Colorado, July 31-August 4. (Poster presentation)

Ackerman, JT, CA Eagles-Smith, and TL Adelsbach. 2006. Mercury accumulation in black-necked stilt chicks in San Francisco Bay. South Bay Science Symposium, San Jose State University, California, June 6. (Poster presentation and published abstract)

Ackerman, JT, CA Eagles-Smith, and TL Adelsbach. 2006. Rapid accumulation of mercury in black-necked stilt chicks growing in San Francisco Bay. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)

Ackerman, JT, CA Eagles-Smith, JY Takekawa, and AK Miles. 2006. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation, and ecotoxicological risk to avian reproduction. Don Edwards San Francisco Bay National Wildlife Refuge, Newark, California, January 23. (Oral presentation and published abstract)

Ackerman, JT, CA Eagles-Smith, JY Takekawa, and TL Adelsbach. 2006. Mercury accumulation in black-necked stilt chicks growing in San Francisco Bay. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)

Ackerman, JT, CA Eagles-Smith, JY Takekawa, SA Demers, TL Adelsbach, JD Bluso, AK Miles, TH Suchanek, and SE Schwarzbach. 2006. Mercury concentrations and space use of pre-breeding American avocets and black-necked stilts in San Francisco Bay. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)

Ackerman, JT, CA Eagles-Smith, TL Adelsbach, and JL Yee. 2006. Are growth rates of Forster's Tern chicks influenced by mercury in San Francisco Bay? Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster

presentation and published abstract)
Ackerman, JT, CA Eagles-Smith, TL Adelsbach, and JL Yee. 2006. Effects of mercury on growth rates of Forster's tern chicks in San Francisco Bay. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)
Ackerman, JT, CA Eagles-Smith, TL Adelsbach, and JL Yee. 2006. Mercury levels and growth rates of Forster's tern chicks in San Francisco Bay. Fish and Wildlife Service Environmental Contaminants Program National Meeting, Colorado Springs, Colorado, July 31-August 4. (Poster presentation)
Ackerman, JT, CA Eagles-Smith, TL Adelsbach, and JL Yee. 2006. Mercury levels and growth rates of Forster's Tern chicks in San Francisco Bay. South Bay Science Symposium, San Jose State University, California, June 6. (Poster presentation and published abstract)
Ackerman, JT, JY Takekawa, and CM Marn. 2005. Survival of American avocet and black-necked stilt chicks in the South San Francisco Bay: variable risks of gull predation. The 7th Biennial State of the Estuary Conference, Oakland, California, October 4–6. (Poster presentation and published abstract)
Ackerman, JT, JY Takekawa, CA Eagles-Smith, CM Marn, and TL Adelsbach. 2006. Survival of American avocet and black-necked stilt chicks in relation to mercury contamination in San Francisco Bay. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)
Ackerman, JT, TL Adelsbach, CA Eagles-Smith, and JL Yee. 2005. Growth rates of Forster's tern chicks at four nesting colonies in the San Francisco Bay. The 7th Biennial State of the Estuary Conference, Oakland, California, October 4–6. (Poster presentation and published abstract)
Ackerman, JT, TL Adelsbach, CA Eagles-Smith, and JL Yee. 2005. Mercury influence on growth rates of Forster's tern chicks in San Francisco Bay. CALFED review panel and California Bay-Delta Authority, Sacramento, California, November 29-December 1. (Poster presentation)
Ackerman, JT. 2006. Gull predation on shorebird and tern nests and chicks in the South San Francisco Bay salt ponds. South Bay Science Symposium, San Jose State University, California, June 6. (Oral presentation and published abstract)
Ackerman, JT. 2006. Linking waterbird and fish mercury research. USGS Fish Research Workshop, Hood River, Oregon, October 26. (Oral presentation)
Adelsbach, TL, CA Eagles-Smith, JT Ackerman, and SE Schwarzbach. 2006. Terns as indicators of mercury and other priority pollutant exposure in San Francisco Bay. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)
Bluso, JB, JY Takekawa, and JT Ackerman. 2007. Colony foraging areas and space use of Forster's terns in South San Francisco Bay. Pacific Seabird Group, Asilomar, California, February 7-11. (Poster presentation and published abstract)
Bluso, JB, M Colwell, JY Takekawa, and JT Ackerman. 2005. Foraging areas of Forster's terns at three colony sites in San Francisco Bay. CALFED review panel and California Bay-Delta Authority, Sacramento, California, November 29-December 1. (Poster presentation)
Bluso, JB, M Colwell, JY Takekawa, and JT Ackerman. 2005. Space use of foraging Forster's terns (*Sterna forsteri*) in South San Francisco Bay, California. The 7th Biennial State of the Estuary Conference, Oakland, California, October 4–6. (Poster presentation and published

abstract)
Bluso, JB, M Colwell, JY Takekawa, and JT Ackerman. 2006. Space use of Foraging Forster's terns (*Sterna forsteri*) in South San Francisco Bay, California. The Wildlife Society, Western Section, Sacramento, California, February 8-10. (Oral presentation and published abstract)
Bluso, JB, MA Colwell, JY Takekawa, and JT Ackerman. 2007. Sex differences in space use of Forster's terns in South San Francisco Bay. Pacific Seabird Group, Asilomar, California, February 7-11. (Oral presentation and published abstract)
Bluso, JD, MA Colwell, JY Takekawa, and JT Ackerman. 2006. Foraging areas and sex differences in space use of Forster's terns in South San Francisco Bay. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)
Bluso, JD, MA Colwell, JY Takekawa, and JT Ackerman. 2006. Space use of foraging Forster's terns in South San Francisco Bay, California. South Bay Science Symposium, San Jose State University, California, June 6. (Poster presentation and published abstract)
Demers, SA, M Colwell, JY Takekawa, and JT Ackerman. 2005. Foraging patterns of American avocets in San Francisco Bay. CALFED review panel and California Bay-Delta Authority, Sacramento, California, November 29-December 1. (Poster presentation)
Demers, SA, M Colwell, JY Takekawa, and JT Ackerman. 2005. Space use of breeding female American avocets in the San Francisco Bay Estuary. The 7th Biennial State of the Estuary Conference, Oakland, California, October 4–6. (Poster presentation and published abstract)
Demers, SA, M Colwell, JY Takekawa, and JT Ackerman. 2006. Space use and foraging patterns of American avocets in the South San Francisco Bay, California. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)
Demers, SA, M Colwell, JY Takekawa, and JT Ackerman. 2006. Space use and habitat selection of American avocets (*Recurvirostra americana*) in the South San Francisco Bay, California. South Bay Science Symposium, San Jose State University, California, June 6. (Poster presentation and published abstract)
Demers, SA, M Colwell, JY Takekawa, and JT Ackerman. 2006. Space use and habitat selection of American avocets (*Recurvirostra americana*) in the South San Francisco Bay, California. Shorebird Science in the Western Hemisphere, Boulder, Colorado, February 22-March 2. (Poster presentation and published abstract)
Demers, SA, M Colwell, JY Takekawa, and JT Ackerman. 2006. Space use and habitat selection of American avocets (*Recurvirostra americana*) in the South San Francisco Bay, California. The Wildlife Society, Western Section, Sacramento, California, February 8-10. (Poster presentation and published abstract)
Eagles-Smith, CA, and JT Ackerman. 2006. Monitoring mercury in Forster's Terns: a dual life-stage approach to assessing effects and toxic thresholds. San Francisco Estuary Institute, Regional Monitoring Program, Exposure and Effects Workgroup, Oakland, California, December 4. (Oral presentation)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2005. Mercury dynamics in Forster's terns: influence of reproductive status and sex. CALFED review panel and California Bay-Delta Authority, Sacramento, California, November 29-December 1. (Poster presentation)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2006. Mercury correlations among six tissues in four species of waterbirds vary by season and taxa. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and

published abstract)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2006. Mercury correlations among six tissues in four species of waterbirds vary by season and taxa. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2006. Mercury concentrations in prebreeding and breeding Forster's terns. Fish and Wildlife Service Environmental Contaminants Program National Meeting, Colorado Springs, Colorado, July 31-August 4. (Poster presentation)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2006. Mercury concentrations in prebreeding and breeding Forster's terns. South Bay Science Symposium, San Jose State University, California, June 6. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2006. Mercury dynamics in waterbirds: influence of reproductive status and sex. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Oral presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, and TL Adelsbach. 2006. Mercury dynamics in waterbirds: influence of reproductive status and sex. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, S De la Cruz, TL Adelsbach, JY Takekawa, AK Miles, and R Keister. 2005. Mercury concentrations vary among waterbird foraging guilds and locations in San Francisco Bay. CALFED review panel and California Bay-Delta Authority, Sacramento, California, November 29-December 1. (Poster presentation)
Eagles-Smith, CA, JT Ackerman, S Wainwright-De La Cruz, TL Adelsbach, JY Takekawa, and AK Miles. 2006. Mercury concentrations vary among waterbird foraging guilds and locations in San Francisco Bay. Fourth Biennial CALFED Science Conference, Sacramento, California, October 23-25. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, S Wainwright-De La Cruz, TL Adelsbach, JY Takekawa, and AK Miles. 2006. Mercury concentrations vary among waterbird foraging guilds and locations in San Francisco Bay. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, S Wainwright-De La Cruz, TL Adelsbach, JY Takekawa, and AK Miles. 2006. Mercury concentrations differ among five species of waterbirds in San Francisco Bay. Fish and Wildlife Service Environmental Contaminants Program National Meeting, Colorado Springs, Colorado, July 31-August 4. (Poster presentation)
Eagles-Smith, CA, JT Ackerman, S Wainwright-De La Cruz, TL Adelsbach, JY Takekawa, and AK Miles. 2006. Mercury concentrations differ among five species of waterbirds in San Francisco Bay. South Bay Science Symposium, San Jose State University, California, June 6. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, TL Adelsbach, JY Takekawa, AK Miles, S Schwarzbach, and T Suchanek. 2007. Mercury risk to avian reproduction in San Francisco Bay: implications for TMDL Implementation. San Francisco Bay Mercury Coordination Meeting, Oakland, California, February 22. (Oral presentation)
Eagles-Smith, CA, JT Ackerman, TL Adelsbach, JY Takekawa, and C Marn. 2006. Mercury concentrations in chicks versus adult avocet and stilts: spatially explicit bioaccumulation inferred via radio telemetry. Fourth Biennial CALFED Science Conference, Sacramento,

California, October 23-25. (Poster presentation and published abstract)
Eagles-Smith, CA, JT Ackerman, TL Adelsbach, JY Takekawa, and CM Marn. 2006. Mercury concentrations in chicks versus adult avocet and stilts: spatially explicit bioaccumulation inferred via radio telemetry. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Poster presentation and published abstract)
Eagles-Smith, CA, TL Adelsbach, JT Ackerman, SE Schwarzbach, TH Suchanek, GH Heinz, JY Takekawa, AK Miles, SE Wainwright-De La Cruz, JD Henderson, SE Spring, L Bowen, JD Bluso, SA Demers, M Ricca, C Marn, C Strong, N Warnock, M Wilson, and T Maurer. 2005. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation, and ecotoxicological risk to avian reproduction. The 7th Biennial State of the Estuary Conference, Oakland, California, October 4–6. (Poster presentation and published abstract)
Heinz, GH, and DJ Hoffman. 2005. Mercury and birds: Future directions in research. The Wildlife Society 12th Annual Conference, Madison, Wisconsin, September 25-29. (talk)
Heinz, GH, and DJ Hoffman. 2005. Species differences in sensitivity of birds to methylmercury. Society of Environmental Toxicology and Chemistry 26th Annual Meeting, Baltimore, Maryland, November 13-17. (poster)
Heinz, GH, and DJ Hoffman. 2005. The use of wild bird eggs to measure the sensitivity of avian embryos to methylmercury. Joint Meeting of the Wilson Ornithological Society and Association of Field Ornithologists, Beltsville, Maryland, April 21–24. (talk)
Heinz, GH, and DJ Hoffman. 2006. Species differences in sensitivity of birds to methylmercury. Society of Environmental Toxicology and Chemistry Chapter meeting, Patuxent Wildlife Research Center, Laurel MD, June 6, 2006. (poster)
Heinz, GH, DJ Hoffman, JD Klimstra, and KR Schoen. 2006. Determining how avian embryos differ in their sensitivity to methylmercury. USGS Patuxent Wildlife Research Center FY 2006 Biennial Science Meeting, Laurel, MD, October 11. (poster)
Heinz, GH, DJ Hoffman, JD Klimstra, and KR Schoen. 2006. Egg injections as a hybrid field-lab technique for assessing the embryotoxicity of methylmercury to different birds. USGS Patuxent Wildlife Research Center FY 2006 Biennial Science Meeting, Laurel, MD, October 11. (poster)
Heinz, GH, DJ Hoffman, JD Klimstra, and KR Schoen. 2006. Potential contaminant interactions between mercury and selenium. The Wildlife Society 13th Annual Conference, Anchorage, AK, September 26. (talk)
Heinz, GH, DJ Hoffman, JD Klimstra, and KR Schoen. 2006. Toxic interactions of mercury and selenium on avian embryos. Twenty-seventh Annual Meeting of the Society of Environmental Toxicology and Chemistry, Montreal, Quebec, Canada, November 8. (talk)
Heinz, GH, DJ Hoffman, JD Klimstra, and KR Schoen. 2006. Toxicological significance of mercury in bird eggs: knowns and unknowns. Eighth International Conference on Mercury as a Global Pollutant, Madison, WI, August 8. (talk)
Heinz, GH, DJ Hoffman, JD Klimstra, and KR Schoen. 2006. Wildlife as a sentinel for mercury contamination." The Wildlife Society 13th Annual Conference, Anchorage, AK, September 27. (poster)
Lok, E and MT Wilson. 2006. Surf scoter migration: a journey from Baja to boreal. Juneau Audubon Society International Migratory Bird Day, Juneau, AK, May 14. (talk)
Schwarzbach, SE, JT Ackerman, CA Eagles-Smith, JY Takekawa, AK Miles, SE Wainwright-De La Cruz, TL Adelsbach, and TH Suchanek. 2006. Mercury legacy to aquatic birds in the San Francisco Estuary: declines from 19th century levels remain insufficient to eliminate

mercury risks to some bird species. Eighth International Conference on Mercury as a Global Pollutant, Madison, Wisconsin, August 6–11. (Oral presentation and published abstract)

Schwarzbach, SE, TH Suchanek, GH Heinz, JT Ackerman, CA Eagles-Smith, TL Adelsbach, JY Takekawa, AK Miles, DJ Hoffman, SE Wainwright-De La Cruz, SE Spring, MA Ricca, and TC Maurer. 2005. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation, and ecotoxicological risk to avian reproduction. CALFED review panel and California Bay-Delta Authority, Sacramento, California, November 29-December 1. (Oral presentation)

Takekawa, JY, JT Ackerman, CA Eagles-Smith, S Wainwright-De La Cruz, TL Adelsbach, AK Miles, G Heinz, D Hoffman, S Schwarzbach, T Suchanek, T Maurer, C Strong, and N Warnock. 2006. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation, and ecotoxicological risk to avian reproduction. South Bay Science Symposium, San Jose State University, California, June 6. (Oral presentation and published abstract)

Wainwright-De La Cruz, SE, and JY Takekawa. 2005. San Francisco Bay Joint Venture assessment: waterfowl populations and threats in San Francisco Bay. North American Waterfowl Management Plan Assessment, Novato, CA, June 16. (invited talk)

Wainwright-De La Cruz, SE, CA Eagles-Smith, TL Adelsbach, JT Ackerman, GH Heinz, SE Schwarzbach, TH Suchanek, JY Takekawa, AK Miles, DJ Hoffman, and TC Maurer. 2006. Mercury in birds of the San Francisco Bay-Delta: trophic pathways, bioaccumulation, and ecotoxicological risk to avian reproduction. San Francisco Estuary Institute Third Annual San Francisco Bay Mercury Coordination Meeting, Oakland, California, February 22. (Oral presentation)

Wainwright-De La Cruz, SE, JY Takekawa, M Wilson, AK Miles. 2006. Cross-seasonal implications of mercury bioaccumulation by surf scoters wintering in San Francisco Bay. The Wildlife Society 13th Annual Conference, Anchorage, AK, September 23-27. (Presentation).

Wainwright-De La Cruz, SE, JY Takekawa, MT Wilson, and AK Miles. 2006. Methyl-mercury and selenium effects on the body condition and winter survival of surf scoters. The Wildlife Society 13th Annual Conference, Anchorage, AK, September 23-27. (talk).

Wainwright-De La Cruz, SE, JY Takekawa, MT Wilson, JM Eadie, and AK Miles. 2006. Effects of over-winter contaminant accumulation and invasive prey species on surf scoter body condition. 4th North American Duck Symposium, Bismarck, ND, August 23-26. (poster)

Wainwright-De La Cruz, SE, JY Takekawa, MT Wilson, JM Eadie, and AK Miles. 2006. Does mercury bioaccumulation influence body condition of surf scoters (*Melanitta perspicillata*) wintering in San Francisco Bay? Eighth International Conference on Mercury as a Global Pollutant, Madison, WI, August 6-11. (poster)

Wainwright-De La Cruz, SE, M Wilson, JY Takekawa, D Nysewander, J Evenson, D. Esler, S. Boyd, D Rosenburg, D Ward, and J Eadie. 2005. Spring migration chronology and breeding areas of surf scoters: A synthesis of Pacific Coast studies. Second North American Sea Duck Conference, Annapolis, MD, November 7-11. (talk)

Wainwright-De La Cruz, SE, MT Wilson, JY Takekawa, AK Miles, and JM Eadie. 2006. Cross-seasonal implications of mercury and selenium bioaccumulation by surf scoters from the San Francisco Bay-Delta. Calfed Science Conference, Sacramento, CA, October 23-26. (talk)

Wainwright-De La Cruz, SE, MT Wilson, JY Takekawa, JM Eadie, AK Miles. 2005. Cross-seasonal implications of mercury bioaccumulation by surf scoters (*Melanitta perspicillata*) from the San Francisco Bay-Delta. Calfed Bay-Delta Program Annual Mercury Review, Sacramento, CA, November 29 – December 1. (poster)

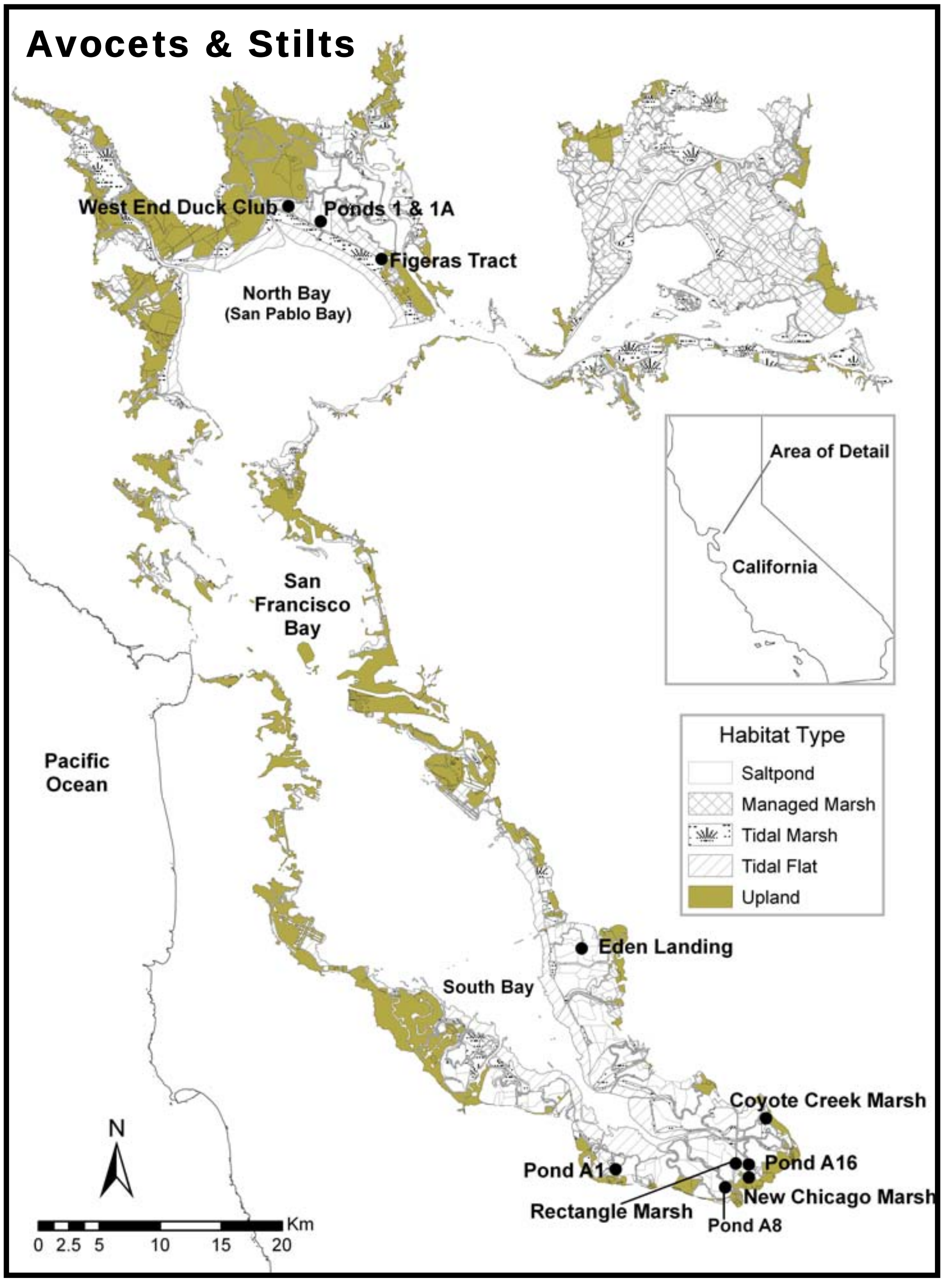
Wilson, M, SE Wainwright-De La Cruz, JY Takekawa, D Nysewander, J Evenson, D Esler, S Boyd, D Ward, and J Eadie. 2006. Breeding Area Affiliations of Pacific Coast Surf Scoters in the Boreal Forest. North American Ornithological Conference, Vera Cruz, MX, October 3-7. (talk)

Wilson, MT, JM Eadie, JY Takekawa, SE Wainwright-De La Cruz, and SA Iverson. 2006. Wintering survival of Pacific surf scoters on San Francisco Bay. 4th North American Duck Symposium, Bismarck, ND, August 23-26. (poster)

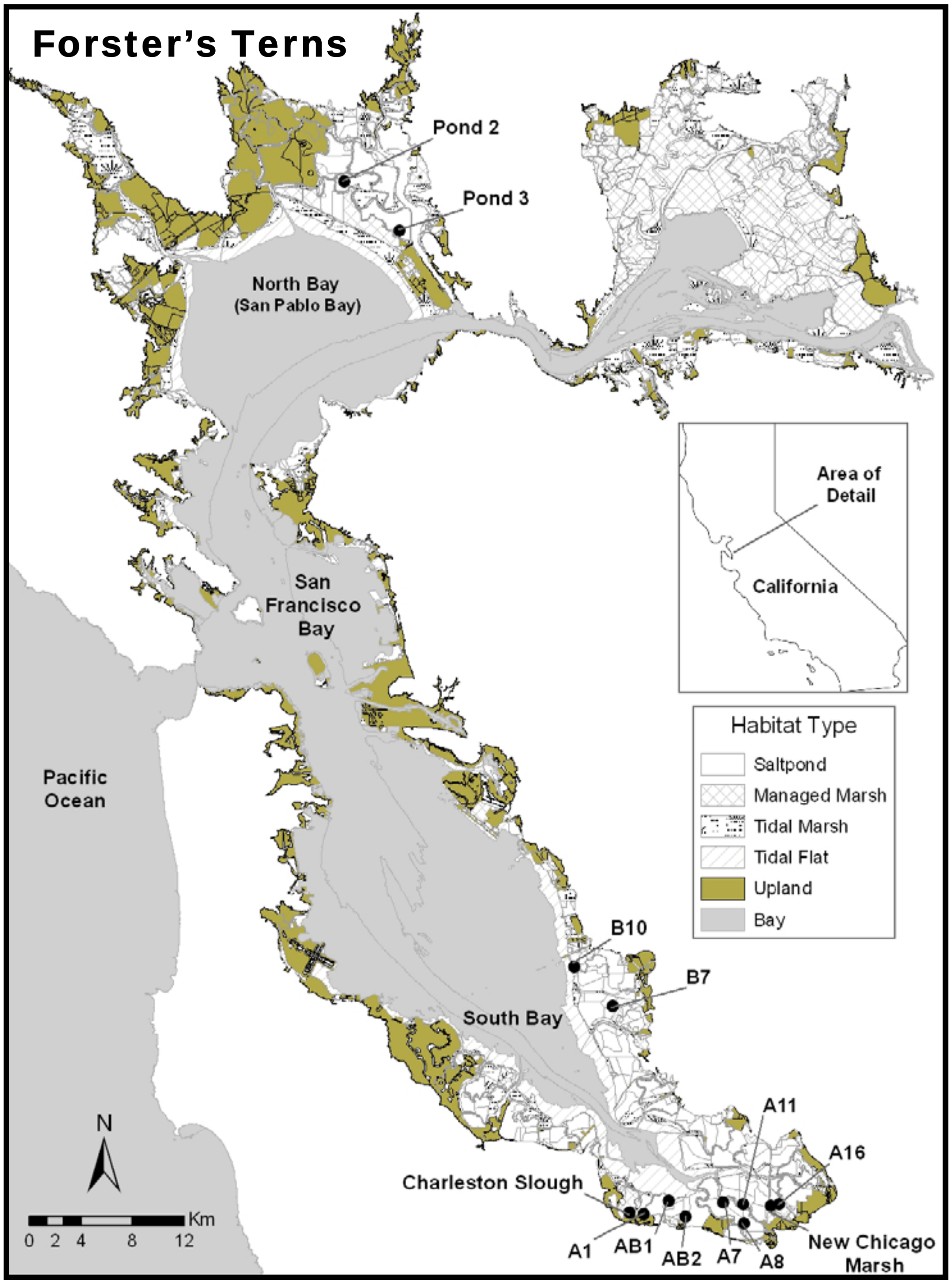
Wilson, MT, SE Wainwright-De La Cruz, JY Takekawa, D Nysewander, J Evenson, D Esler, S Boyd, D Ward, and JM Eadie. 2006. Breeding area affiliations of Pacific Coast surf scoters in the boreal forest. North American Ornithological Conference, Vera Cruz, MX, October 3-7. (invited talk)

Wilson, M, JM Eadie, JY Takekawa, SE Wainwright-De La Cruz, SA Iverson. 2006. Wintering survival of Pacific Surf Scoters on San Francisco Bay. Calfed Science Conference, Sacramento, CA, October 23-26. (Poster)

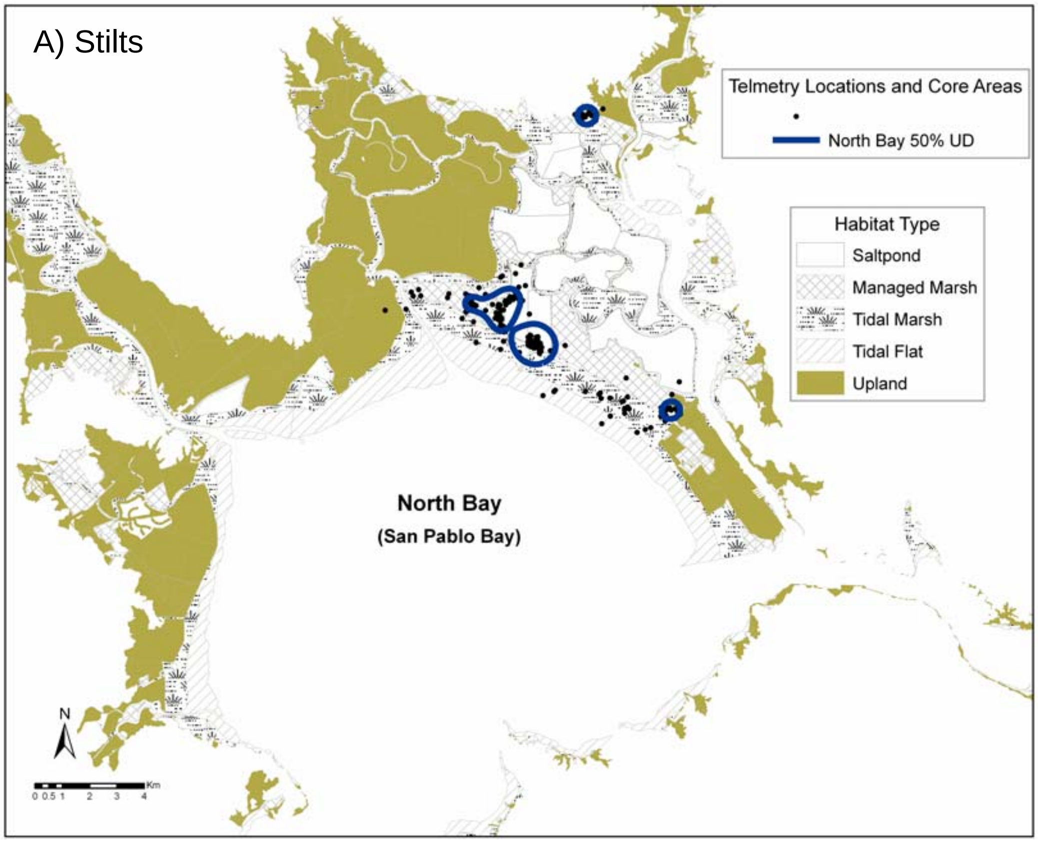
***Appendix 3***. Map depicting main study sites for avocets and stilts.

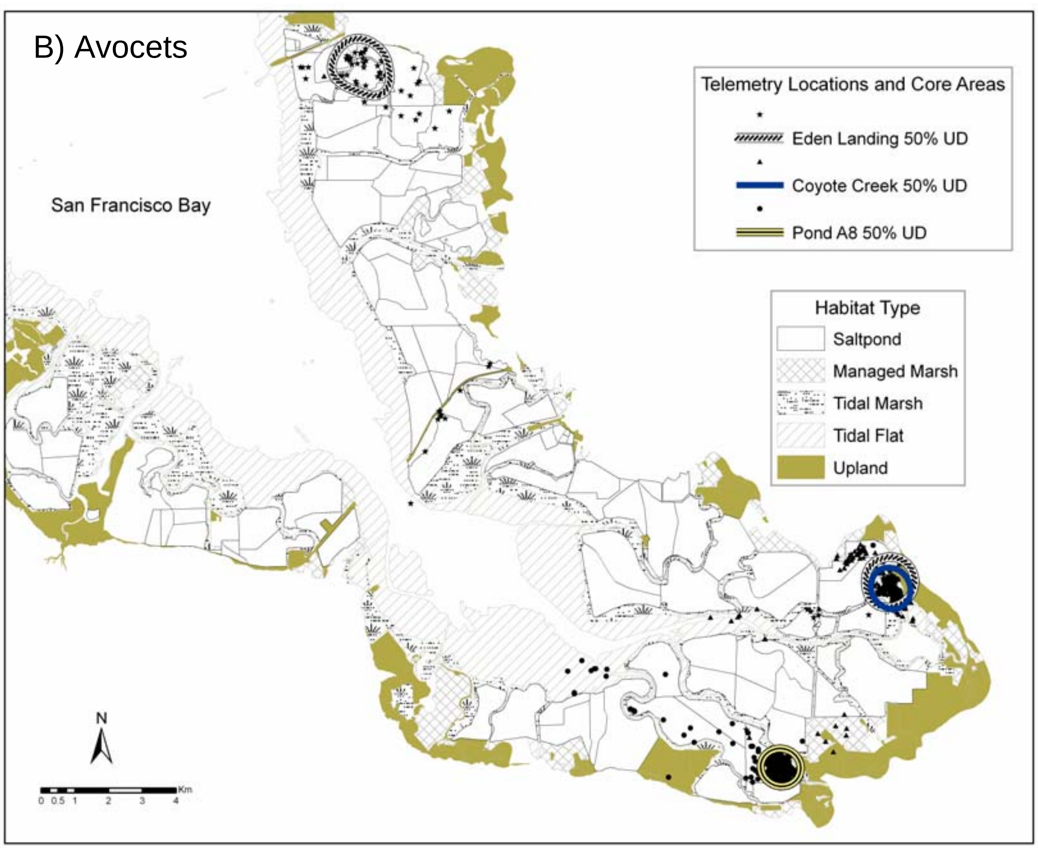


***Appendix 4***. Map depicting main study sites for Forster's terns.

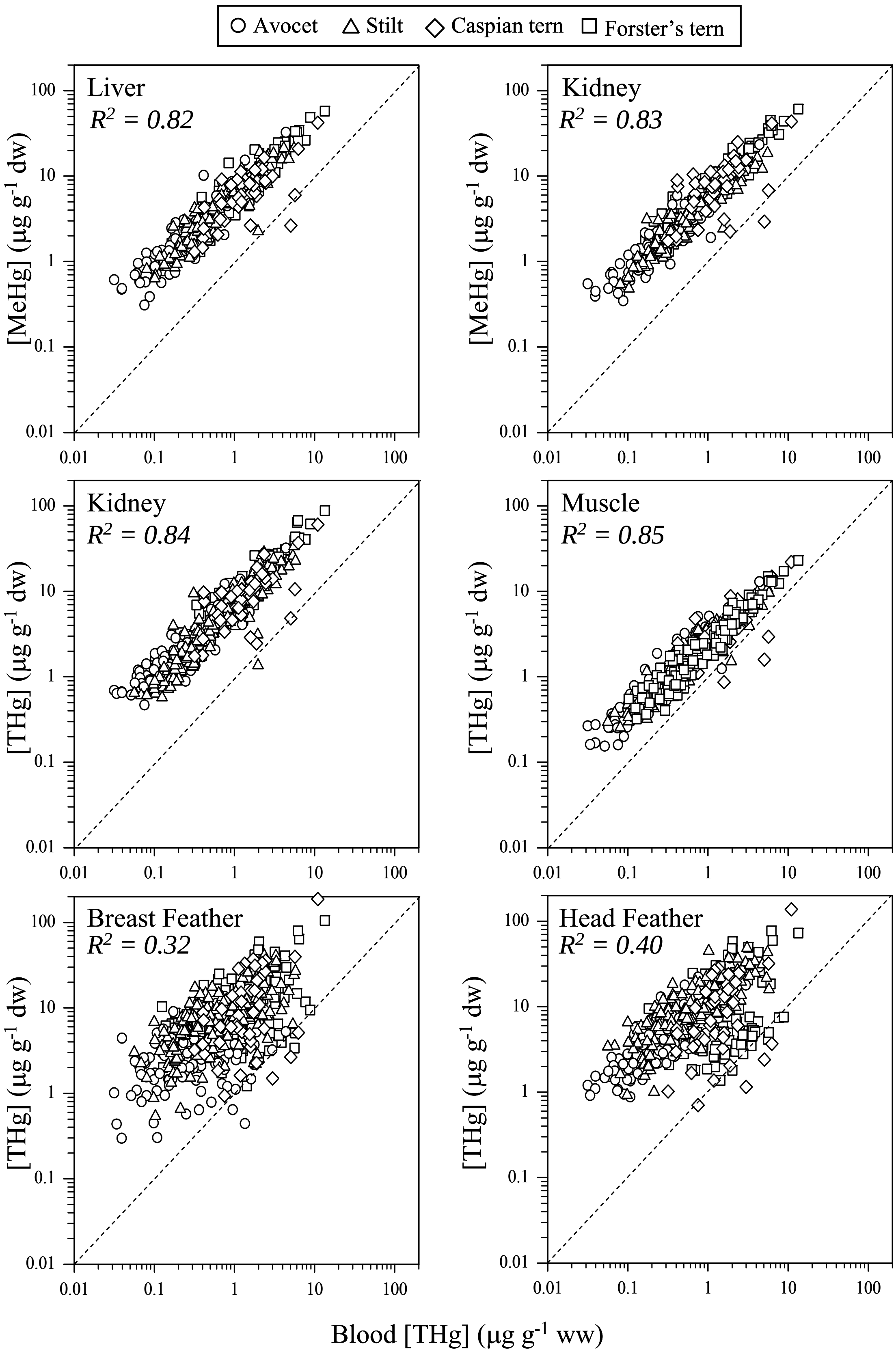


***Appendix 5.*** Telemetry locations and core use home ranges of pre-breeding (A) black-necked stilts in North San Francisco Bay and (B) American avocets in South San Francisco Bay determined using radio telemetry in 2005.



***Appendix 6***. Blood THg concentrations were highly correlated with both THg and MeHg concentrations in internal tissues and less highly correlated with THg concentrations in feathers.



***Appendix 7*. AIC MODEL SELECTION**

We used Akaike's Information Criterion (AIC) to select the best models from an *a priori* set of candidate models. AIC typically performs better than restricting the selected model to those variables with statistically significant effects in hypothesis-based tests, especially for observational data. To reduce text length, we have presented only the final best model, although each AIC analysis compared numerous competing models. To improve clarity, we have presented traditional p-values and statistics (for hypothesis oriented tests) based on the best model.

We used a second-order AIC: $AICc = -2(\text{log-likelihood}) + 2K(N / N - K - 1)$, where $K$ is the number of fitted parameters including variance and $N$ is the sample size. We considered the model with the smallest AIC*c* to be the most parsimonious. We used the AIC*c* differences between the best model and the other candidate models ($\Delta AICc_i = AICc_i -$ minimum AIC*c*) to determine the relative ranking of each model. For biological importance, we considered models for which $\Delta AICc_i \leq 2$. Additionally, we calculated Akaike weights ($w_i = \exp[-\Delta AICc_i/2] / \sum \exp[-\Delta AICc_i/2]$) to assess the weight of evidence that the selected model was the actual Kullback-Leibler best model in the set of models considered. We also calculated variable weights by summing Akaike weights across models that incorporated the same variable to help assess the relative importance of each variable.

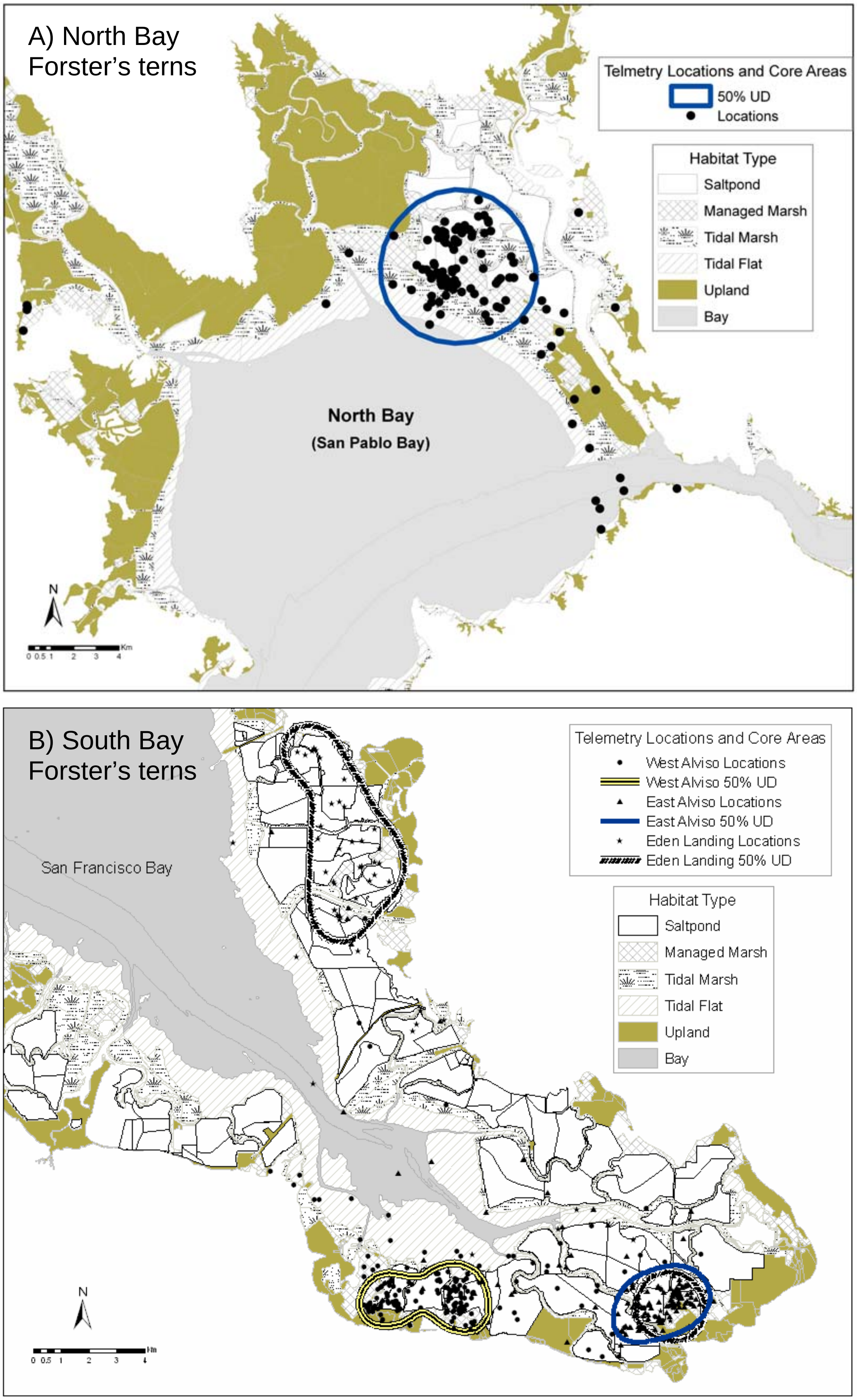
References:

Anderson DR, Burnham KP, Thompson WL. 2000. Null hypothesis testing: problems, prevalence, and an alternative. J Wildl Manage 64:912-923.

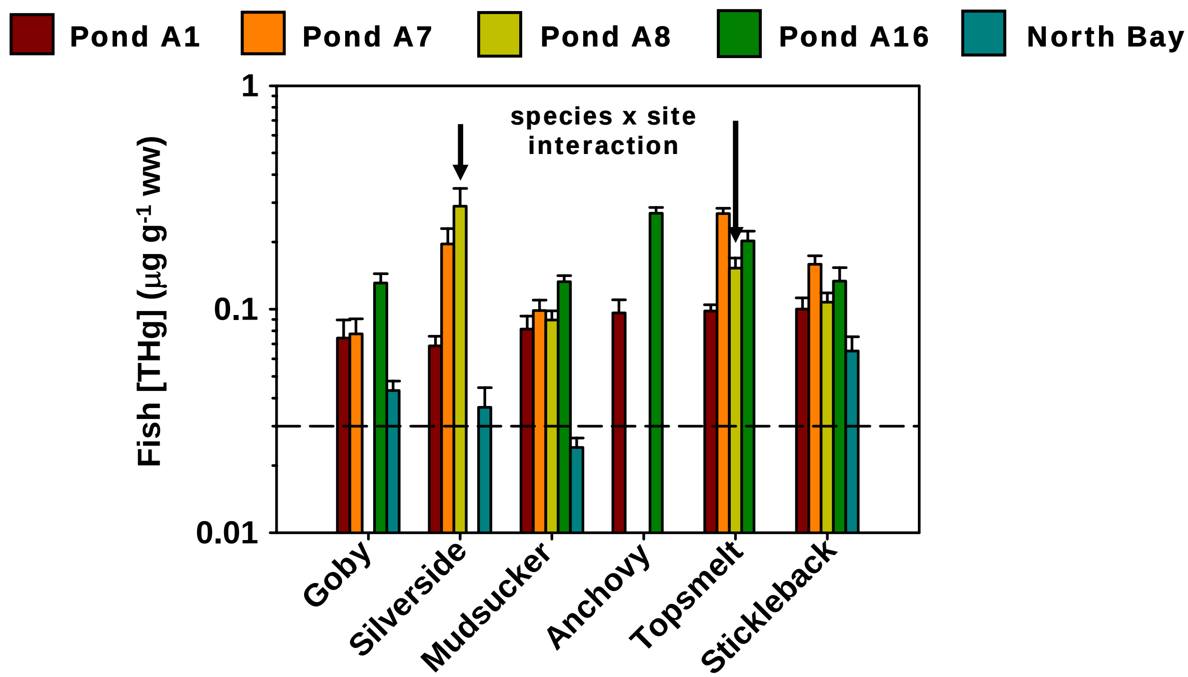
Anderson DR, Link WA, Johnson DH, Burnham KP. 2001. Suggestions for presenting the results of data analyses. J Wildl Manage 65:373-378.

Burnham KP, Anderson DR. 1998. Model Selection and Inference: a Practical Information-theoretic Approach. Springer-Verlag, New York, New York, U.S.A.

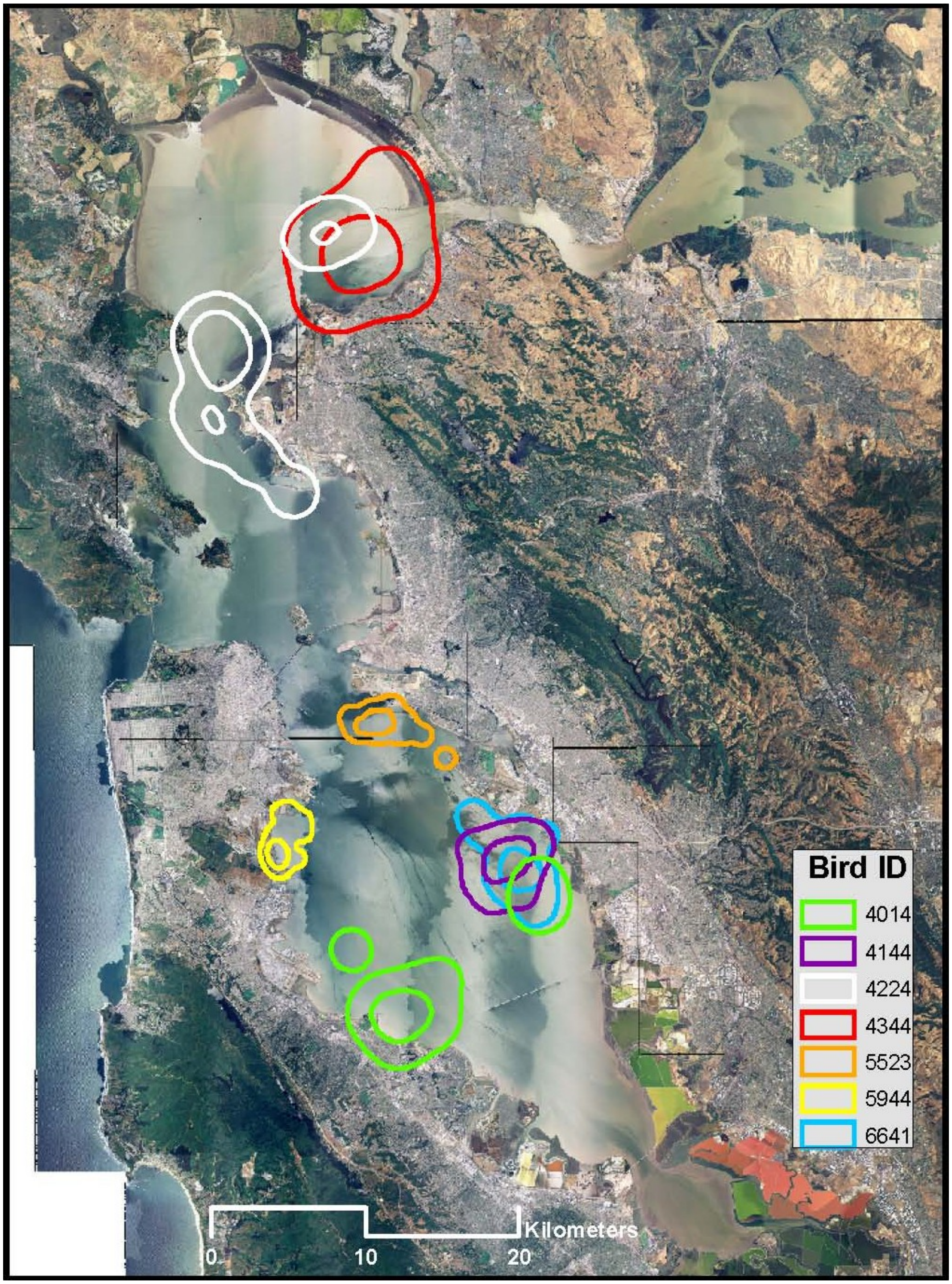
***Appendix 8.*** Telemetry locations and core use home ranges of pre-breeding Forster's terns in 2005 determined using radio telemetry in (A) North Bay and (B) South Bay.



***Appendix 9.*** Fish THg concentrations sampled within core use home ranges of pre-breeding Forster's terns determined using radio telemetry in San Francisco Bay.



***Appendix 10.*** Core use areas and home ranges of individual surf scoters determined using radio telemetry in 2006.



***Appendix 11***. The number of avocet, stilt, and Forster's tern nests monitored and their nest success during 2005 and 2006 breeding seasons in the San Francisco Bay-Delta. A nest was considered successful if ≥1 egg hatched. Nest success was determined for each pond using Mayfield (1961, 1975) techniques modified for waterbirds (Johnson 1979).

| | Avocet | | | | Stilt | | | | Forster's Tern | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2005 | | 2006 | | 2005 | | 2006 | | 2005 | | 2006 | |
| Site | *N* | Nest Success | *N* | Nest Success | *N* | Nest Success | *N* | Nest Success | *N* | Nest Success | *N* | Nest Success |
| South Bay | | | | | | | | | | | | |
| A16 | 164 | 86% | 20 | 11% | 3 | *na* | 6 | 19% | 168 | 94% | 131 | 23% |
| A8 | 188 | 35% | 211 | 40% | 0 | *na* | 2 | *na* | 115 | 73% | 63 | 59% |
| New Chicago | 28 | 33% | 77 | 30% | 98 | 48% | 302 | 22% | 17 | 63% | 91 | 26% |
| Moffett | 11 | 60% | 55 | 28% | 0 | *na* | 0 | *na* | 124 | 94% | 3 | 41% |
| A7 | --- | --- | 4 | 23% | --- | --- | 0 | --- | --- | --- | 198 | 65% |
| Coyote Creek | --- | --- | 37 | 16% | --- | --- | 8 | 3% | --- | --- | 0 | *na* |
| Rect. Marsh | --- | --- | 18 | 15% | --- | --- | 9 | 80% | --- | --- | 0 | *na* |
| Newark | --- | --- | 83 | 53% | --- | --- | 35 | 50% | --- | --- | 231 | 80% |
| Eden Landing | 24 | 33% | 72 | 22% | 32 | 44% | 22 | 51% | 21 | 62% | 0 | *na* |
| North Bay | | | | | | | | | | | | |
| Rush Creek | 2 | *na* | --- | --- | 24 | 3% | --- | --- | 0 | *na* | --- | --- |
| Pond 4 | 13 | 5% | --- | --- | 0 | *na* | --- | --- | 0 | *na* | --- | --- |
| Figeras Tract | 0 | *na* | --- | --- | 11 | 67% | --- | --- | 0 | *na* | --- | --- |
| Pond 2 | 0 | *na* | --- | --- | 0 | *na* | --- | --- | 136 | 57% | --- | --- |
| **Total** | **391** | | **505** | | **101** | | **362** | | **424** | | **717** | |

--- indicates that we did not search the area for nests

NA indicates that birds did not nest in high enough densities to sufficiently calculate nest success

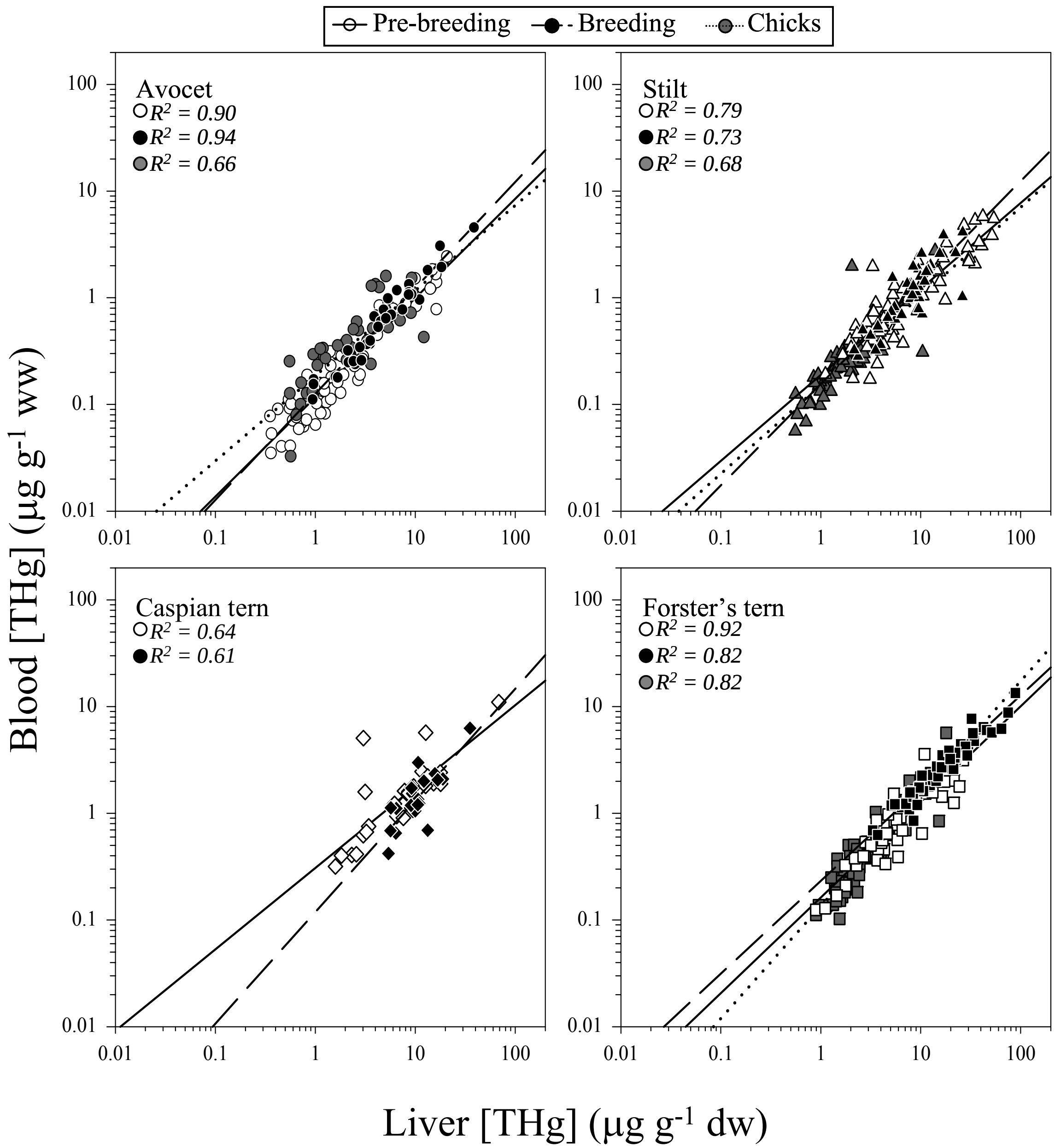
References:

Mayfield HF. 1961. Nest success calculated from exposure. Wilson Bulletin 73:255-261

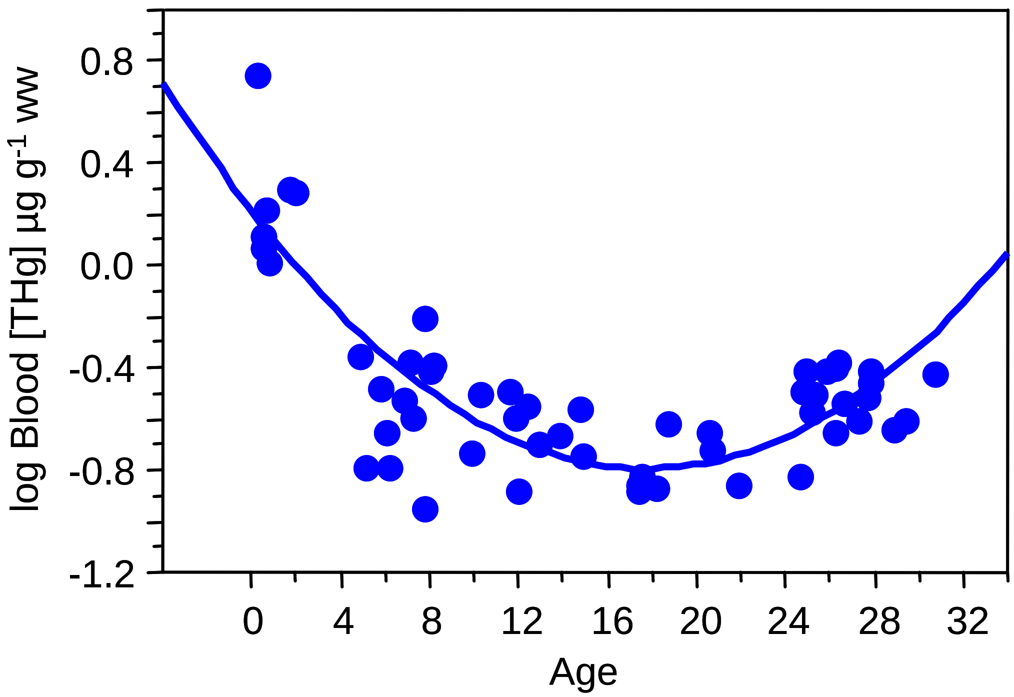
Mayfield HF. 1975. Suggestions for calculating nest success. Wilson Bulletin 87:456-466.

Johnson DH. 1979. Estimating nest success: the Mayfield method and an alternative. Auk 96:651–661.

***Appendix 12.*** Relationships between THg concentrations in liver (µg g$^{-1}$ dw) and THg concentrations in blood (µg g$^{-1}$ ww) for chicks, pre-breeding adults, and breeding adults.



***Appendix 13.*** Age-specific blood THg concentrations (µg $g^{-1}$ ww) in Forster's tern chicks at Newark salt ponds in 2006. The line was fitted with a second-order polynomial.



### *Appendix 14*. BIOCHEMICAL MARKERS MEASURED IN TERNS

We analyzed liver, kidney, and brain tissues from Forster's terns and Caspian terns collected in 2005 and 2006 for a suite of biomarkers and enzymatic systems for evidence of impacts due to Hg and polyhalogenated aromatic compounds (polychlorinated biphenyls (PCBs), dioxins, furans, polybrominated diphenyl ethers (PBDEs) etc.) exposure. We assessed 12 different oxidative stress parameters linked to Hg and selenium toxicity and physiological response. Please see appendix for list of parameters measured, biochemical relevance, and general response to Hg exposure. From the 2005 fieldseason we analyzed 63 livers, 61 kidney, and 63 brain tissues samples from Forster's terns and 10 liver, kidney, and brain samples from pre-breeding Caspian terns. In 2006 we analyzed 30 liver, kidney, and brain samples from Caspian terns and 79 liver, kidney and brain samples from Forster's terns for the oxidative stress parameters. To date we have received biomarker and Hg and selenium analytical results for all liver and kidney samples from 2005 and are awaiting Hg analytical results form 2005 brain samples. Results summarized here will be primarily for liver samples.

Many of the biochemical bioindicators measured in this study are indicators in birds and other vertebrates of organ oxidative stress including ones of altered glutathione status and lipid peroxidation as well as induction of cytochrome P450. Oxidative stress can be caused by different environmental contaminants in birds including Hg, selenium, lead and PCBs but the response exhibited may vary depending upon the contaminant and its concentration in specific tissues as well as potential interaction with other contaminants and nutrition. Changes in these bioindicators have been associated with organ damage and related physiological disturbances following Hg exposure in birds. Induction of cytochrome P450 has been associated with the presence of polyhalogenated aromatic hydrocarbons (PHAHs) such as PCBs in birds. The following is a summary of the bioindicators that were measured in this study including Hg-related effects previously reported in birds in other studies:

***GSH***, reduced glutathione, is a tripeptide and major antioxidant occurring in most tissues of birds and other living organisms. GSH is a component in both conjugation reactions and in reduction reactions.  Low levels of Hg can sometimes stimulate the production of GSH seen as an initial protective response, but higher levels may eventually deplete the reserve of GSH resulting in cellular damage. Hg is eliminated through conjugation with glutathione, and reduced glutathione also serves as a means to reduce harmful oxidative intermediates by reduction reactions.

***GSSG***, oxidized glutathione, is a product of oxidative stress, found to increase with higher levels of tissue Hg. In conjunction with increased GSSG at higher concentrations of Hg the ratio of GSSG to GSH tends to increase reflecting a burden of the oxidized status over the reduced status. Depletion of reduced glutathione (GSH) serves to further aggravate this, increasing the ratio of GSSG to GSH still further.

***Total SH***, total reduced thiols, include the sum of GSH and protein bound thiols (***PBSH***). With increased Hg exposure of tissues there is a tendency for oxidation of PBSH as well as GSH, lowering the concentration of TSH in at least several organs including liver.

***TBARS***, thiobarbituric acid reactive substances, are generated in the process of toxic tissue lipid peroxidation and therefore are used as a measurement of lipid peroxidation, reflecting cellular membrane and associated damage following generally higher Hg exposure in different organs.

Important enzymes related to glutathione metabolism were assayed as well as the above constituents since these enzymes may reflect early response of interrupted glutathione status. These include:

***Total glutathione peroxidase*** activity (using cumene hydroperoxide as the substrate). This enzyme results in the formation of GSSG from GSH following the donation of H ions to help reduce harmful oxidative intermediates such as hydrogen peroxide. Higher levels of Hg tend to decrease the activity.

***Selenium-dependent glutathione peroxidase*** activity (using tertbutyl hydroperoxide as the substrate) has been reported to be sometimes stimulated by Hg.

***GSSG reductase*** activity is related to the recovery of GSH by converting GSSG back to the reduced form. Hg can stimulate the activity but high concentrations appear to depress it.

***GSH-S-Transferase*** detoxifies compounds by covalently linking glutathione to a hydrophobic substrate, forming less reactive and more polar gluatathione *S*-conjugates. Hg is eliminated by conjugation with glutathione. Hg can stimulate the activity but high concentrations appear to depress it.

***G-6-PDH*** or glucose -6-phosphate dehydrogenase is related to the production of the antioxidant NADPH which is essential to GSSG reductase activity in order to regenerate reduced glutathione from GSSG. Hg can stimulate the activity but high concentrations appear to depress it.

***GGT*** or gamma glutamyl transferase is mainly present in the kidneys of birds and is involved in the transfer of amino acids across cell membranes and in glutathione metabolism. GGT activity can be initially stimulated by Hg.

***Cytochrome P450 1A*** (CYP1A) in the liver and other tissues is often measured as ***EROD*** (ethoxyresorufin-*O*-deethylase) enzyme activity, and induction of activity has been associated with increasing concentrations of polyhalogenated aromatic hydrocarbons (PHAHs) such as PCBs and dioxins in birds and other vertebrates. There is a potential for high concentrations of heavy metals to inhibit activity.

***AChE***, acetylcholinesterase, activity in brain tissue in birds is inhibited by OP and carbamate pesticides but may also be altered by Hg in some instances.

References:
Hoffman DJ, Ohlendorf HM, Marn CM, Pendleton GW. 1998. Association of mercury and selenium with altered metabolism and oxidative stress in diving ducks from the San Francisco Bay region, USA. *Environ Toxicol Chem* 17:167-72.

Hoffman DJ, Heinz GH. 1998. Effects of mercury and selenium on glutathione metabolism and oxidative stress in mallard ducks. *Environ Toxicol Chem* 17:161-166.

Henny CJ, Hill EF, Hoffman DJ, Spalding MG, Grove RA. 2002. Nineteenth century mercury: Hazard to wading birds and cormorants of the Carson River, Nevada. *Ecotoxicology* 11:213-231.

Hoffman, D.J., Spalding, M.G., Frederick, P.C. 2005. Subchronic effects of methylmercury on plasma and organ biochemistries in great egret nestlings. *Environ. Toxicol. Chem* 24:3078-3084

Henny, C.J., E.F. Hill, D.J. Hoffman, R.A.Grove and J.L. Kaiser (2006). An evaluation of mercury exposure and effects on waterbirds along the lower Carson River in Nevada (1997-2004), with special emphasis on survival rates of young snowy egrets (2002-2004). Final EPA Report, National Center for Environmental Assessment and Region IX Superfund Division, San Francisco, CA

Melancon, M.J. 2003. Bioindicators of contaminant exposure and effect in aquatic and terrestrial monitoring. Pages 257-278 in D. J. Hoffman, B.A. Rattner, G. A. Burton, Jr. and J. Cairns, Jr. editors, Handbook of Ecotoxicology, 2nd Ed.

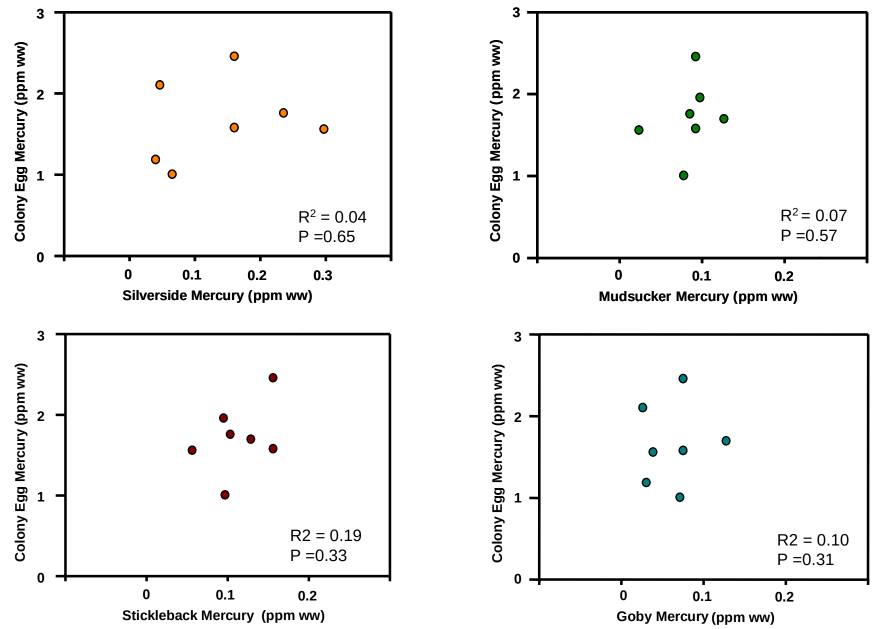
***Appendix 15.*** List of species whose eggs have been tested by injections of MeHg.

| Order | Species (N=26) |
|---|---|
| Pelecaniformes | Brown pelican (*Pelecanus occidentalis*), anhinga (*Anhinga anhinga*), double-crested cormorant (*Phalacrocorax auritus*) |
| Ciconiiformes | Great egret (*Ardea alba*), snowy egret (*Egretta thula*), tricolored heron (*Egretta tricolor*), white ibis (*Eudocimus albus*) |
| Charadriiformes | American avocet (*Recurvirostra americana*), black-necked stilt (*Himantopus mexicanus*), herring gull (*Larus argentatus*), laughing gull (*Larus atricilla*), royal tern (*Sterna maxima*), Caspian tern (*Sterna caspia*), common tern (*Sterna hirundo*) |
| Galliformes | Chicken (*Gallus gallus*), ring-necked pheasant (*Phasianus colchicus*) |
| Gruiformes | Clapper rail (*Rallus longirostris*), sandhill crane (*Grus canadensis*) |
| Anseriformes | Mallard (*Anas platyrhynchos*), Canada goose (*Branta canadensis*), lesser scaup (*Aythya affinis*), hooded merganser (*Lophodytes cucullatus*) |
| Passeriformes | Common grackle (*Quiscalus quiscula*), tree swallow (*Tachycineta bicolor*) |
| Falconiformes | American kestrel (*Falco sparverius*), osprey (*Pandion haliaetus*) |

## ***Appendix 16.*** **BIOINDICATORS OF MERCURY**

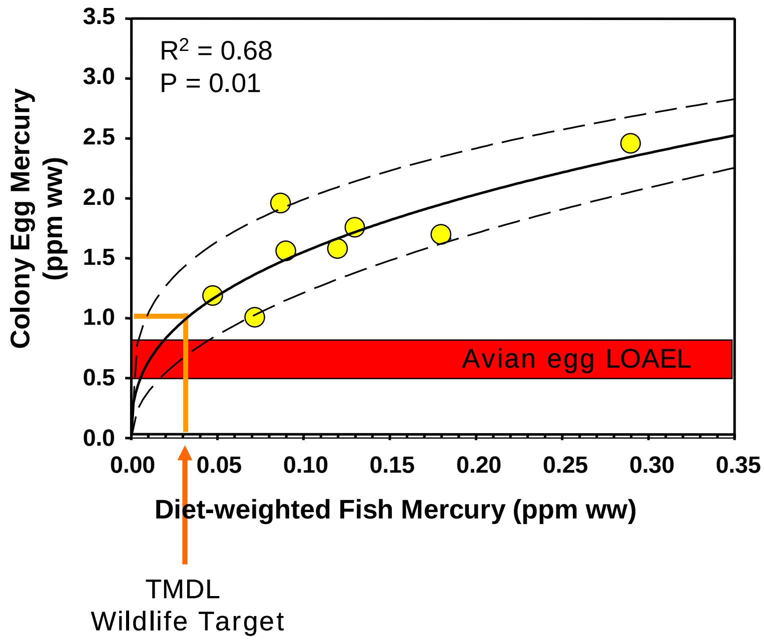
We found very poor relationships between THg concentrations in individual fish species and tern eggs sampled at the same sites, indicating that monitoring individual fish species is not sufficient to determine risk to fish-eating birds (A). However, we were able to derive a relationship between egg THg concentrations and fish THg concentrations by using a more sophisticated model where we incorporated our site-specific telemetry, bird diet, and fish THg concentrations (B). Because of the large amount of data that is necessary to derive this relationship between fish Hg and bird Hg, and the relative logistical ease and cost-effectiveness of sampling bird eggs, we suggest that eggs should be monitored to directly address risk to birds.

**A)**




*Colony egg THg concentrations in relation to individual fish THg concentrations.*

**B)**




*Colony egg THg concentrations in relation to diet-weighted fish THg concentrations determined from colony-specific foraging locations and diet composition.*