

## MERCURY CONCENTRATIONS IN BLOOD AND FEATHERS OF PREBREEDING FORSTER'S TERNS IN RELATION TO SPACE USE OF SAN FRANCISCO BAY, CALIFORNIA, USA, HABITATS

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**Abstract**—We examined mercury concentrations and space use of prebreeding Forster's terns (*Sterna forsteri*) in San Francisco Bay, California, USA, to assess factors influencing mercury levels in piscivorous birds. In 2005 and 2006, we collected blood and feathers from 122 Forster's terns and radio-marked and tracked 72 terns to determine locations of dietary mercury uptake. Capture site and capture date were the most important factors explaining variation in blood mercury concentrations (geometric mean  $\pm$  standard error:  $1.09 \pm 0.89$   $\mu\text{g/g}$  wet wt), followed by sex and year. Accordingly, radiotelemetry data revealed that Forster's terns generally remained near their site of capture and foraged in nearby salt ponds, managed and tidal marshes, and tidal flats. In contrast, capture site and capture date were not important factors explaining variation in feather mercury concentrations, probably because feathers were grown on their wintering grounds several months prior to our sampling. Instead, sex and year were the most important factors explaining mercury concentrations in breast feathers ( $9.57 \pm 8.23$   $\mu\text{g/g}$  fresh wt), and sex was the most important factor for head feathers ( $6.94 \pm 7.04$   $\mu\text{g/g}$  fresh wt). Overall, 13 and 22% of prebreeding Forster's terns were estimated to be at high risk for deleterious effects due to mercury concentrations in blood ( $>3.0$   $\mu\text{g/g}$  wet wt) and feathers ( $>20.0$   $\mu\text{g/g}$  fresh wt), respectively. Breeding terns are likely to be even more at risk because blood mercury concentrations more than tripled during the 45-d prebreeding time period. These data illustrate the importance of space use and tissue type in interpreting mercury concentrations in birds.

**Keywords**—Blood Mercury Telemetry Terns San Francisco Bay

### INTRODUCTION

Piscivorous birds are good indicators of mercury contamination and risk to wildlife in aquatic food webs because they forage at a high trophic level [1] and methylmercury biomagnifies through aquatic food chains [2]. Despite a large body of literature assessing waterbird exposure to mercury [2–5], few studies have simultaneously examined mercury concentrations and space use in birds. Instead, most studies have examined mercury contamination in birds at a regional or landscape scale [6,7], possibly because their mobility is presumed to be a key disadvantage of using birds as biomonitors [8]. However, many birds often show strong fidelity to foraging, roosting, and breeding sites [9,10], and therefore they can also be used to assess site-specific contamination at smaller spatial and temporal scales. The usefulness of birds as biomonitors to assess variation in local contamination will depend on adequately documenting their movement and foraging locations as well as sampling appropriate tissues that represent recent mercury accumulation.

Feathers are often used to measure mercury exposure because they are easily obtained and noninvasively sampled. Feather mercury represents blood mercury concentrations at

the time of feather growth and often is derived from mercury stored in body tissues [6,11,12]. Feathers are the major elimination pathway for methylmercury, and an adult bird's plumage can contain from 56 to 93% of the total body burden of mercury [6,13,14]. However, using feathers to monitor exposure can be problematic because mercury concentrations vary significantly among and within feather tracts and also depend on the timing of molt [11]. For example, feathers grown early during molt have higher mercury concentrations than feathers grown later, as the total body burden of mercury is reduced throughout the molting sequence [6,11]. Although using hatchling feathers is one way to assess recent mercury exposure, as are eggs [8,15,16], this limits sampling to only a short time period each year during the breeding season.

Mercury concentrations in blood, on the other hand, represent exposure at the time of sampling and are a dynamic equilibrium of recent dietary mercury uptake and internal tissue redistribution [17]. Mercury concentrations in blood are more highly correlated with mercury concentrations in internal tissues than are feathers (Ackerman et al., unpublished data). Almost all mercury in blood is methylmercury bound to red blood cells [5,18] and has a half-life of one to three months [19,20]. Therefore, blood may be the best tissue to estimate short-term mercury exposure in wild birds [5], and it can be sampled throughout the year in a nonlethal manner.

We examined blood and feather mercury concentrations in

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prebreeding Forster's terns (*Sterna forsteri*) at several sites in San Francisco Bay, USA, and simultaneously used radiotelemetry to assess space use and distribution of dietary mercury exposure. San Francisco Bay has a long history of mercury contamination from both mercury mining and gold extraction in its tributaries [21]. Methylmercury might become even more bioavailable within the estuary as current restoration plans will convert several thousand hectares of former salt evaporation ponds into tidal marsh [21]. Forster's terns are an ideal species to monitor mercury contamination in San Francisco Bay because they are piscivorous and forage at a high trophic level [22], nest at several sites throughout the estuary [23], and forage along the bay's margins within salt ponds and marshes where increased mercury methylation rates associated with habitat restoration may occur [21].

We used mercury concentrations in blood as our short-term index of mercury exposure and concentrations in head and breast feathers to represent past mercury exposure. Body feathers, especially breast feathers, typically have lower variability in mercury concentrations among individual feathers than other feather tracts and, therefore, are preferred as a tool for monitoring mercury concentrations [11]. We additionally examined mercury concentrations in head feathers because they are replaced during the late winter and early spring molt just before and during the prebreeding season [22]. We predicted that small-scale differences in mercury concentrations would be reflected in blood, such as site and date, whereas larger-scale differences would mainly be reflected in feathers, such as sex and year.

## MATERIALS AND METHODS

### *Study site*

We studied mercury concentrations in Forster's terns throughout the San Francisco Bay (37.8°N, 122.3°W; Fig. 1) at both the north and the south Bay regions where terns breed [23]. Currently, approximately 30% of the Pacific coast breeding population of Forster's terns nest within the San Francisco Bay Estuary [22] at 10 separate colonies [23]. In 2005 and 2006, we captured or collected Forster's terns at four main sites: the north San Francisco Bay (San Pablo Bay, Napa-Sonoma Marsh Wildlife Area ponds 2 and 3), the south-central San Francisco Bay at the Eden Landing Ecological Reserve (ponds B7 and B10), and the southernmost San Francisco Bay in the East Alviso salt pond complex of the Don Edwards San Francisco Bay National Wildlife Refuge (ponds A7, A8, A11, and A16 and New Chicago Marsh) or in the West Alviso salt pond complex of the Don Edwards San Francisco Bay National Wildlife Refuge (ponds A1, AB1, and AB2 and Charleston Slough; Fig. 1).

### *Bird captures and collections*

During the prebreeding season from April 7 to May 19, 2005, and April 18 to May 17, 2006, we captured Forster's terns with remotely detonated net launchers (Coda Enterprises, Mesa, AZ, USA) set at known roosting and (future) breeding sites, and we collected additional birds with a shotgun and steel shot while they were foraging as part of a larger study examining contaminant levels in San Francisco Bay birds. We captured, collected, and marked birds under California Department of Fish and Game scientific collection permits, federal U.S. Fish and Wildlife Service permits, and U.S. Geological Survey Bird Banding Laboratory permits, and we con-

ducted research under the guidelines of the U.S. Geological Survey, Western Ecological Research Center, Animal Care and Use Committee.

We collected whole blood from live birds via the brachial vein using heparinized 23- or 25-gauge needles. We restricted the volume of blood collected to <1% of the bird's body mass (<1.5 ml). From collected birds, we drew 1 to 5 ml of blood via cardiac puncture with a heparinized 23-gauge needle. Each bird was sampled only once for blood and feathers. We immediately transferred whole blood to polypropylene cryovials and stored it on dry ice in the field until we transferred it to the laboratory for storage at -20°C until analysis. We stored blood samples for less than six months prior to laboratory analysis (see the following discussion). We also collected a drop of unheparinized blood from each tern to determine their sex using genetic analysis (Zoogen Services, Davis, CA, USA) [24]. We confirmed the sex of collected specimens via necropsy. Additionally, we collected fully grown breast and head feathers from each bird and stored them in Whirl-paks® (Nasco, Modesto, CA, USA) until laboratory analysis.

### *Radiotelemetry*

We marked Forster's terns with a radio transmitter (Model A2470, Advanced Telemetry Systems, Isanti, MN, USA) attached to a metal leg band on their right tibia. Transmitters weighed 3.4 g in 2005 and 2.3 g in 2006 (<3% of bird body mass), had a 13-cm external whip antenna pointing downward, and had a battery life of four to six months. We held terns in shaded and screen-lined poultry cages (model 5KTC, Murray McMurray Hatchery, Webster City, IA, USA), and we released terns at the capture site within 3 h. We tracked radio-marked terns from trucks and fixed-wing aircraft equipped with dual four-element Yagi antenna systems (Advanced Telemetry Systems). Trucks had null-peak systems (AVM Instrument, Livermore, CA, USA) to accurately determine bearings, and aircraft had left-right systems (Advanced Telemetry Systems) to circle and pinpoint signals on either side of the plane. We located terns daily by truck and every two weeks by aircraft from their date of capture until May 20 of each year, when the prebreeding time period ended. For example, of 450 Forster's tern nests we monitored in San Francisco Bay, only 10% were initiated by May 17 in 2005 (J.T. Ackerman, unpublished data). We ensured complete tracking coverage throughout the south San Francisco Bay subregions by using fixed tracking routes through all the major salt ponds (including Alviso, Moffett, Newark, and Eden Landing ponds), marshes (New Chicago Marsh and Coyote Creek Lagoon), and south bay mudflats and bay margins. For each location by truck, we obtained two bearings within 15 min to minimize movement error and used triangulation program software (LOAS, Location of a Signal Ver. 3.0.1, Ecological Software Solutions, Urnäsch, Switzerland) to calculate universal transverse mercator coordinates and error polygon sizes for each location. Error polygons were calculated for each triangulation by assuming a constant variance (two standard deviations; LOAS). We determined the accuracy of our telemetry locations by placing 14 test transmitters throughout the study area and having different observers search for these additional frequencies without knowing the location of the test transmitters. We estimated that our telemetry locations were  $154 \pm 25$  m (standard error [SE]) from their true positions.

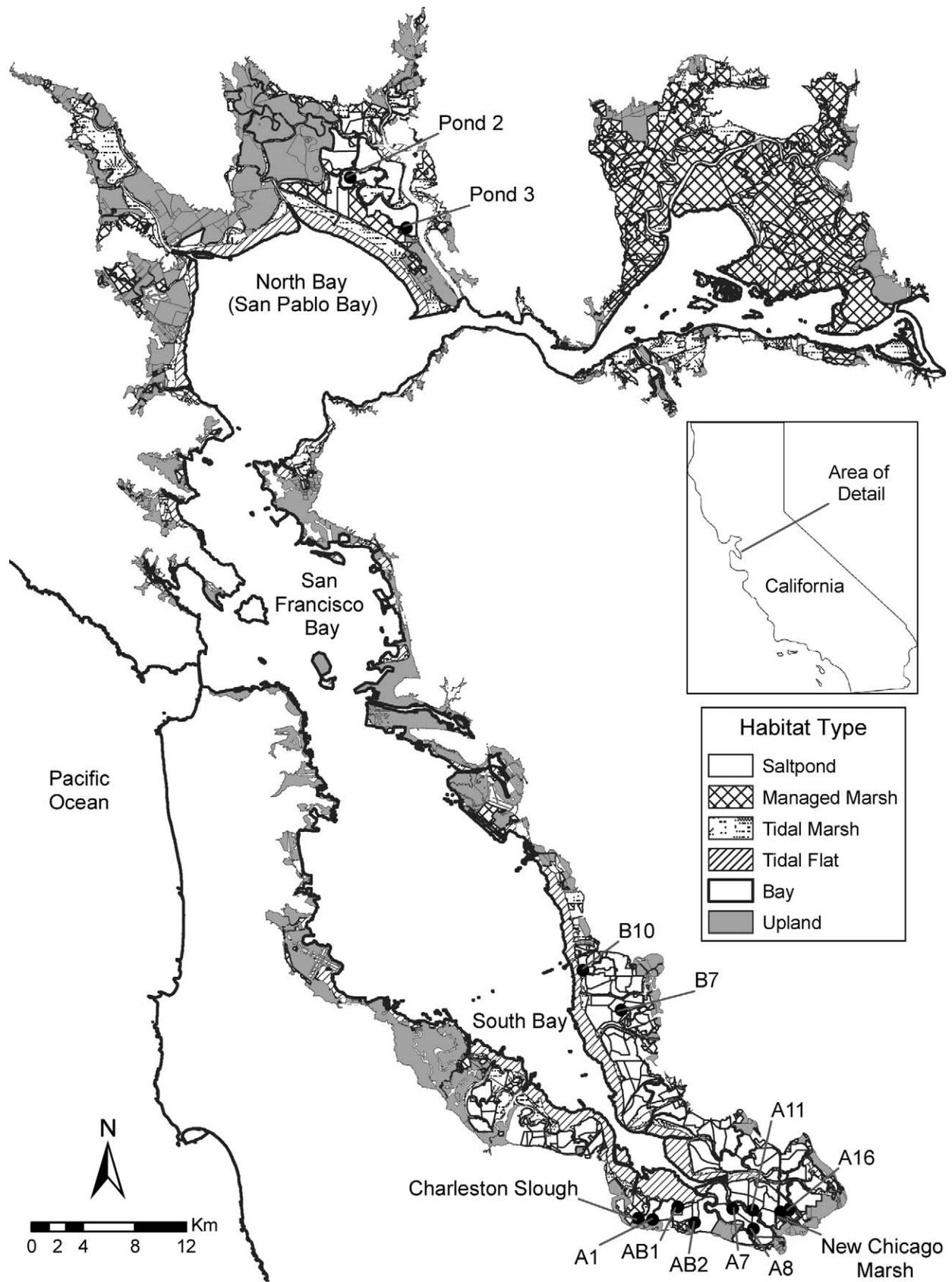


Fig. 1. Study area map of San Francisco Bay, California, USA, with Forster's tern capture sites and habitat types indicated. Terns were captured at four main sites: north San Francisco Bay (San Pablo Bay, Napa-Sonoma Marsh Wildlife Area ponds 2 and 3), south-central San Francisco Bay at the Eden Landing Ecological Reserve (ponds B7 and B10), and the southernmost San Francisco Bay in the East Alviso salt pond complex of Don Edwards San Francisco Bay National Wildlife Refuge (ponds A7, A8, A11, and A16 and New Chicago Marsh) or in the West Alviso salt pond complex of Don Edwards San Francisco Bay National Wildlife Refuge (ponds A1, AB1, and AB2 and Charleston Slough). Habitat types depicted include salt ponds, managed marshes, tidal marshes, tidal flats, uplands, and open bay.

Table 1. Ranking of candidate models describing mercury concentrations in prebreeding Forster's tern blood in the San Francisco Bay, California, USA, during 2005 and 2006. Models that have substantial support ( $\Delta\text{AICc} \leq 2.0$ ) are in italics

Model no.	Model structure	<i>n</i>	RSS <sup>a</sup>	<i>k</i> <sup>b</sup>	Log likelihood	AICc <sup>c</sup>	$\Delta\text{AICc}^d$	Akaike weight <sup>e</sup>
1	<i>Site + sex + year + date</i>	122	76.32	8	-28.62	-39.96	0.00	0.451
2	Site + sex + year	122	82.54	7	-23.84	-32.69	7.27	0.012
3	<i>Site + sex + date</i>	122	78.50	7	-26.90	-38.82	1.15	0.254
4	<i>Site + year + date</i>	122	79.10	7	-26.43	-37.88	2.08	0.159
5	Sex + year + date	122	86.57	5	-20.93	-31.33	8.63	0.006
6	Site + sex	122	84.67	6	-22.28	-31.83	8.13	0.008
7	Site + year	122	84.75	6	-22.22	-31.71	8.25	0.007
8	Site + date	122	81.30	6	-24.76	-36.78	3.18	0.092
9	Sex + year	122	98.77	4	-12.88	-17.42	22.54	0.000
10	Sex + date	122	90.41	4	-18.28	-28.22	11.74	0.001
11	Year + date	122	88.81	4	-19.37	-30.40	9.56	0.004
12	Site	122	86.91	5	-20.69	-30.86	9.11	0.005
13	Sex	122	102.98	3	-10.34	-14.47	25.49	0.000
14	Year	122	100.45	3	-11.86	-17.51	22.45	0.000
15	Date	122	92.67	3	-16.77	-27.34	12.62	0.001
16	Intercept + variance (null)	122	313.91	2	57.65	119.40	159.36	0.000

<sup>a</sup> Residual sum of squares from the analysis of covariance model.

<sup>b</sup> The number of estimated parameters in the model including the variance.

<sup>c</sup> Second-order Akaike's Information Criterion (AICc).

<sup>d</sup> The difference in the value between AICc of the current model and the value for the most parsimonious model.

<sup>e</sup> The likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0).

### Mercury determination

We analyzed all blood and feather samples for total mercury because previous research has demonstrated that >95% of the mercury in avian blood and feathers is methylmercury [5,18,25]. Most Forster's tern blood samples were elevated in mercury to such an extent that, in order to avoid saturating the atomic absorbance cells and carryover effects that are common with high concentrations [26], we diluted the blood sample by using a ratio of four parts deionized water to one part blood. We pipetted 200  $\mu\text{l}$  of diluted blood into a quartz sample vessel and weighed it (to the nearest 0.0001 g; Ohaus Adventurer Balance, model AR0640, Ohaus Corporation, Pine Brook, NJ, USA). For feathers, we washed each feather in a 1% Alconox solution (Alconox, White Plains, NY, USA) while mechanically scrubbing each feather to remove surface debris. We then dried feathers at 60°C for 24 to 48 h, weighed them to the nearest 0.0001 g (Mettler Toledo, Model AT201, Greifensee, Switzerland), and transferred each feather into a quartz sample vessel. Following U.S. Environmental Protection Agency method 7473 [27], we analyzed each blood or feather sample for total mercury at the U.S. Geological Survey, Davis Field Station Mercury Lab, on a Milestone DMA-80 direct mercury analyzer (Milestone, Monroe, CT, USA) using an integrated sequence of drying (160°C for 140 s), thermal decomposition (850°C for 240 s), catalytic conversion, and then amalgamation, followed by atomic absorption spectroscopy. Prior to analysis, we calibrated the analyzer with dilutions of a certified mercury standard solution (SPEX CertiPrep Metuchen, NJ, USA). Quality assurance measures included analysis of two certified reference materials (either dogfish muscle tissue [DORM-2], dogfish liver [DOLT-3], or lobster heptopancreas [TORT-2]; National Research Council of Canada, Ottawa, ON, Canada), two system and method blanks, two duplicates, one matrix spike, and one matrix spike duplicate per batch. Recoveries averaged  $103.8 \pm 1.7\%$  ( $n = 82$ ) and  $100.5 \pm 1.7\%$  ( $n = 133$ ) for certified reference materials and calibration checks, respectively. Matrix spike recoveries averaged  $100.4 \pm 3.8\%$  ( $n = 34$ ) and  $100.9 \pm 1.5\%$  ( $n = 42$ )

for feathers and blood, respectively. Absolute relative percent difference for all duplicates and matrix spike duplicates averaged 8.6% for feathers and 3.5% for blood.

### Statistical analysis

We examined variation in mercury concentrations among prebreeding terns using Akaike's Information Criterion (AIC) and selected the best model from an a priori set of candidate models. This approach often performs better than restricting the selected model to those variables with statistically significant effects in hypothesis-based tests, especially for observational data [28]. We built a set of 15 candidate models based on potential effects of capture site, Julian capture date, sex, and year and included a 16th null model (intercept and variance only) with no effects (Tables 1 to 3). We calculated values used in AIC analysis for each candidate model using analysis of variance or analysis of covariance with JMP® Version 4.0.4 [29]. We log<sub>e</sub>-transformed mercury concentrations (wet wt for blood and fresh wt for feathers) to improve normality and reported geometric means  $\pm$  SE based on back-transformed least-squares means  $\pm$  SE in the text for clarity.

We used a second-order AIC (AICc) and considered the model with the smallest AICc to be the most parsimonious [28]. We used the AICc differences between the best model and the other candidate models ( $\Delta\text{AICc}_i = \text{AICc}_i - \text{minimum AICc}$ ) to determine the relative ranking of each model. We considered candidate models for biological importance when  $\Delta\text{AICc}_i \leq 2.0$  [28]. We calculated Akaike weights ( $w_i = \exp[-\Delta\text{AICc}_i/2] / \sum \exp[-\Delta\text{AICc}_i/2]$ ) to assess the weight-evidence that the selected model was actually the best model in the set of models considered [28]. We also calculated variable weights by summing Akaike weights across models that incorporated the same variable to assess the relative importance of each variable.

We used radiotelemetry to examine space use by Forster's terns to better understand differences in mercury exposure among capture sites. To assess whether terns captured at specific sites remained within the local area or foraged elsewhere,

Table 2. Ranking of candidate models describing mercury concentrations in prebreeding Forster's tern breast feathers in the San Francisco Bay, California, USA, during 2005 and 2006. Models that have substantial support ( $\Delta\text{AICc} \leq 2.0$ ) are in italics

Model no.	Model structure	<i>n</i>	RSS <sup>a</sup>	<i>k</i> <sup>b</sup>	Log likelihood	AICc <sup>c</sup>	$\Delta\text{AICc}^d$	Akaike weight <sup>e</sup>
1	Site + sex + year + date	121	84.36	8	-21.82	-26.36	6.13	0.022
2	Site + sex + year	121	84.39	7	-21.80	-28.61	3.88	0.069
3	Site + sex + date	121	88.65	7	-18.82	-22.65	9.83	0.004
4	Site + year + date	121	90.79	7	-17.37	-19.76	12.73	0.001
5	<i>Sex + year + date</i>	<i>121</i>	<i>85.59</i>	<i>5</i>	<i>-20.94</i>	<i>-31.37</i>	<i>1.12</i>	<i>0.274</i>
6	Site + sex	121	88.66	6	-18.82	-24.90	7.59	0.011
7	Site + year	121	91.00	6	-17.24	-21.74	10.75	0.002
8	Site + date	121	95.31	6	-14.44	-16.14	16.35	0.000
9	<i>Sex + year</i>	<i>121</i>	<i>86.34</i>	<i>4</i>	<i>-20.42</i>	<i>-32.49</i>	<i>0.00</i>	<i>0.481</i>
10	Sex + date	121	89.90	4	-17.97	-27.60	4.89	0.042
11	Year + date	121	92.19	4	-16.45	-24.56	7.93	0.009
12	Site	121	95.45	5	-14.35	-18.18	14.31	0.000
13	Sex	121	90.85	3	-17.34	-28.47	4.02	0.064
14	Year	121	92.99	3	-15.93	-25.65	6.84	0.016
15	Date	121	96.70	3	-13.56	-20.92	11.57	0.001
16	Intercept + variance (null)	121	97.54	2	-13.04	-21.98	10.51	0.003

<sup>a</sup> Residual sum of squares from the analysis of covariance model.

<sup>b</sup> The number of estimated parameters in the model including the variance.

<sup>c</sup> Second-order Akaike's Information Criterion (AICc).

<sup>d</sup> The difference in the value between AICc of the current model and the value for the most parsimonious model.

<sup>e</sup> The likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0).

we calculated the population range of prebreeding terns for each site by using all telemetry locations from terns that were captured in a specific area each year (either West Alviso, East Alviso, or Eden Landing). We defined population range size for each site as the size of the overall distribution of radio-marked terns originating from that capture site [30]. We used only those locations that were separated by >1 h to reduce any potential autocorrelation among locations, and most locations (90%) were separated by >3 h. We also excluded any locations with error-polygon sizes >5 ha. We estimated the size of radio-marked terns' population range and core use area in ArcGIS Version 9.1 (ESRI, Redlands, CA, USA) using Animal Space Use Version Beta 1.1 [31]. We used the fixed-kernel method with the cross-validation smoothing parameter

selection [31] to calculate 50% (hereafter core use area) and 95% (hereafter population range size) utilization distributions.

We then overlaid Bay Area EcoAtlas habitat coverages Version 1.50b [32] on terns' 50 and 95% utilization distributions and quantified the proportion of habitat types used by each group of terns. Habitat types were categorized as salt ponds (active and former salt evaporation ponds), managed marshes (diked marshes, managed marshes, and baylands), tidal marshes (high-, mid-, and low-elevation tidal marshes and muted tidal marshes), tidal flats (tidal flats and channel flats), bay (shallow-water bay and deep-water bay), sloughs (sloughs and major channels), lagoons (lagoons and storage treatment ponds), and uplands (developed and undeveloped fill, farmed and grazed baylands, and urban uplands).

Table 3. Ranking of candidate models describing mercury concentrations in prebreeding Forster's tern head feathers in the San Francisco Bay, California, USA, during 2005 and 2006. Models that have substantial support ( $\Delta\text{AICc} \leq 2.0$ ) are in italics

Model no.	Model structure	<i>n</i>	RSS <sup>a</sup>	<i>k</i> <sup>b</sup>	Log likelihood	AICc <sup>c</sup>	$\Delta\text{AICc}^d$	Akaike weight <sup>e</sup>
1	Site + sex + year + date	122	118.34	8	-1.86	13.56	7.33	0.010
2	Site + sex + year	122	118.92	7	-1.56	11.86	5.63	0.023
3	Site + sex + date	122	118.57	7	-1.74	11.50	5.27	0.028
4	Site + year + date	122	128.27	7	3.05	21.09	14.86	0.000
5	Sex + year + date	122	120.65	5	-0.68	9.16	2.93	0.090
6	Site + sex	122	119.13	6	-1.45	9.82	3.59	0.064
7	Site + year	122	129.27	6	3.53	19.79	13.56	0.000
8	Site + date	122	128.63	6	3.23	19.18	12.95	0.001
9	<i>Sex + year</i>	<i>122</i>	<i>121.63</i>	<i>4</i>	<i>-0.18</i>	<i>7.97</i>	<i>1.74</i>	<i>0.162</i>
10	<i>Sex + date</i>	<i>122</i>	<i>121.08</i>	<i>4</i>	<i>-0.46</i>	<i>7.42</i>	<i>1.19</i>	<i>0.214</i>
11	Year + date	122	130.43	4	4.07	16.49	10.26	0.002
12	Site	122	129.60	5	3.69	17.89	11.66	0.001
13	Sex	122	122.03	3	0.01	6.23	0.00	0.388
14	Year	122	131.94	3	4.78	15.75	9.52	0.003
15	Date	122	131.07	3	4.37	14.95	8.72	0.005
16	Intercept + variance (null)	122	132.48	2	5.03	14.15	7.92	0.007

<sup>a</sup> Residual sum of squares from the analysis of covariance model.

<sup>b</sup> The number of estimated parameters in the model including the variance.

<sup>c</sup> Second-order Akaike's Information Criterion (AICc).

<sup>d</sup> The difference in the value between AICc of the current model and the value for the most parsimonious model.

<sup>e</sup> The likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0).

## RESULTS

We captured or collected 130 Forster's terns during the prebreeding seasons in 2005 and 2006. Of these, we were able to collect a sufficient sample of blood and feathers from 122 terns. Overall, geometric mean mercury concentrations for Forster's terns in San Francisco Bay were  $1.09 \pm 0.89 \mu\text{g/g}$  wet wt for blood,  $9.57 \pm 8.23 \mu\text{g/g}$  fresh wt for breast feathers, and  $6.94 \pm 7.04 \mu\text{g/g}$  fresh wt for head feathers. Although total mercury concentrations in blood, breast feathers, and head feathers were correlated (linear regressions: blood vs breast feathers:  $r^2 = 0.26$ ,  $p < 0.0001$ ; blood vs head feathers:  $r^2 = 0.30$ ,  $p < 0.0001$ ; head feathers vs breast feathers:  $r^2 = 0.76$ ,  $p < 0.0001$ ), we found that factors influencing mercury concentrations differed among tissue types (see the following discussion).

*Mercury in blood*

Using blood as our matrix for short-term mercury exposure, we found that the most parsimonious model explaining differences in mercury concentrations among terns contained capture site, capture date, sex, and year and had an Akaike weight of 0.45 (Table 1). Three other models containing capture site and capture date—or these two variables with either sex or year—also provided a reasonably good fit to the data. Using evidence ratios, the full model was 1.8 times more likely than the next best model containing capture site, capture date, and sex and 2.8 times more likely than the third best model containing capture site, capture date, and year. Models containing the variables capture site and capture date had a combined AIC weight of 96%, indicating their overriding importance for explaining differences in blood mercury concentrations among birds.

We used variable weights to assess the order of importance for each variable and found that capture site (99%) and capture date (97%) were the most important followed by sex (73%) and year (64%). We also qualified the relative importance of the variables using evidence ratios by removing each variable in a stepwise fashion from the best model and comparing their Akaike weights (i.e., we compared Akaike weights of model number 5 to 2, 5 to 4, and 5 to 3; Table 1). Using this procedure, capture site was two times more important than capture date, 26.5 times more important than sex, and 42.2 times more important than year. These data indicate that capture site and capture date contained the most information but that sex and year also contained some useful information about variation in mercury concentrations in tern blood.

Mercury concentrations in Forster's tern blood were highest in the extreme south San Francisco Bay at East Alviso ( $1.66 \pm 0.22 \mu\text{g/g}$  wet wt), followed by north San Francisco Bay ( $0.97 \pm 0.17 \mu\text{g/g}$  wet wt), south San Francisco Bay at West Alviso ( $0.91 \pm 0.12 \mu\text{g/g}$  wet wt), and south-central San Francisco Bay at Eden Landing Ecological Reserve ( $0.77 \pm 0.14 \mu\text{g/g}$  wet wt; Fig. 2a). Mercury concentrations also increased with capture date (Fig. 2b); using the best model, we estimated that blood mercury concentrations increased by  $207 \pm 112\%$  during the 45-d prebreeding time period. Male terns ( $1.20 \pm 0.13 \mu\text{g/g}$  wet wt) had higher mercury concentrations than females ( $0.88 \pm 0.10 \mu\text{g/g}$  wet wt), and concentrations in 2005 ( $1.18 \pm 0.13 \mu\text{g/g}$  wet wt) were generally higher than in 2006 ( $0.90 \pm 0.10 \mu\text{g/g}$  wet wt).

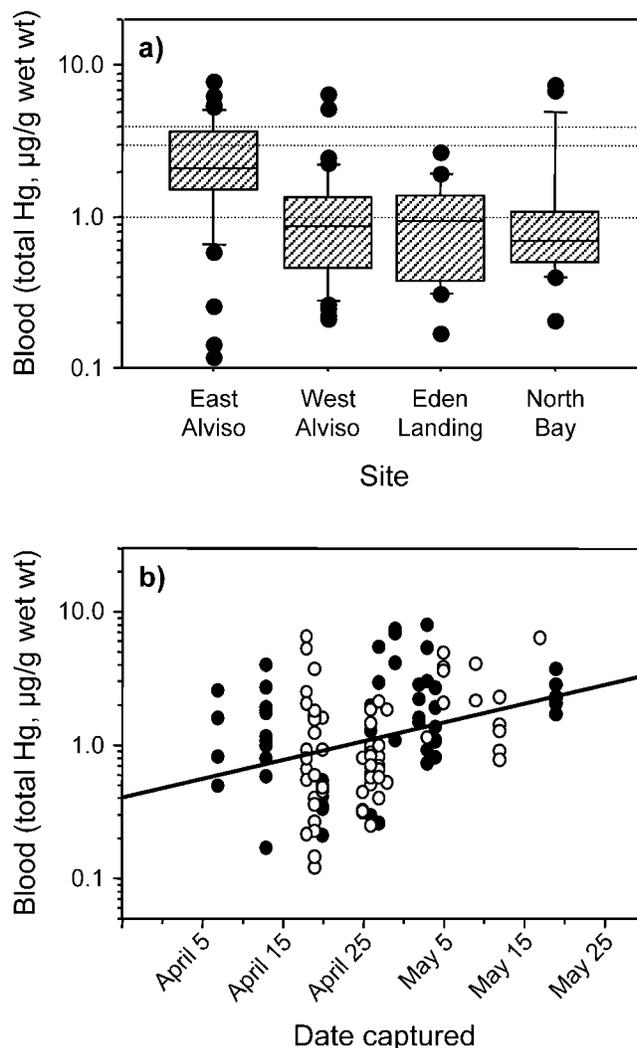


Fig. 2. Total mercury concentrations ( $\mu\text{g/g}$  wet wt) in blood of Forster's terns (a) differed among sites and (b) increased with capture date in San Francisco Bay, California, USA, during spring 2005 and 2006. Sample sizes were (a) 40 in East Alviso, 40 in West Alviso, 20 in Eden Landing Ecological Reserve, and 22 in North Bay and (b) 58 in 2005 (●) and 65 in 2006 (○). Dashed lines represent levels of risk to birds, including moderate risk ( $>1.0 \mu\text{g/g}$  wet wt), high risk ( $>3.0 \mu\text{g/g}$  wet wt), and extra-high risk ( $>4.0 \mu\text{g/g}$  wet wt), that have been associated with deleterious effects in other species [47].

*Mercury in feathers*

Next, we ran separate analyses for mercury concentrations in both breast and head feathers. Unlike mercury concentrations in blood, we found that the most parsimonious models explaining differences in mercury concentrations among feathers did not contain capture site or date. Instead, the most parsimonious model for mercury concentrations in breast feathers contained only sex and year and had an Akaike weight of 0.48 (Table 2). The next best model contained these two variables and capture date. However, the log-likelihood values for these competing models were very similar ( $-20.42$  and  $-20.94$ ), indicating that the addition of the capture date variable neither improved nor hurt the fit of the best model. Models containing the variables sex and year had a combined AIC weight of 85%.

Using variable weights, we found that sex (97%) was the most important variable explaining differences in mercury concentrations among breast feathers, followed by year (88%). Mercury concentrations in breast feathers of male terns ( $12.42$

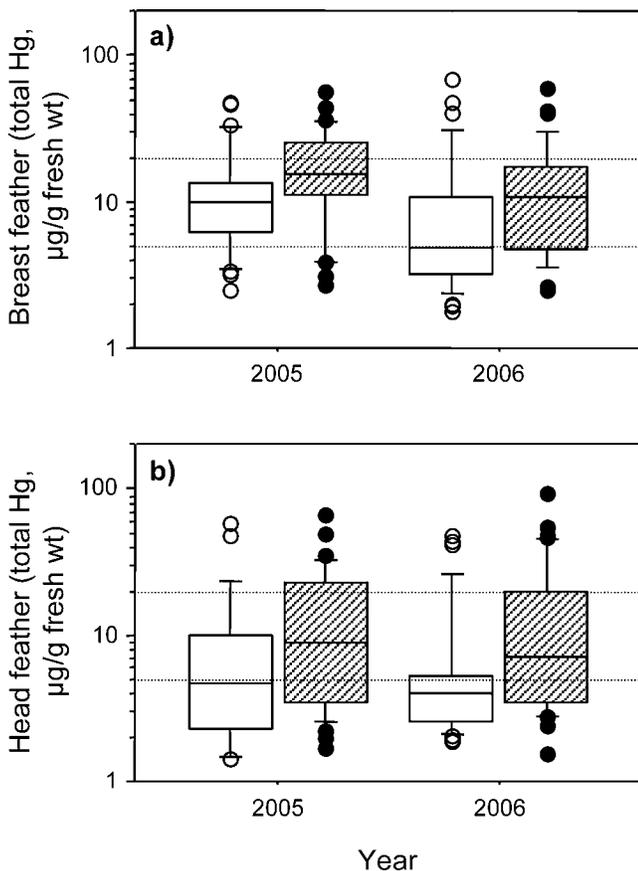


Fig. 3. Total mercury concentrations ( $\mu\text{g/g}$  fresh wt) in (a) breast and (b) head feathers of male (●) and female (○) Forster's terns in San Francisco Bay, California, USA, during 2005 and 2006. Dashed lines through box plots at 5 and 20  $\mu\text{g/g}$  fresh wt represent levels associated with deleterious effects in other species of birds [following 8,47–49]. Sample sizes were 26 (a) and 24 (b) females and 28 (a) and 30 (b) males in 2005 and 33 (a) and 33 (b) females and 35 (a) and 36 (b) males in 2006.

$\pm 1.39 \mu\text{g/g}$  fresh wt) were higher than in females ( $7.79 \pm 0.91 \mu\text{g/g}$  fresh wt), and concentrations in 2005 ( $11.98 \pm 1.44 \mu\text{g/g}$  fresh wt) were generally higher than in 2006 ( $8.08 \pm 0.91 \mu\text{g/g}$  fresh wt; Fig. 3a). Capture date (35%) and capture site (11%) variable weights verified that they contained little information about differences in breast-feather mercury concentrations. By removing each variable in a stepwise fashion from the best model and comparing their Akaike weights (i.e., we compared Akaike weights of model number 13 to 14; Table 2), we found that sex was 4.1 times more important than year.

Similar to mercury concentrations in breast feathers, we also found that capture site and date contained little information that helped explain mercury concentrations in head feathers. Instead, the most parsimonious model explaining mercury concentrations in head feathers contained only sex and had an Akaike weight of 0.39 (Table 3). Two other models provided a reasonably good fit to the data, including models containing sex and capture date, and sex and year. Again, the log-likelihood values for these competing models were very similar ( $-0.46$ – $0.01$ ), indicating that the addition of the capture date or year variables neither improved nor hurt the fit of the best model. Models containing sex had a combined AIC weight of 98%, indicating sex's overriding importance for explaining differences in mercury concentrations in head feathers. Mercury concentrations in head feathers of male terns

( $9.35 \pm 1.20 \mu\text{g/g}$  fresh wt) were higher than in females ( $5.27 \pm 0.73 \mu\text{g/g}$  fresh wt; Fig. 3b).

#### Radiotelemetry and space use

To understand capture site differences in blood mercury concentrations, we radio-marked and tracked 72 Forster's terns and obtained 1,012 telemetry locations. We used 899 locations in analyses after omitting locations with error polygon sizes  $>5$  ha (9%) and locations  $<1$  h apart (3%). Radio-marked terns generally remained within the area where they were captured, although there was some overlap between terns captured at East Alviso and Eden Landing in 2005 (Fig. 4) and East Alviso and West Alviso terns in 2006 (Fig. 5). For example, 37 to 87% of Forster's tern core use areas were within the pond site of capture, depending on the specific site and year (Table 4). We also used the average distance terns traveled between the capture site and subsequent telemetry locations to assess site fidelity. On average, tern locations were 2.4 (2005) and 2.2 km (2006) from their capture site at East Alviso, 2.3 (2005) and 5.0 km (2006) at West Alviso, and 7.7 km (2005) at Eden Landing. Terns utilized mainly salt ponds, managed and tidal marshes, and tidal flats and were relatively absent from bays, sloughs, and lagoons (Table 4).

#### DISCUSSION

Factors explaining mercury concentrations in Forster's terns differed among tissue types, with smaller-scale patterns being best explained by concentrations in blood. Capture site and capture date were by far the most important variables influencing blood mercury concentrations of prebreeding Forster's terns, but sex and year also influenced blood concentrations to a smaller degree. In particular, mercury concentrations in blood differed among capture sites (Fig. 2a). Using radiotelemetry, we found that terns were located mainly near their region of capture during the prebreeding season (Figs. 4 and 5), indicating that differences in tern mercury concentrations among capture sites may have been partly due to differences in foraging areas and locations of dietary mercury uptake. Terns mainly were located within salt ponds, followed by managed marshes, tidal marshes, and tidal flats, and were relatively absent from open bay habitats.

Forster's terns captured within the southernmost San Francisco Bay had the highest blood mercury concentrations, especially within the East Alviso salt pond complex of the Don Edwards San Francisco Bay National Wildlife Refuge. We also have found the highest blood mercury concentrations in black-necked stilts (*Himantopus mexicanus*) and American avocets (*Recurvirostra americana*) within the East Alviso ponds [33]. This area is known to have high levels of mercury derived from contaminated sediments because it is the discharge point for Alviso Slough and the Guadalupe River watershed, which contains the historic New Almaden mercury mine [34]. The East Alviso pond area has at least four separate breeding colonies of terns (in ponds A7, A8, and A16 and New Chicago Marsh) and, depending on the year, holds many of the breeding Forster's terns in the San Francisco Bay [23]. For example, 32 and 22% of all Forster's terns breeding in the San Francisco Bay nested within East Alviso in 2005 and 2006, respectively (C. Strong, San Francisco Bay Bird Observatory, Milpitas, CA, USA, unpublished data). Therefore, a large number of breeding terns are nesting in areas that have the highest potential for exposure to mercury.

Capture date also had an important influence on blood mer-

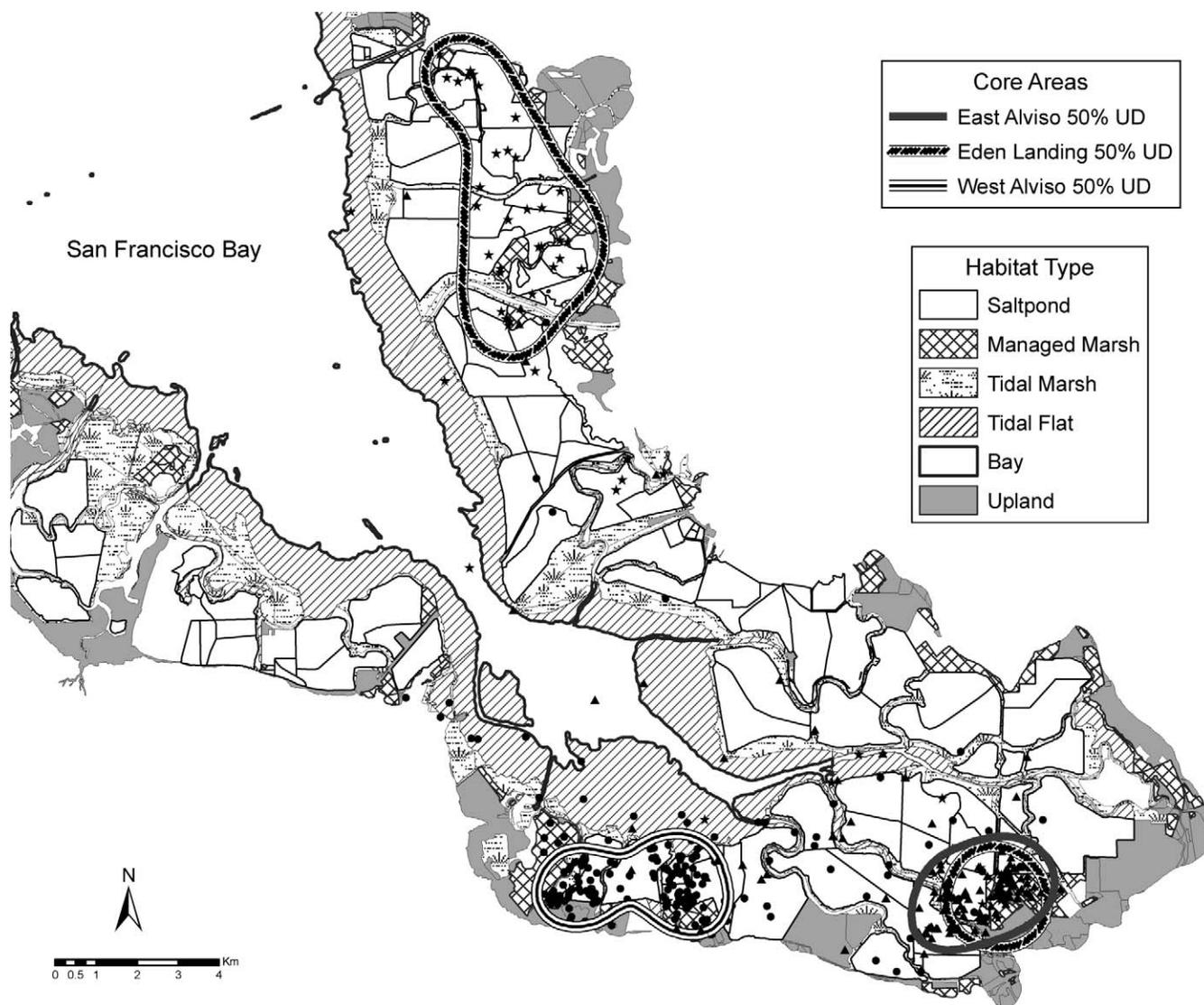


Fig. 4. Core use areas (50% utilization distributions [UD]) and telemetry locations of Forster's terns radio-marked within West Alviso (●,  $n = 206$ ), East Alviso (▲,  $n = 141$ ), and Eden Landing Ecological Reserve (★,  $n = 62$ ) sites in south San Francisco Bay, California, USA, during spring 2005. Habitat types depicted include salt ponds, managed marshes, tidal marshes, tidal flats, uplands, and open bay.

cury concentrations. Although some Forster's terns overwinter in San Francisco Bay [22], monthly bird surveys (2002–2006) within salt ponds along the bay's margins indicate that tern abundance is relatively low during winter (October–March) when compared to the breeding season (April–September; J.Y. Takekawa, U.S. Geological Survey, Vallejo, CA, USA). These data suggest that many terns overwinter outside San Francisco Bay. If this holds true in the open bay as well, then Forster's terns arriving in San Francisco Bay in late March to early April are exposed to potentially elevated mercury levels for about a month and a half before breeding begins in mid-May. We estimated that Forster's tern blood mercury concentrations more than tripled during the 45-d prebreeding period from the time of their arrival in San Francisco Bay to nest initiation. Thus, breeding Forster's terns may have even higher mercury concentrations than those we observed during prebreeding.

Tissue type should be considered when identifying which factors influence contaminant exposure. Mercury concentrations in blood represent both recent dietary uptake and internal tissue redistribution [17] and are thought to indicate relatively short-term mercury exposure in wild birds [5]. In contrast,

mercury concentrations in feathers represent the amount of mercury in the blood at the time of feather growth and are therefore dependent on the timing of the most recent molt [6,11,12]. We examined breast and head feathers because variation in mercury concentrations among individual feathers in these areas is smaller than in other feather types [11]. Although molt cycles for different feather tracts in Forster's terns are not entirely understood, it is thought that adults undergo a definitive prealternate molt during January through April, at which time they replace their breast and head feathers [22]. Therefore, mercury concentrations in breast and head feathers most likely represents mercury accumulated during late winter and early spring, when they may still be overwintering outside San Francisco Bay. In accordance with the timing of feather molt, we found no influence of capture site or capture date on mercury concentrations in feathers. Instead, sex and year were the most important factors for breast feathers, and sex was the single most important factor explaining variation in mercury concentrations among head feathers. These data illustrate the importance of tissue type when interpreting mercury concentrations in birds.

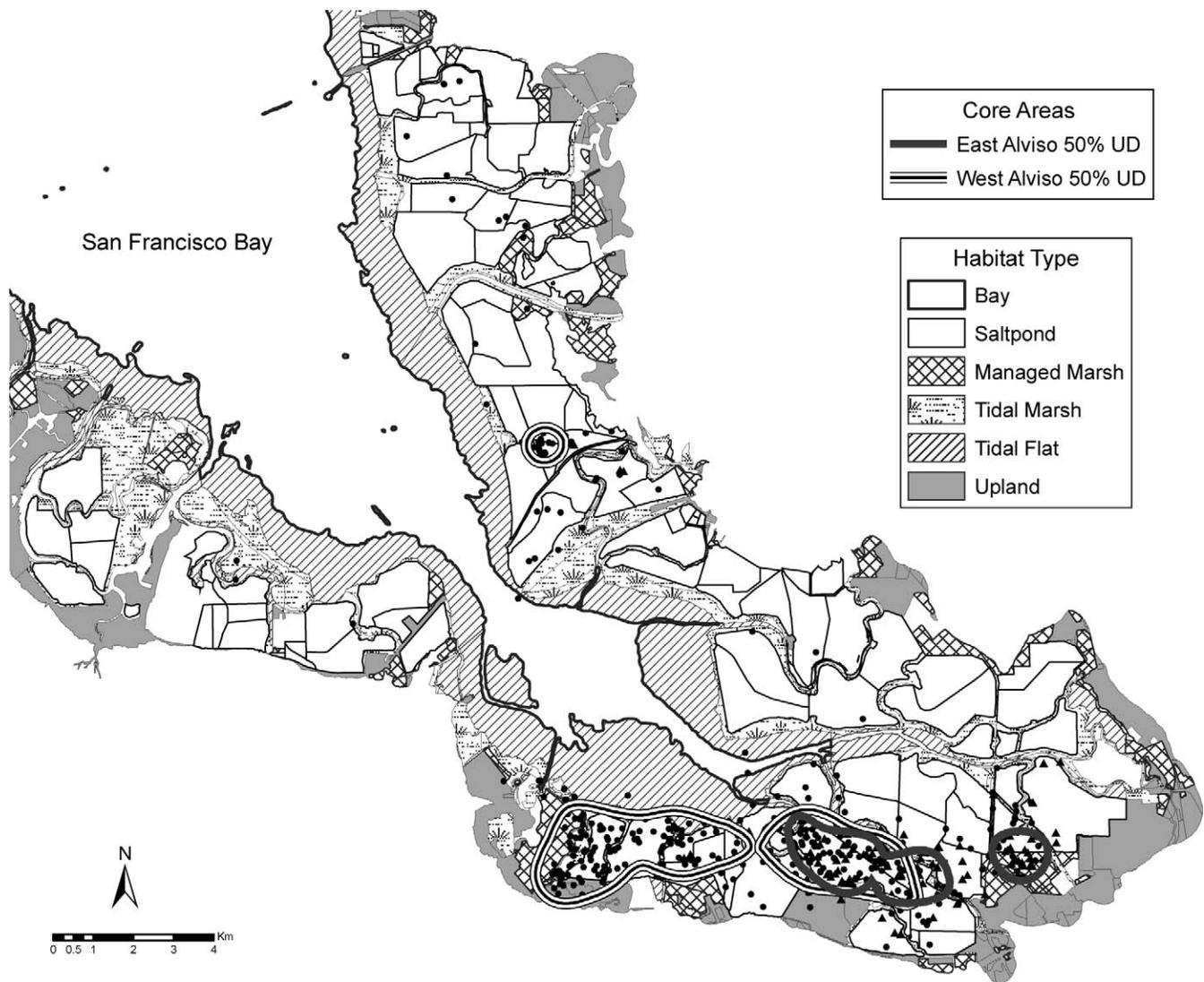


Fig. 5. Core use areas (50% utilization distributions [UD]) and telemetry locations of Forster's terns radio-marked within West Alviso (●,  $n = 360$ ) and East Alviso (▲,  $n = 111$ ) sites in south San Francisco Bay, California, USA, during spring 2006. Habitat types depicted include salt ponds, managed marshes, tidal marshes, tidal flats, uplands, and open bay.

Mercury concentrations in blood, and especially in feathers, were higher in male than in female Forster's terns (Fig. 3). Overall, mercury concentrations in males were 1.4, 1.6, and 1.8 times higher than females for blood, breast feathers, and head feathers, respectively. Males typically have higher mercury concentrations than females during the breeding season, indicating mercury depuration into eggs [6,14,35–37]. In contrast, mercury concentrations are generally not found to differ between sexes when tissues representing accumulation during the nonbreeding season are analyzed [38–40]. Because we used several tissues representing different prebreeding time frames, it is unlikely that mercury depuration into eggs by females could be the sole explanation for the sex differences we observed. Several authors have suggested that males have higher mercury burdens than females because they are larger and, therefore, consume more and larger prey [5,36,37]. However, in our case, there is no sexual size dimorphism in body mass for Forster's terns [24]. Hence, it is unclear why we found sex differences in mercury concentrations of prebreeding Forster's terns.

Geometric mean mercury concentrations for prebreeding

Forster's terns in San Francisco Bay were  $9.6 \mu\text{g/g}$  fresh wt for breast feathers,  $6.9 \mu\text{g/g}$  fresh wt for head feathers, and  $1.1 \mu\text{g/g}$  wet wt for blood. These feather concentrations are, in general, higher than levels reported for several waterbird species studied throughout the world [8,11,25] but lower than those of common loons (*Gavia immer*) in North America [35–37,41]. For example, average mercury concentrations in common tern (*Sterna hirundo*) feathers were  $2.3 \mu\text{g/g}$  fresh wt in the mid-North Atlantic Ocean [7],  $2.5 \mu\text{g/g}$  fresh wt in Massachusetts [42], and  $5.0 \mu\text{g/g}$  fresh wt in New York [43]. Unfortunately, we are aware of no other studies that have examined mercury concentrations in blood or feathers of adult Forster's terns for comparison.

San Francisco Bay has a legacy of mercury contamination from both mercury mining and gold extraction [21], and methylmercury levels within the estuary are thought to impair avian reproduction [44]. Blood mercury concentrations in Forster's terns were similar to black-necked stilts and higher than American avocets sampled during the same time period and at similar sites within San Francisco Bay [33]. We might expect Forster's tern mercury concentrations to be higher than stilts

Table 4. Population range sizes and percent use of habitat types within 50 and 95% utilization distributions (UD) of prebreeding Forster's terns radio-marked at each site during spring 2005 and 2006 in the San Francisco Bay, California, USA

Site	No. radio-marked birds	No. telemetry locations	Population range size (ha)	Percentage of UD within capture site	Habitat type <sup>a</sup>							
					Salt pond	Managed marsh	Tidal marsh	Tidal flat	Bay	Slough	Lagoon	Upland
2005												
Forster's terns: 50% UD												
East Alviso	12	141	7,373	41%	61%	22%	6%	2%	0%	0%	0%	9%
West Alviso	13	206	8,270	65%	54%	17%	10%	6%	0%	0%	2%	11%
Eden Landing	6	62	23,300	87%	70%	16%	5%	0%	0%	1%	0%	8%
Forster's terns: 95% UD												
East Alviso	12	141	32,829	34%	57%	6%	8%	2%	0%	2%	4%	21%
West Alviso	13	206	63,051	13%	47%	9%	9%	20%	2%	1%	2%	12%
Eden Landing	6	62	128,251	16%	47%	8%	9%	11%	6%	2%	2%	21%
2006												
Forster's terns: 50% UD												
East Alviso	10	111	6,294	37%	73%	12%	10%	2%	0%	3%	0%	0%
West Alviso	22	360	14,643	42%	67%	8%	12%	5%	0%	2%	2%	4%
Forster's terns: 95% UD												
East Alviso	10	111	25,820	44%	72%	8%	11%	2%	0%	2%	5%	0%
West Alviso	22	360	80,396	10%	55%	8%	11%	12%	2%	1%	3%	10%

<sup>a</sup> Similar habitat types are grouped into categories as follows: salt ponds (includes active and inactive salt evaporation ponds), managed marshes (includes diked marshes, managed marshes, baylands, and ruderal baylands), tidal marshes (includes high-, mid-, and low-elevation tidal marshes and muted tidal marshes), tidal flats (includes tidal flats and channel flats), bay (includes shallow-water bay and deep-water bay), sloughs (includes major channels), lagoons (includes lagoons and storage treatment ponds), and uplands (includes developed and undeveloped fill, farmed and grazed baylands, and urban uplands). Geographic information system habitat coverages are from the Bay Area EcoAtlas [32].

because they are piscivorous [22] and forage at a higher trophic level than stilts, which forage mainly on aquatic invertebrates [45]. However, unlike many Forster's terns, stilts and avocets overwinter within San Francisco Bay [46] and therefore are exposed to high mercury levels that are prevalent throughout the estuary for a longer period of time. Accordingly, capture date was not an important factor describing variation in blood mercury concentrations in prebreeding stilts or avocets [33] like it was for Forster's terns in San Francisco Bay. Instead, it appears that Forster's terns arrive in San Francisco Bay with relatively lower mercury concentrations and then rapidly accumulate mercury prior to and during breeding (Fig. 2b).

To estimate the proportion of Forster's terns at risk for impaired reproduction and other deleterious effects due to mercury contamination, we used previously developed toxicity categories based on other bird species. For blood, we categorized risk based on a hazard assessment established for common loons [47], whereas feather thresholds were established with several species [8,47–49]. Although sensitivity to methylmercury toxicity is known to vary among species [2,3], these data are the best available to establish risk categories in wild bird blood and feathers. Applying these risk categories to our data, 50% of Forster's terns were considered to be at or above moderate risk (>1.0 µg/g wet wt [47]), 13% were at or above high risk (>3.0 µg/g wet wt [47]), and 9% were at extra-high risk (>4.0 µg/g wet wt [47]) for potentially impaired reproduction due to their blood mercury concentrations. For breast feathers, 69 and 22% of Forster's terns exceeded 5 [8,49] and 20 µg/g fresh wt [47,48], respectively, which have been associated with deleterious effects in other birds. Similarly, 50 and 22% of head feather mercury concentrations exceeded these exposure levels, respectively. We sampled prebreeding

Forster's terns only, but they were still accumulating mercury at the beginning of the breeding season when the present study ended (mid-May; Fig. 2b). Based on blood mercury accumulation rates, it is likely that mercury concentrations in breeding terns were even higher than prebreeding terns since the nesting season continued for more than two additional months [50]. Consequently, a substantial portion of Forster's Terns breeding in San Francisco Bay may be at risk from mercury exposure, and future research should focus on examining whether mercury is impairing reproductive success.

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