Developing Impairment Thresholds for the Effects of Mercury on Forster's Tern Reproduction in San Francisco Bay

Data Summary

Photo © Michael Kern, used with permission

Collin A. Eagles-Smith and Josh T. Ackerman

U. S. Geological Survey, Davis Field Station,
University of California

USGS
science for a changing world

Developing Impairment Thresholds for the Effects of Mercury on Forster's Tern Reproduction in San Francisco Bay

Data Summary

Collin A. Eagles-Smith[1] and Josh T. Ackerman[1]

U. S. GEOLOGICAL SURVEY

[1] U. S. Geological Survey, Western Ecological Research Station, Davis Field Station, One Shields Avenue, University of California, Davis, CA 95616; ceagles-smith@usgs.gov and jackerman@usgs.gov

Prepared for:

Regional Monitoring Program, Exposure and Effects Workgroup
San Francisco Estuary Institute
Don Edwards San Francisco Bay National Wildlife Refuge
South Bay Salt Pond Restoration Project
California Department of Fish and Game
U. S. Fish and Wildlife Service
U. S. Geological Survey

Davis, California
[2010]

U.S. DEPARTMENT OF THE INTERIOR
Ken Salazar, Secretary

U.S. GEOLOGICAL SURVEY
Marcia McNutt, Acting Director

Suggested citation:
Eagles-Smith, C. A., and J. T. Ackerman. 2010. Developing Impairment Thresholds for the Effects of Mercury on Forster's Tern Reproduction in San Francisco Bay. Data Summary, U. S. Geological Survey, Western Ecological Research Center, Davis, CA 21 pp.

For additional information, contact:

Center Director
Western Ecological Research Center
U. S. Geological Survey
3020 State University Dr. East
Modoc Hall, 3rd Floor, Room 3006
Sacramento, CA 95819
916-278-9490; steven_schwarzbach@usgs.gov

Acknowledgments:
This research was funded from generous contributions by the Regional Monitoring Program's Exposure and Effects Workgroup administered by the San Francisco Estuary Institute, the US Fish and Wildlife Service Don Edwards National Wildlife Refuge, the USGS Western Ecological Research Center, and the efforts of Meg Sedlak and Jay Davis. We thank Dena Spatz and Khara Strum for field assistance, and Robin Keister, Margot Wood, and Brittany Wensky for their help in the lab. We also thank Meg Sedlak, Jay Davis, San Francisco Estuary Institute, Cheryl Strong, Eric Mruz, Joy Albertson, Mendel Stewart, and the staff at the Don Edwards San Francisco Bay National Wildlife Refuge for logistical support.

DEVELOPING IMPAIRMENT THRESHOLDS FOR THE EFFECTS OF MERCURY ON FORSTER'S TERN REPRODUCTION IN SAN FRANCISCO BAY

Data Summary

By Collin A. Eagles-Smith and Josh T. Ackerman

INTRODUCTION

Mercury contamination is a high priority issue for the San Francisco Bay because elevated concentrations in aquatic biota pose potentially serious health risks to humans and wildlife. As a result, the San Francisco Bay is designated as an impaired water body according to Section 303d of the Federal Clean Water Act. In response, the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) has completed a methylmercury total maximum daily load (TMDL) for the Bay (RWQCB 2003) in order to protect humans and wildlife from harm due to mercury exposure. In the TMDL, the SFBRWQCB specifies the use of small fish as a monitoring tool to regulate mercury concentrations within the Bay because they integrate exposure over time better than sediment or water measures, and can be more strongly linked to wildlife exposure. However, recent work has shown that even in small fish, mercury concentrations at the same location can vary by 40% over the span of only a few weeks, so their use as a monitoring tool to estimate mercury exposure to wildlife during the critical breeding period is not strong (Eagles-Smith and Ackerman 2009).

Importantly, to ensure a better linkage to wildlife risk, the SFBRWQCB also included a bird egg monitoring target (0.5 μg/g fresh wet weight) that was indicative of impaired hatching success in controlled laboratory studies. However, the monitoring target was based on data from a single bird species (mallard ducks) and there can be substantial differences among bird species in their sensitivity to mercury (Heinz et al. 2009). Additionally, lab-based thresholds do not account for the inherent environmental stressors to which bird populations are exposed, and likely do not adequately characterize the risk of mercury to wild birds in San Francisco Bay. In order to adequately characterize mercury risk to waterbirds breeding in San Francisco Bay, studies are needed to evaluate the relative exposure of mercury among bird species, and examine whether

exposure occurs at levels likely to impair reproduction. Recent work has shown that Forster's terns (*Sterna forsteri*) have the highest mercury concentrations in their tissues (Eagles-Smith et al. 2009, Ackerman et al. 2008) and eggs (Ackerman et al. 2009) of any waterbird species studied in San Francisco Bay, with 58% of breeding adults containing blood concentrations above levels (3 μg/g ww) known to impair reproduction in other species (Evers et al. 2008). These studies prompted the development of Forster's tern eggs as the primary biosentinel tool for annual monitoring of mercury risk to wildlife within the San Francisco Bay.

In order to maximize the utility of mercury biosentinels it is important to link their concentrations to applicable endpoints. For Forster's terns, the relationship between egg mercury concentrations and reproductive endpoints such as egg hatchability, nest success, and chick survival would allow managers to quantify the risk of mercury exposure to tern populations in the Bay. Additionally, the derivation of thresholds for reproductive impairment can assist managers in setting acceptable limits of exposure, as well as action levels at which mercury concentrations become a concern.

In this study, we evaluated the effects of mercury on Forster's terns at several scales. First, we examined the differences in egg mercury concentrations among viable eggs, and eggs that failed to hatch for various reasons. To provide more predictive power, we next assessed the relationship between egg mercury concentrations and the success of the nests from which they were collected. Finally, using a novel microsampling technique, we assessed the influence of mercury on the hatching success of an individual egg. Together, these approaches provide both an integrated measure of the potential effect of mercury on Forster's tern reproduction, as well as a set of quantitative regulatory targets for mercury risk to wildlife in San Francisco Bay.

OBJECTIVES

Forster's terns are an important biosentinel for evaluating mercury risk to wildlife in San Francisco Bay. Regular annual monitoring of mercury concentrations in Forster's tern eggs will be important for identifying whether mercury concentrations in the food web reach critically high levels that threaten avian populations, or alternatively whether concentrations have declined below levels of serious concern. However, these interpretations require the identification of

threshold concentrations in eggs that signal a potential deleterious effect on reproduction due to mercury exposure. The objectives detailed below employ a suite of methods to apply a quantitative weight of evidence approach that allow scientists and managers to monitor mercury concentrations in avian eggs and assess potential effects on avian reproduction.

Objective 1. Compare mercury concentrations among eggs that were abandoned, failed-to-hatch, or randomly sampled from active nests

Egg hatching success is among the most direct and commonly employed estimates for evaluating contaminant toxicity to avian reproduction (Heinz et al. 2009). However, field-based studies are complicated by the fact that mercury can exert its effect on hatching success through direct embryo mortality (Heinz et al. 2009), as well as by impairing adult breeding behavior (Evers et al. 2008). However, the final fates of nests are commonly unknown when eggs within them are collected, which can hamper assessment of generational (e.g. parental nesting behavior) or direct inducement of mercury effects on reproduction. Previous studies (Ackerman and Eagles-Smith 2008) found differences in mercury concentrations among failed-to-hatch eggs, abandoned eggs, and randomly collected eggs from successful nests. In *Objective 1*, we expanded these studies and compared mercury concentrations among these three classifications of eggs collected in 2009.

Objective 2. Assess the relationship between mercury concentrations in a randomly-sampled egg with the fate of the remaining eggs in the nest (surrogate eggs study)

The surrogate egg technique is a classic method for evaluating contaminant effects on avian reproduction in the wild. The basic premise of this method lies on the assumption that mercury concentrations in the sampled egg are representative of other eggs in the nest. Thus, by determining mercury concentrations in one egg from a clutch, and subsequently following the fate of the remaining eggs, one can assess whether mercury exposure is influencing nest success. The power in this approach is that it incorporates the variability associated with nest survival in the field. In other words, mercury alone may not cause embryo mortality at a given concentration, but it may contribute to nest abandonment, poor nest site selection, or reduced nest attentiveness which may enhance predation risk. Thus, this approach allows one to assess the effect of mercury on the ultimate fate of a nest. In *Objective 2*, we evaluated the effect to

mercury on nest success by randomly sampling a single egg from Forster's tern nests, and subsequently following the fate of each nest.

Objective 3. Microsample live Forster's tern eggs to determine the effect of mercury on individual hatching success

Mercury toxicity thresholds for avian reproduction that have been developed using laboratory egg-injection techniques may not be appropriate for application to wild birds because the injected mercury is thought to be much more toxic than maternally derived mercury (Heinz et al. 2006). The surrogate-egg technique described above can be hampered by the high intra-clutch variability of egg mercury concentrations (Kennamer et al. 2005, Authors' unpublished data). For example, the intra-clutch variation in egg contaminant concentrations can be as high as 50% for mercury in the Bay (Authors, unpublished data) which can limit the detection of contaminant effects on reproductive success. Additionally, intra-clutch variability increases at high mercury concentrations where effects are likely to occur. Thus, the surrogate egg technique might mask true effects if mercury concentrations within a clutch overlap toxicity levels.

Recently, we developed a new technique (Stebbins et al. 2009; the micro-sampling technique) that allows us to non-destructively determine mercury concentrations in an egg, and follow the fate of the same individual egg as it is incubated naturally by its parents. In *Objective 3*, we employed this technique to evaluate the toxicity of mercury to hatching success, on an individual-egg basis.

STUDY AREA

We conducted our study on Forster's terns during the 2009 nesting season (April to August) in South San Francisco Bay, California (**Figure 1**). Our study sites were located at the Don Edwards San Francisco Bay National Wildlife Refuge (37.4º N, 122.0º W), where tern colonies occurred on islands within former salt evaporation ponds within the Alviso (Ponds A7, A8, A12, and A16), Moffett (Ponds A1, A2W, and AB2), and Ravenswood (Pond R1) salt pond complexes (**Figure 1**).

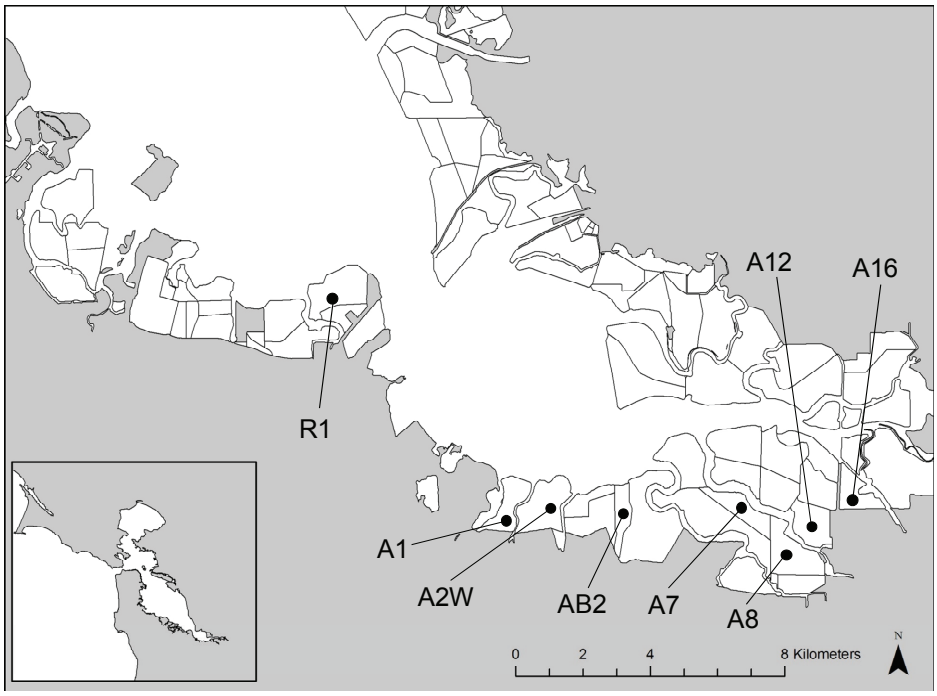

Figure 1. Forster's tern colonies sampled during the 2009 nesting season in South San Francisco Bay.

METHODS

Objective 1. Compare mercury concentrations among eggs that were abandoned, failed-to-hatch, or randomly sampled from active nests.

Detailed methods for *Objective 1* were described previously in Ackerman and Eagles-Smith (2008), so we briefly outline our approach here. We visited Forster's tern nests every seven days from late April to August 2009 at several colonies throughout the South San Francisco Bay. During each visit we recorded embryo development via floating (Ackerman and Eagles-Smith 2010), clutch size, overall nest fate (hatched, failed, abandoned, or depredated), and the fate of each individual egg (hatched, failed-to-hatch, abandoned, depredated, or research collected) was determined.

We randomly collected a single egg from several nests that were actively being incubated and followed the fate of the remaining sibling eggs until a nest fate could be determined. If ≥1 of the sibling eggs hatched we classified the nest as successful. If no eggs hatched in the nest then we classified the nest as unsuccessful. From our sample of random eggs, we only included eggs from successful nests in our analysis. Additionally, we collected failed-to-hatch and abandoned

eggs from nests during the course of nest monitoring. We considered an egg to be failed-to-hatch if it did not hatch despite at least one other sibling egg in the nest successfully hatching. We excluded from our failed-to-hatch category all eggs from nests that were depredated, abandoned, or where all eggs were dead. Eggs were considered to be abandoned if they were from nests that were naturally abandoned by their parents with no obvious signs of depredation or other disturbance.

Statistical Analysis for Objective 1

We compared mercury concentrations among failed-to-hatch eggs, abandoned eggs, and randomly sampled eggs using a mixed-effects general linear model. Fixed factors in the model included egg type (random, failed-to-hatch, or abandoned), and colony, whereas nest identification number was included as a random effect.

Objective 2. Assess the relationship between mercury concentrations in a randomly-sampled egg with the fate of the remaining eggs in the nest (surrogate eggs study)

We randomly selected a subset of nests that were between 9 and 12 days in incubation and collected one egg from the nest. We then followed the progress of the remaining eggs in the nest until a final fate could be assigned to the nest (e.g. successful or unsuccessful). We considered a nest to be successful if ≥1 egg successfully hatched from the nest. Nests were considered unsuccessful if at least 1 egg did not hatch. Importantly, for this analysis we included abandoned, depredated, and otherwise destroyed nests in the unsuccessful category to assess the influence of mercury on overall nest fate.

Statistical Analysis for Objective 2

We employed two different statistical approaches in *Objective 2*. First, we used analysis of variance to compare mercury concentrations between randomly sampled eggs which came from nests that were either subsequently successful or unsuccessful. In this analysis, we included colony site as a factor. Secondly, we used a logistic regression to quantify the influence of egg mercury concentrations on the probability of a nest being successful or unsuccessful. Nest fate was the dependent variable, and egg mercury concentration and colony site were independent variables.

Objective 3. Microsample live Forster's tern eggs to determine the effect of mercury on individual hatching success

For *Objective 3*, we employed a recently developed (Stebbins et al. 2009), novel technique to non-destructively determine mercury concentrations in an egg, and link the fate of that naturally-incubated egg to mercury exposure. To reduce any interference with embryo development, nests were only chosen for microsampling if all eggs in the nest had been incubated for <3 days. We only selected nests containing >1 egg to ensure adequate controls. When the clutch size of a nest was 2 eggs, we randomly selected 1 egg to be microsampled and 1 as a control (treated identically, but no holes drilled in the second egg). If the clutch size was 3 eggs or more, we randomly selected 1 egg for microsampling, 1 egg as the control, and 1 egg as a sham where the egg was drilled and a needle inserted into the extraction site, but no albumen was removed. Details of the method can be found in Stebbins et al. (2009), and Eagles-Smith and Ackerman (2009; **Figure 2**). Briefly, we dipped each microsampled, control, or sham egg in a dilute (1%) betadine solution and wiped the shell breach sites with isopropanol. We then breached the shell in two locations (the top of the egg above the air cell to allow venting, and one-third of the way up from the bottom of the egg for albumen extraction) using a rotary tool (Dremel Rotary tool, 7.2V Cordless MultiPro, Racine, WI, USA) with a diamond-tipped grinding bit. We then extracted a small amount of albumen (~1% of egg content fresh mass) using a sterile 20 gauge needle and 1-ml syringe. After extraction, we quickly sealed the holes with hot paraffin glue followed by a thin layer of cyanoacrylate to ensure an adequate seal. The sampled albumen was immediately transferred to a clean cryovial and stored at -20ºC until mercury analysis.

Figure 2. Photo sequence of the egg microsampling technique.

In order to estimate whole-egg mercury concentrations from the microsampled albumen, we collected a subset of freshly laid eggs, microsampled their albumen, and then homogenized the remainder of the egg contents for mercury determination (See Eagles-Smith and Ackerman 2009 for details).

Statistical Analyses for Objective 3

We reconstructed mercury concentrations in the whole egg by combining mercury concentrations determined for the albumen sampled from the fresh egg and the remaining whole egg-homogenate. To do so, we weighed (wet weight; ww) the entire sample of albumen removed from the fresh egg and the remaining whole-egg homogenate separately before determining their respective mercury concentrations (ww; accuracy to 0.0001 g). We then multiplied the weight of the albumen removed from the embryo by its specific mercury concentration and added the product of the weight of the remaining whole-egg homogenate and the mercury concentration of the whole-egg homogenate. This resulted in the total mercury burden in the whole egg, and we divided this quantity by the combined mass (ww) of the removed albumen and the remaining whole-egg homogenate to yield the mercury concentration of the reconstructed whole-egg homogenate at sampling.

Although these eggs were sampled soon after being laid, it is unknown how much moisture loss may have occurred prior to sampling. Thus, we adjusted the wet weight mercury concentration of the reconstructed whole-egg homogenate to a fresh egg wet weight mercury concentration (fww) by dividing the total mass (ww) of the egg content at processing by the predicted fresh egg mass (ww) at laying, and multiplying that value by the wet weight mercury concentration (following Stickel et al. 1973). The fresh egg mass (ww) was estimated using egg morphometrics following Hoyt (1979).

All data were natural-log transformed for analysis, and we report all egg mercury concentrations in fresh wet weight (fww); the mean (± SE) moisture content in eggs was 74.07 ± 0.14%. Albumen mercury is reported in wet weight (ww).

To evaluate the effect of mercury on egg fate from microsampled eggs, we used a logistic

regression model in which we coded the fate of microsampled eggs as either hatched or failed-to-hatch. In order to specifically evaluate effects of mercury on egg hatchability, we excluded from our analysis any eggs from nests that were depredated, abandoned, or otherwise destroyed. In our full model, we included albumen mercury concentration, colony site, and year as independent factors, as well as mercury × site and mercury × year interactions. We then iteratively removed any factors from our final model that were not significant at $\alpha = 0.05$ (see *Results*).

Contaminant Determination

Mercury

We measured total mercury (THg) concentrations in both eggs and albumen (U. S. Geological Survey, Davis Field Station Mercury Lab) following EPA Method 7473 (U. S. EPA 2000) on a Milestone DMA-80 Direct Mercury Analyzer (Milestone Inc., Monroe, Connecticut, USA) as described in Ackerman and Eagles-Smith (2009). Prior to analysis, we thawed albumen samples to room temperature and ensured sample homogeneity by inverting the cryovials several times and thoroughly mixed the albumen by stirring with a clean pipette tip. We pipetted 50-100 µl of albumen from each cryovial and weighed each aliquot into a quartz sample vessel. For eggs, we dried the entire egg contents at 50°C for 48 hrs or until completely dried and re-weighed the egg contents to determine moisture content prior to analysis. We then ground the dried egg contents to a powder in a Wiley mill and/or porcelain mortar and pestle. Quality assurance measures included analysis of two certified reference materials, two system and method blanks, two duplicates, one matrix spike, and one matrix spike duplicate per sample batch. Recoveries of certified reference materials, and calibration checks, respectively, averaged (± SE) 102.64 ± 2.31% (n = 24), 98.44 ± 1.03% (n = 34). Absolute relative percent difference for all duplicates averaged (± SE) 3.92 ± 1.84% (n = 26).

RESULTS

Objective 1. Compare mercury concentrations among eggs that were abandoned, failed-to-hatch, or randomly sampled from successful nests

In 2009, we salvaged 83 abandoned and 81 failed-to-hatch eggs, and randomly collected 77 eggs from nests that were subsequently successful at seven different Forster's tern colonies in South

San Francisco Bay. Total mercury concentrations (μg/g fresh wet weight [FWW]) differed among egg types ($F_{2, 192.7} = 10.13$, $P < 0.0001$; **Figure 3**), with concentrations (back-transformed LS mean ± SE) higher in abandoned eggs (1.45 ± 0.12) than failed-to-hatch eggs (1.11 ± 0.08) or random eggs (0.94 ± 0.07), which did not differ from one another (Tukey's Post-Hoc Pairwise Comparison, $\alpha = 0.05$). THg concentrations did not vary among colonies after controlling for egg type ($F_{6,186.2} = 1.67$, $P = 0.13$)

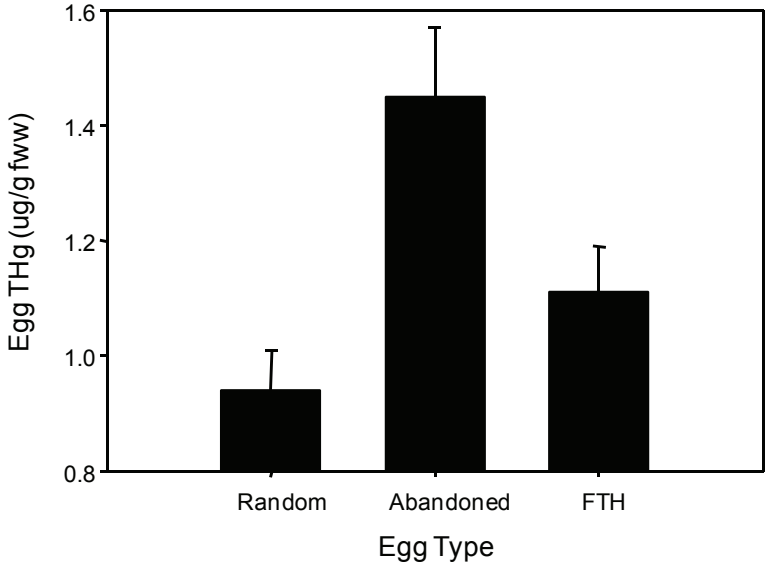

Figure 3. Total mercury concentrations (THg) in randomly sampled Forster's tern eggs from successful nests in comparison with abandoned and failed-to-hatch eggs collected in San Francisco Bay in 2009.

Objective 2. Assess the relationship between mercury concentrations in a randomly-sampled egg with the fate of the remaining eggs in the nest (surrogate egg study)

We sampled a single viable egg between 9 and 12 days of incubation from each of 81 different nests at seven Forster's tern colonies in South San Francisco Bay during 2009. We subsequently followed the fate of the remaining 1-2 eggs in the nest until a final fate could be assigned. THg concentrations differed among nest fate categories ($F_{1,81} = 13.79$, $P = 0.0004$; **Figure 4**) with unsuccessful nests having significantly higher THg concentrations (1.60 ± 0.20) than successful nests (0.95 ± 0.08).

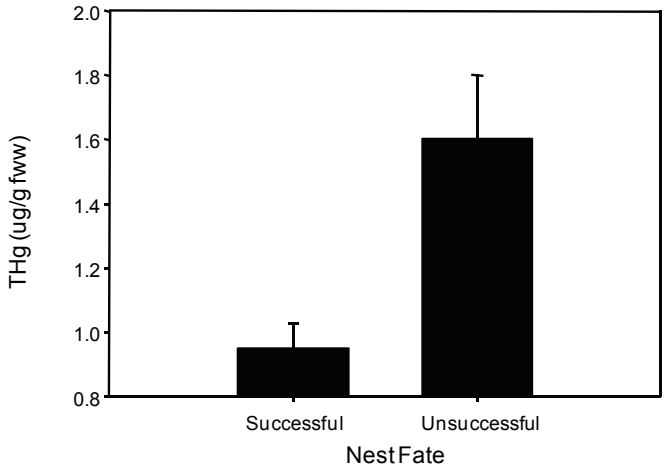

Figure 4. Total mercury (THg) concentrations in randomly sampled Forster's tern eggs from nests that were either successful or unsuccessful in San Francisco Bay in 2009.

To evaluate the influence of egg THg concentrations on the probability of nest failure, we used a binomial logistic model with egg THg and colony site as independent variables, and nest fate as the dependent variable. Site did not significantly influence the probability of nest success (χ^2_5 = 6.93, P = 0.23), thus it was removed from the final mode which included only egg THg concentration as an independent variable. THg concentrations in the surrogate eggs were significantly related to the probability of nest failure (χ^2_1 = 10.83, P = 0.001; **Figure 5**). Specifically, the probability of a nest being successful declined as the surrogate egg's THg concentration increased.

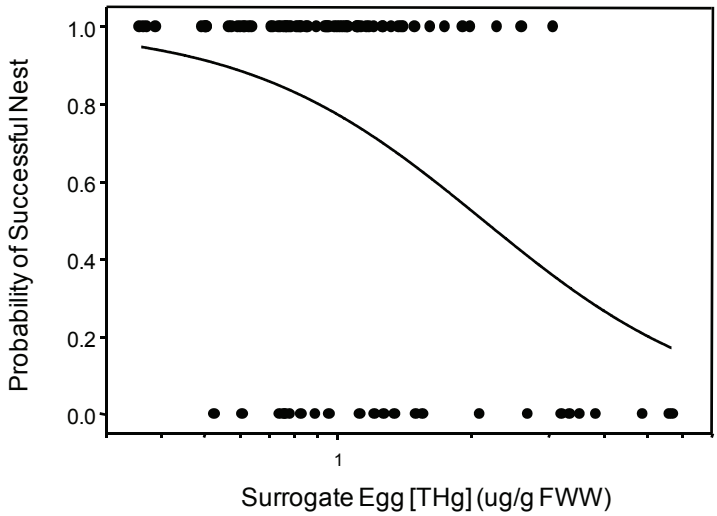

Figure 5. The probability of the remaining eggs in a Forster's tern nest being successful as a function of total mercury (THg) concentrations from a randomly sampled surrogate egg within the same nest in *San* Francisco Bay in 2009.

Objective 3. Microsample live Forster's tern eggs to determine the effect of mercury on <u>individual</u> hatching success

To test the effects of mercury on egg hatchability on an individual-egg basis, we microsampled 130 Forster's tern nests in 2009, and a total of 309 nests between 2007 and 2009. However, in the South Bay Salt Ponds, many nests are depredated or otherwise naturally destroyed, thereby limiting the effective sample size. Thus, we were able to use 82 of 130 (63%) nests from 2009, and 181 of 309 (59%) nests overall between 2007 and 2009 for analysis. In our global model, neither site ($\chi^2_8 = 7.99$, P = 0.43) nor year ($\chi^2_2 = 0.52$, P = 0.77) influenced the probability of the microsampled egg hatching, therefore site and year were removed from the final model which included only albumen THg concentration as the independent variable. Combining data across sites and years, the probability of the microsampled egg hatching decreased with albumen THg concentration ($\chi^2_1 = 4.22$, P = 0.04; **Figure 6**, presented using predicted whole-egg THg concentrations).

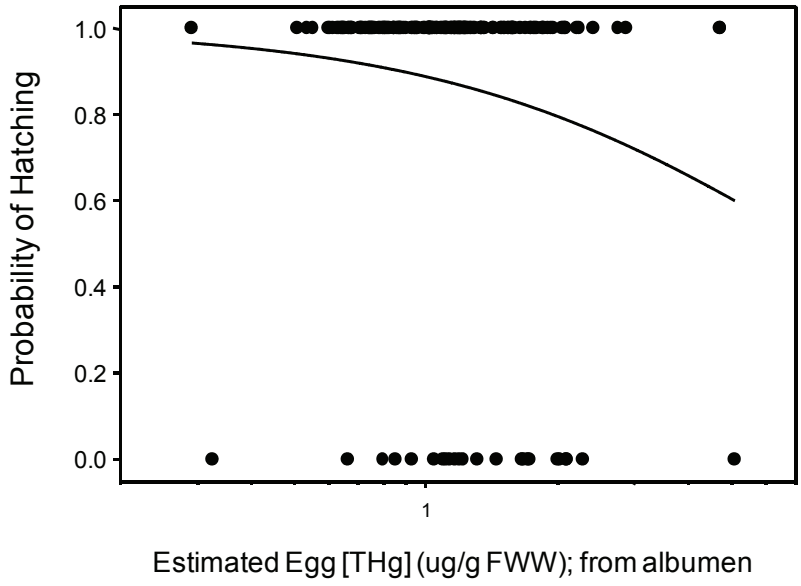

Figure 6. The probability of a microsampled egg hatching decreased with albumen total mercury (THg) concentrations for Forster's terns in San Francisco Bay from 2007-2009. Egg THg concentrations were derived from the whole-egg vs albumen THg relationships derived in Eagles-Smith and Ackerman (2009).

TOXICITY THRESHOLDS FOR FORSTER'S TERNS IN SAN FRANCISCO BAY

The series of studies and results presented above and in Ackerman and Eagles-Smith (2008) indicate that mercury exposure in San Francisco Bay clearly influences tern reproduction, and they provide the information necessary to begin establishing regulatory targets and risk thresholds. However, the estimated effect size is dependent upon the reproductive endpoint that is studied. For example, egg hatchability is a common toxicity endpoint because avian embryos are sensitive to mercury exposure and it is relatively easier to study in the laboratory. Using the mean egg mercury concentration in Forster's tern eggs from San Francisco Bay (1.2 μg/g FWW) as an arbitrarily chosen benchmark, our logistic model estimated that egg hatchability is 13% lower than it would be in uncontaminated eggs (**Figure 7**). However, for an egg to have an opportunity to hatch it must first be incubated throughout the entire incubation period and survive predation and other environmental pressures. Importantly, mercury is a neurotoxin and it may impair adult nesting behavior (Evers et al. 2008). Thus, when behavioral manifestations of mercury exposure that occur naturally in the environment are incorporated into our model, there is a relatively greater impact on reproduction that would be missed by using only egg hatchability as the reproductive endpoint. More specifically, when assessing overall nest fate as (opposed to only egg fate or hatchability) by including nests that have been abandoned, depredated, and other real-life scenarios, nest survival was 28% lower at 1.2 μg/g (fww) than if eggs were not contaminated with mercury (**Figure 7**).

In order to fully understand the influence of mercury on Forster's tern reproduction, other reproductive endpoints should also be considered. Although the influence of mercury on other reproductive endpoints, such as chick growth and survival and parental nesting behavior, are currently unknown, these effects are likely to occur at even lower egg mercury concentrations than those impairing egg hatchability and nest survival (**Figure 7**). Thus, in order to establish egg toxicity thresholds and regulatory targets that are most informative with respect to overall risk to avian populations, we must first have an understanding of mercury effects on all critical reproductive endpoints, and ultimately population level effects.

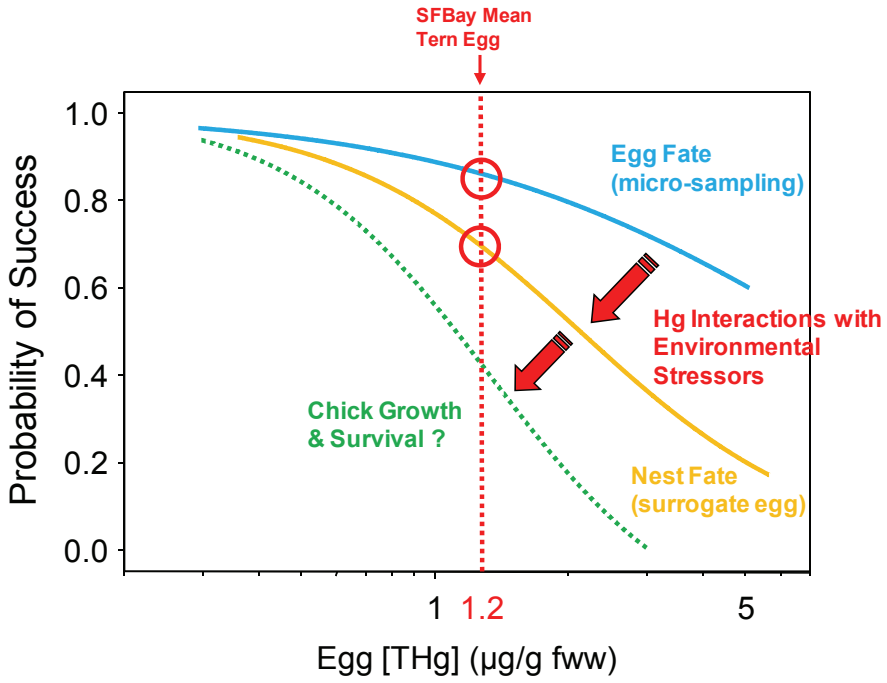

Figure 7. The effect of egg mercury concentrations on the probability of an egg successfully hatching (blue line: 2007-2009), a nest surviving (yellow line: 2009), and potentially of chick growth or survival (green line) on Forster's terns in San Francisco Bay.

Although our results indicate that current levels of mercury exposure in San Francisco Bay are negatively affecting Forster's tern reproduction, the overall population-level impacts of mercury on Forster's terns are unknown and further studies are needed to assess the sensitivity of the Forster's tern population to reduced nest success and egg hatchability. An acceptable level of harm to Forster's tern populations in San Francisco Bay must also be established in order to develop egg toxicity thresholds and regulatory targets that are appropriately protective. However, the traditional approach of using egg hatchability as the critical endpoint for mercury toxicity levels should be re-examined because the potentially complicated interactions between mercury exposure, nesting behavior, and predation may exacerbate risk to avian reproduction, beyond just egg hatchability. Other reproductive endpoints such as nest survival and chick survival typically have a larger influence on a population's growth rate (lambda) than egg hatchability, and future work should focus on integrating the critical toxicity endpoints to develop a target threshold that is ecologically relevant (see Ackerman and Eagles-Smith 2009). For example, if we select an arbitrary 10% reduction in egg hatchability as a maximum allowable

effect to birds, then the egg regulatory target based on egg hatchability would be 0.88 µg/g THg (fww), which also would result in a 18% reduction in nest survival (**Figure 8**). If the 10% reduction level were applied to nest survival, then the egg regulatory target based on nest survival would be 0.54 µg/g THg (fww; **Figure 8**).

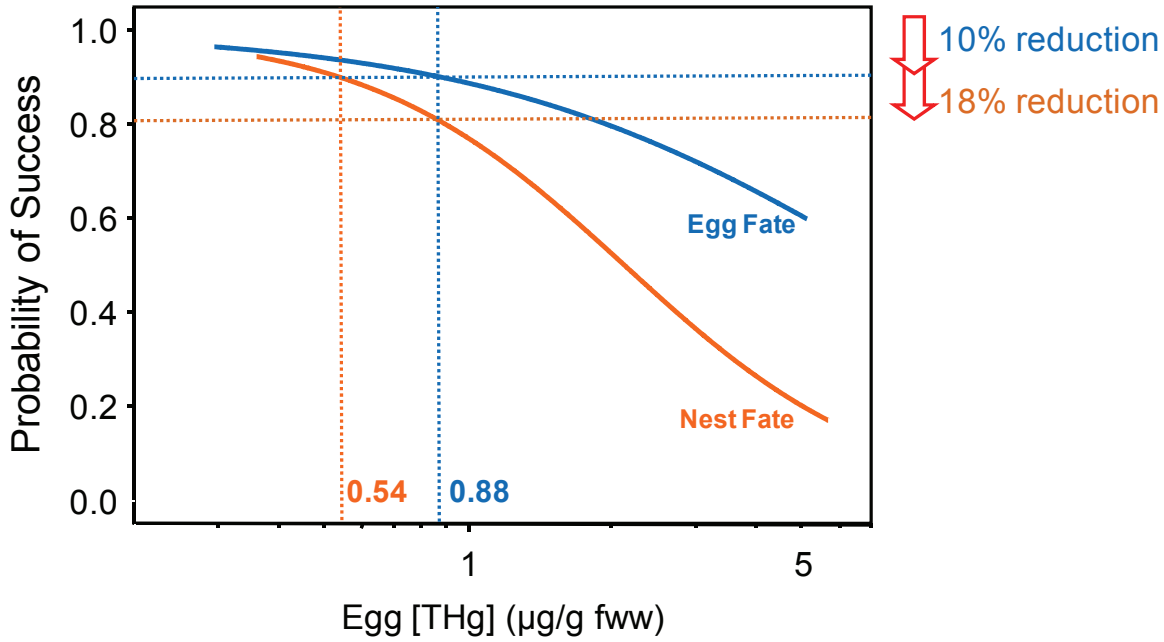

Figure 8. Mercury (THg) concentrations where egg hatching success (egg fate, blue line) or nest success (nest fate, orange line) are reduced by 10% due to mercury exposure. If a 10% reduction in egg hatchability at 0.88 µg/g THg (fww) is used as an acceptable level of harm to bird populations, then there would be an additional 18% reduction in nest survival. There would be a 10% reduction in nest survival at 0.54 µg/g THg (fww).

FORSTER'S TERN RISK AND MONITORING SUGGESTIONS

Our results indicate that current mercury concentrations in Forster's terns breeding in San Francisco Bay are causing reduced nest survival and egg hatchability. However, without additional studies to assess the sensitivity of the San Francisco Bay Forster's tern population to reduced nest success, the overall population-level impacts of mercury on Forster's terns are unknown. Moreover, recent work has noted high variability in egg mercury concentrations among years (**Figure 9**) to such an extent that substantial reductions to Forster's tern reproduction may occur in any given year. We therefore recommend that the triennial monitoring of Forster's tern eggs through the Regional Monitoring Program be expanded to annual monitoring to more adequately capture the changes in risk to wildlife as extensive

wetland restoration projects occur near primary waterbird breeding areas in San Francisco Bay over the next decade. Additionally, in order to adequately capture the variance in mercury risk to avian populations, it is important to focus monitoring efforts on sampling individual eggs as opposed to composite samples.

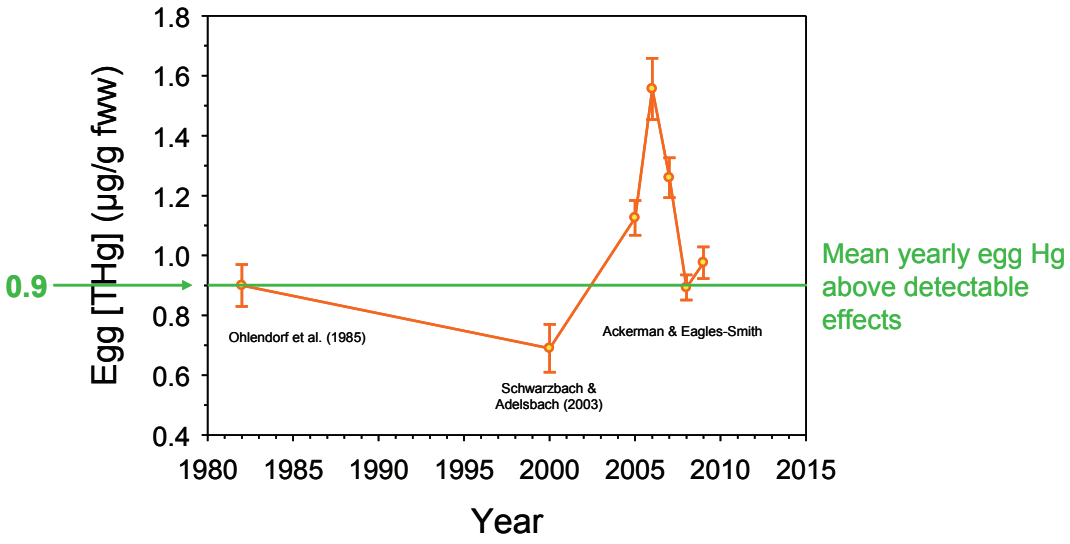

Figure 9. Forster's tern egg mercury concentrations in San Francisco Bay have been highly variable over the years and are well above detectable effects levels in recent years (0.9 µg/g THg fww reduces egg hatchability by 10% and nest survival by 18%).

LITERATURE CITED

Ackerman JT, CA Eagles-Smith, JY Takekawa, JD Bluso, TL Adelsbach. 2008. Mercury concentrations in blood and feathers of pre-breeding Forster's terns in relation to space use of San Francisco Bay habitats. Environmental Toxicology and Chemistry 27:897-908.

Ackerman JT and CA Eagles-Smith. 2008. A dual life-stage approach to monitoring the effects of mercury concentrations on the reproductive success of Forster's Terns in San Francisco Bay. Annual Report, U. S. Geological Survey, Western Ecological Research Center, Davis, CA 47 pp.

Ackerman JT and CA Eagles-Smith. 2009. Integrating toxicity risk in bird eggs and chicks: using chick down feathers to estimate mercury concentrations in eggs. Environmental Science and Technology 43:2166-2172.

Ackerman, JT, and CA Eagles-Smith. 2010. Accuracy of egg flotation throughout incubation to determine embryo age in shorebirds and terns. Condor, in press.

Eagles-Smith, CA, and JT Ackerman. 2009. Mercury-selenium effects on reproductive success of Forster's terns in San Francisco Bay. Administrative Report, U. S. Geological Survey, Western Ecological Research Center, Davis, CA; 26 pp.

Eagles-Smith, CA, and JT Ackerman. 2009. Rapid changes in small fish mercury concentrations: implications for wildlife risk and monitoring programs. Environmental Science and Technology 43:8658-8664.

Eagles-Smith CA, JT Ackerman, SW De La Cruz, JY Takekawa. 2009. Mercury bioaccumulation and risk to three waterbirds foraging guilds is influenced by foraging ecology and breeding stage. Environmental Pollution 157:1993-2002.

Evers DC, LJ Savoy, CR DeSorbo, DE Yates, W Hanson, KM Taylor, LS Siegel, JH Cooley, MS Bank, A Major, K Munney, BF Mower, HS Vogel, N Schoch, MM Pokras, WM Goodale, J Fair. 2008. Adverse effects from environmental mercury loads on breeding common loons. Ecotoxicology 17:69-81

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

Heinz GH, DJ Hoffman, JD Klimstra, KR Stebbins, SL Konrad, CA Erwin. 2009. Species

differences in the sensitivity of avian embryos to methylmercury. Archives of Environmental Contamination and Toxicology 56:129-138.

Hoyt DF. 1979. Practical methods of estimating volume and fresh weight of bird eggs. Auk 96:73-77.

Kennamer RA, JR Stout, BP Jackson, SV Colwell, IL Brisbin Jr., J Burger. 2005. Mercury patterns in wood duck eggs from a contaminated reservoir in South Carolina, USA. Environmental Toxicology and Chemistry 24:1793-1800.

RWQCB (California Regional Water Quality Control Board, San Francisco Bay Region), 2003. Mercury in San Francisco Bay, Total Maximum Daily Load (TMDL) Project Report. June 6, 2003. Available on the World Wide Web: (http://www.swrcb.ca.gov/rwqcb2/TMDL/SFBayMercury/SFBayMercuryTMDLProjectReport.pdf).

Stebbins, KR, JD Klimstra, CA Eagles-Smith, JT Ackerman, GH Heinz. 2009. Micro-sampling eggs to monitor the effects of methylmercury on wild birds. Environmental Toxicology and Chemistry 28:465-470.

Stickel LF, SN Wiemeyer, LJ Blus. 1973. Pesticide residue in eggs of wild birds: adjustments for loss of moisture and lipid. Bulletin of Environmental Contamination and Toxicology 9:193-196.