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ScienceDirect
Science of the Total Environment 384 (2007) 452–466
Science of the Total Environment
An International Journal for Scientific Research into the Environment and its Relationship with Humankind
www.elsevier.com/locate/scitotenv

Mercury concentrations and space use of pre-breeding American avocets and black-necked stilts in San Francisco Bay

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Received 13 February 2007; received in revised form 27 March 2007; accepted 10 April 2007
Available online 27 June 2007

Abstract

We examined factors influencing mercury concentrations in pre-breeding American avocets (*Recurvirostra americana*) and black-necked stilts (*Himantopus mexicanus*), the two most abundant breeding shorebirds in San Francisco Bay, California. We tested the effects of species, site, sex, year, and date on total mercury concentrations in blood of pre-breeding adult birds and used radio telemetry to determine space use and sites of dietary mercury exposure. We collected blood from 373 avocets and 157 stilts from February to April in 2005 and 2006, radio-marked and tracked 115 avocets and 94 stilts, and obtained 2393 avocet and 1928 stilt telemetry locations. Capture site was the most important factor influencing mercury concentrations in birds, followed by species and sex. Mercury concentrations were higher in stilts (geometric mean: 1.09 μg g^{-1} wet weight [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). Mercury concentrations were highest for both species at the southern end of San Francisco Bay, especially in salt pond A8 (stilts: 3.31 μg g^{-1} ww; avocets: 0.58 μg g^{-1} ww). Radio telemetry data showed that birds had strong fidelity to their capture site. Avocets primarily used salt ponds, tidal marshes, tidal flats, and managed marshes, whereas stilts mainly used salt ponds, managed marshes, and tidal marshes. Our results suggest that variation in blood mercury concentrations among sites was attributed to differences in foraging areas, and species differences in habitat use and foraging strategies may increase mercury exposure in stilts more than avocets.

Keywords: Avocets; Blood; Mercury; Telemetry; San Francisco Bay; Stilts

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doi:10.1016/j.scitotenv.2007.04.027

1. Introduction

San Francisco Bay Estuary has a legacy of mercury contamination from both mercury mining and gold extraction (reviews by Davis et al., 2003; Wiener et al., 2003a), and this pollution is thought to reduce reproductive success of some waterbirds breeding within the estuary (Schwarzbach et al., 2006). Sedimentary mercury deposits might become more bioavailable within the estuary because of current restoration plans to convert existing habitats, especially former salt evaporation ponds, into tidal marshes (Goals Project, 1999). San Francisco Bay is the largest estuary on the west coast of North America, but it has lost nearly 80% of its tidal salt marshes and 40% of its tidal flats over the past two centuries due to urban development, agriculture, and salt production (Goals Project, 1999). In particular, more than 13,000 ha of artificial salt evaporation ponds were constructed within the former baylands (Goals Project, 1999). Recently, however, over 10,000 ha of salt ponds have been transferred to government ownership and federal and state agencies are beginning to implement a plan to convert some of these salt ponds into tidal and managed marsh habitats (Steere and Schaefer, 2001; Siegel and Bachand, 2002; Life Science, 2003; COE, 2003). The restoration of these wetlands might accelerate the production of methyl mercury and increase the contamination of aquatic biota within the estuary (reviews by Davis et al., 2003; Wiener et al., 2003a).

San Francisco Bay supports over half a million wintering and migrating shorebirds annually and is recognized as a site of hemispheric importance to shorebirds (Page et al., 1999; Stenzel et al., 2002). Shorebird populations are largest during spring when they either breed locally or stage in San Francisco Bay during migration to acquire the necessary resources to travel to distant breeding areas and successfully reproduce (Warnock and Bishop, 1998; Stenzel et al., 2002). In addition, more than a quarter million ducks over-winter in the estuary (Accurso, 1992). Thus, nearly one million pre-breeding waterbirds may be at risk to mercury contamination accumulated while foraging within the estuary.

In order to understand current mercury levels in locally breeding waterbirds, we examined blood mercury concentrations of pre-breeding American avocets (*Recurvirostra americana*, hereafter avocets) and black-necked stilts (*Himantopus mexicanus*, hereafter stilts) at several sites in San Francisco Bay and used radio telemetry to assess space use and sites of dietary mercury uptake. Avocets and stilts are the two most abundant breeding shorebirds in San Francisco Bay (Stenzel et al., 2002; Rintoul et al., 2003). More than 4000 avocets and 1000 stilts, roughly 20% of their wintering populations, breed locally, making San Francisco Bay the largest breeding area for these species on the Pacific Coast (Stenzel et al., 2002; Rintoul et al., 2003). Any increase in mercury methylation rates associated with habitat restoration within the estuary will likely occur in wetlands along the bay's margins where avocets and stilts forage and nest. Although shorebirds are highly mobile, they often show strong fidelity to foraging, roosting, and breeding sites within San Francisco Bay (Warnock and Takekawa, 1995; 1996; Takekawa et al., 2002). We therefore predicted that mercury concentrations in avocets and stilts would differ among sites and reflect mercury contamination in the localized foraging areas.

2. Materials and methods

2.1. Study site

We studied mercury concentrations in avocets and stilts in the North (San Pablo Bay) and South Bay regions of the San Francisco Bay, California (37.8° N, 122.3° W; Fig. 1). The major wetland habitats in the North Bay included salt ponds (2892 ha), tidal flats (6615 ha), tidal marsh (6615 ha), and diked wetlands (3085 ha; Goals Project, 1999). The major wetland habitats in the South Bay include salt ponds (11 053 ha), tidal flats (3778 ha), tidal marsh (3777 ha), and diked wetlands (2310 ha; Goals Project, 1999). In 2005 and 2006, we captured or collected avocets at several North Bay (Napa-Sonoma Marsh Wildlife Area ponds 1, 1A, and West End Duck Club) and South Bay sites (Don Edward's San Francisco Bay National Wildlife Refuge ponds A1, A8, A16, Rectangle Marsh, and Coyote Creek Marsh; Eden Landing Ecological Reserve ponds 8, 11, 12, 14, and 17) and stilts at several North Bay (Napa-Sonoma Marsh Wildlife Area ponds 1, West End Duck Club, and Figeras Tract) and South Bay sites (Don Edward's San Francisco Bay National Wildlife Refuge ponds A8, Rectangle Marsh, and New Chicago Marsh; Eden Landing Ecological Reserve ponds 8, 11, 12, and 17; Fig. 1).

2.2. Bird captures and collections

During the pre-breeding season from 3 March to 15 April 2005 and 15 February to 12 April 2006, we captured avocets and stilts with either remotely

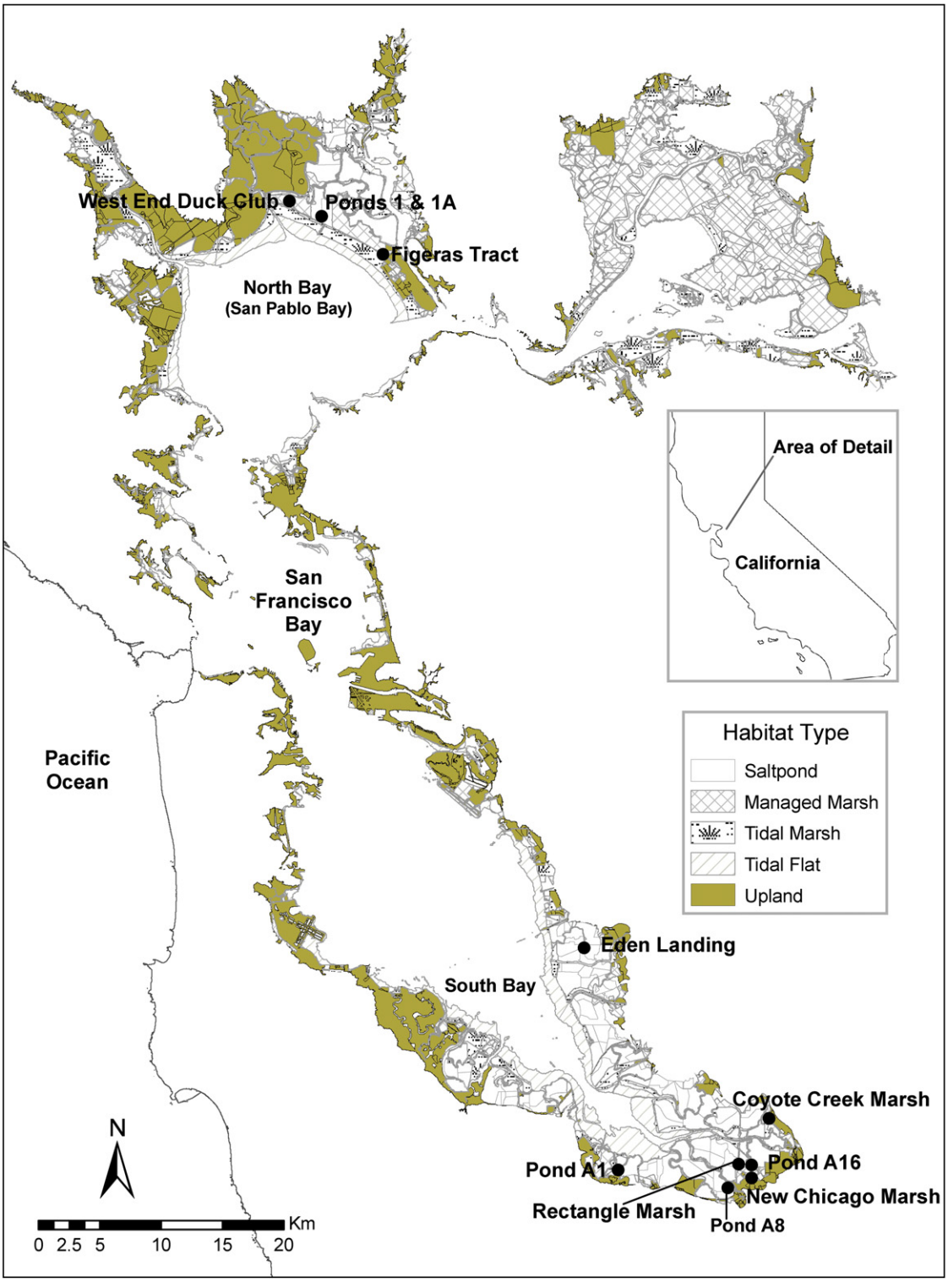

Fig. 1. Study area map of San Francisco Bay Estuary, California, U.S.A., with North and South Bay capture sites and habitat types indicated.

detonated net-launchers (Coda Enterprises, Mesa, Arizona, U.S.A.) or rocket nets (Dill and Thornsberry, 1950) set at known foraging and roosting sites. We collected additional foraging birds with a shotgun and steel shot as part of a larger study examining contaminant levels in San Francisco Bay birds (Ackerman et al., 2007). Birds were captured, collected, and marked under California Department of Fish and Game Scientific Collection permit SC-801034-05, Federal U.S. Fish and Wildlife Service permits MB102896, and U.S. Geological Survey Bird Banding Laboratory permit 22911, and research was conducted under the guidelines of the U.S. Geological Survey, Western Ecological Research Center, Animal Care and Use Committee.

We used bill shape of avocets (Robinson et al., 1997) and plumage coloration of stilts (Robinson et al., 1999) to determine sex of each bird. We confirmed the sex of collected specimens via necropsy. For contaminant analyses, we collected whole blood from live birds via the brachial vein using heparinized 25 to 27 gauge needles. The volume of blood collected was restricted to less than 1% of the bird's body mass (<3.0 ml for avocets and <1.5 ml for stilts). From collected birds, we drew 1.0–10.0 ml of blood via cardiac puncture with a heparinized 23 gauge needle. Whole blood was immediately transferred to polypropylene cryovials and held on dry ice until transfer to the laboratory for storage at −20 °C until analysis. All samples were stored for less than six months prior to laboratory analysis (see below).

2.3. Radio-marking and telemetry

After we collected blood from birds in 2005 and 2006, we marked adult female avocets and adult male and female stilts with a radio transmitter (Model A2470, Advanced Telemetry Systems Inc., Isanti, Minnesota, U.S.A.) attached with epoxy to a metal leg band on their right tibiotarsus (following Plissner et al., 2000; Haig et al., 2002), a darvic color leg band (AC Hughes Ltd., Hampton Hill, Middlesex, United Kingdom) above the transmitter, and three darvic color leg bands on their left tibiotarsus. Unique color-band combinations improved our ability to re-sight individuals. Transmitters weighed 4.1 g for avocets and 3.4 g for stilts (<2% of bird body mass), had a 16-cm external whip antenna pointing downwards, and had a battery life of 4–6 months. We held birds in shaded and screen-lined poultry cages (model 5KTC, Murray McMurray Hatchery, Webster City, Iowa, U.S.A.) and we released birds at the capture site within 3 h.

We tracked radio-marked avocets and stilts from trucks and fixed-wing aircraft equipped with dual 4-element Yagi antenna systems (Advanced Telemetry Systems Inc., Isanti, Minnesota, U.S.A.); trucks had null-peak systems (AVM Instrument Co., Livermore, California, U.S.A.) to accurately determine bearings, whereas aircraft had left–right systems (Advanced Telemetry Systems Inc., Isanti, Minnesota, U.S.A.) so transmitter signals could be pinpointed on either side of the plane (Gilmer et al., 1981). We attempted to locate birds daily by truck and every two weeks by aircraft from their date of capture until 15 April when pre-breeding typically ended (of 404 avocet and 136 stilt nests we monitored in 2005, only 10% had been initiated by 18 April and 20 April, respectively [J. T. Ackerman, U. S. Geological Survey, unpublished data]). We tracked birds by truck during the day and night because avocets and stilts forage at both times (Johnson et al., 2003; Kostecke and Smith, 2003); 17% of avocet (2393) and 11% of stilt (1928) telemetry locations were collected at night. To ensure coverage throughout San Francisco Bay, we used fixed tracking routes through all main North and South Bay salt ponds (includes North Bay, Alviso, Moffett, and Eden Landing salt ponds), marshes (Napa-Sonoma Marsh Wildlife Area, New Chicago Marsh, and Coyote Creek Marsh), and mud flats. For each location by truck, we obtained at least two azimuths within several minutes to minimize movement error. In South San Francisco Bay, Warnock and Takekawa (1995) reported average error rates of 1.5 degrees for bearings, 58±35 (SE) m for distances between true and calculated locations, and 1.1 ha for error-polygon size with similar truck systems and location distances (e.g. <3 km). We used triangulation program software (LOAS, version 3.0.1, Ecological Software Solutions, Schwägalpstrasse 2, 9107 Urnäsch, Switzerland) to calculate Universal Transverse Mercator coordinates for each location.

2.4. Mercury analysis

Previous research has demonstrated that, regardless of feeding strategy, greater than 95% of the mercury in avian blood is methyl mercury (Fournier et al., 2002; Evers et al., 2005; Rimmer et al., 2005); thus, we analyzed all blood samples for total mercury (U. S. Geological Survey, Davis Field Station Mercury Lab). Prior to analysis, we thawed samples to room temperature. To ensure sample homogeneity, we inverted the cryovials several times and thoroughly mixed the blood by stirring with a clean pipette tip. We pipetted

200 μl of blood from each cryovial and weighed (to the nearest 0.0001 g, Ohaus Adventurer Balance, model AR0640, Ohaus Corporation, Pine Brook, New Jersey, U.S.A.) each aliquot into a quartz sample vessel. Following EPA Method 7473 (U. S. EPA, 2000), we analyzed each sample for total mercury on a Milestone DMA-80 Direct Mercury Analyzer (Milestone Inc., Monroe, Connecticut, U.S.A.) 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 each analytical run, we calibrated the analyzer with dilutions of a certified mercury standard solution (SPEX CertiPrep, Metuchen, New Jersey, U.S.A.). Quality assurance measures included analysis of two certified reference materials (either dogfish muscle tissue [DORM-2; National Research Council of Canada, Ottawa, Canada], dogfish liver [DOLT-3; National Research Council of Canada, Ottawa, Canada], or lobster hepatopancreas [TORT-2; National Research Council of Canada, Ottawa, Canada]), two system and method blanks, two duplicates, one matrix spike, and one matrix spike duplicate per sample batch. Recoveries of certified reference materials, calibration checks, and matrix spikes, respectively, averaged 99.92±3.48% (N=29), 97.16±5.48% (N=51), and 100.14±2.69% (N=34). Absolute relative percent difference for all duplicates and matrix spike duplicates averaged 2.35%, and never exceeded 10%.

Table 1
Ranking of candidate models describing mercury concentrations in pre-breeding American avocets and black-necked stilts in San Francisco Bay, California, U.S.A. during spring 2005 and 2006

Model number	Model structure	N	RSS[a]	k[b]	Log-likelihood	$_{AICc}$[c]	D_{AICc}[d]	Akaike weight[e]
1	Species+site+sex+year+date	530	47.21	13	−640.85	−1254.99	3.39	0.09
2	**Species+site+sex+year**	**530**	**47.26**	**12**	**−640.58**	**−1256.56**	**1.81**	**0.20**
3	**Species+site+sex+date**	**530**	**47.26**	**12**	**−640.58**	**−1256.56**	**1.81**	**0.20**
4	Species+site+year+date	530	49.12	12	−630.35	−1236.09	22.29	0.00
5	Species+sex+year+date	530	81.56	6	−495.95	−979.74	278.64	0.00
6	Site+sex+year+date	530	62.55	12	−566.29	−1107.98	150.40	0.00
7	**Species+site+sex**	**530**	**47.28**	**11**	**−640.44**	**−1258.38**	**0.00**	**0.50**
8	Species+sex+year	530	83.44	5	−489.93	−969.74	288.64	0.00
9	Species+year+date	530	86.43	5	−480.58	−951.04	307.34	0.00
10	Species+site+year	530	49.19	11	−629.93	−1237.36	21.02	0.00
11	Species+site+date	530	49.15	11	−630.20	−1237.88	20.49	0.00
12	Species+sex+date	530	81.67	5	−495.59	−981.07	277.31	0.00
13	Site+sex+year	530	62.59	11	−566.13	−1109.76	148.62	0.00
14	Site+sex+date	530	62.87	11	−564.91	−1107.31	151.06	0.00
15	Site+year+date	530	65.29	11	−554.92	−1087.33	171.05	0.00
16	Sex+year+date	530	137.18	5	−358.17	−706.22	552.16	0.00
17	Species+site	530	49.20	10	−629.90	−1239.37	19.01	0.00
18	Species+sex	530	84.07	4	−487.92	−967.76	290.62	0.00
19	Species+year	530	88.15	4	−475.37	−942.67	315.71	0.00
20	Species+date	530	86.52	4	−480.31	−952.54	305.83	0.00
21	Site+sex	530	62.87	10	−564.91	−1109.40	148.98	0.00
22	Site+year	530	65.36	10	−554.64	−1088.86	169.51	0.00
23	Site+date	530	65.58	10	−v553.76	−1087.10	171.28	0.00
24	Sex+year	530	139.66	4	−353.43	−698.79	559.59	0.00
25	Sex+date	530	137.32	4	−357.90	−707.72	550.66	0.00
26	Year+date	530	146.72	4	−340.36	−v672.64	585.74	0.00
27	Date	530	146.83	3	−340.15	−674.26	584.12	0.00
28	Year	530	148.96	3	−336.33	−666.62	591.75	0.00
29	Sex	530	140.48	3	−351.87	−697.69	560.68	0.00
30	Site	530	65.59	9	−553.73	−1089.10	169.27	0.00
31	Species	530	88.70	3	−473.73	−941.42	316.96	0.00

The most parsimonious model includes species, site, and sex, and all models for which $\Delta AICc<2$ are bolded.
[a] Residual sum of squares from ANOVA or ANCOVA model.
[b] The number of estimated parameters in the model including variance.
[c] Akaike's Information Criterion.
[d] The difference in the value between AICc of the current model and the value for the most parsimonious model.
[e] The likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0).

2.5. Statistical analysis

To examine the spatial and temporal variation in mercury concentrations among pre-breeding birds, 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 (Burnham and Anderson, 1998; Anderson et al., 2000). We built a set of 31 candidate models based on potential effects of species, capture site, sex, year, and Julian capture date (Table 1). Low densities of birds in the North Bay and Eden Landing Ecological Reserve limited our sample size and our ability to test differences among specific ponds in these subregions; we therefore pooled all birds captured or collected from ponds within these subregions. We were comfortable pooling these data because mercury concentrations in these subregions had relatively low variability compared to South San Francisco Bay sites (see Results). We calculated and compared AIC values for candidate models using ANOVA or ANCOVA with StatView® version 5.0.1 (SAS Institute, 1998) and calculated least-squares means with Statistica version 7.1 (StatSoft, 2005). We $\log_e$-transformed mercury concentrations (wet weight; hereafter ww) to improve normality and reported geometric means ± SE based on back-transformed least-squares means ± SE in the text for clarity.

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 (Burnham and Anderson, 1998; Anderson et al., 2000). We considered the model with the smallest AICc to be the most parsimonious (Burnham and Anderson, 1998; Anderson et al., 2000). We used the AICc differences between the best model and the other candidate models ($\Delta AICc_i = AICc_i - \text{minimum } AICc$) to determine the relative ranking of each model. For biological importance, we considered models for which $\Delta AICc_i \leq 2$ (Anderson et al., 2001). Additionally, we calculated Akaike weights ($w_i = \exp[-\Delta AICc_i /$

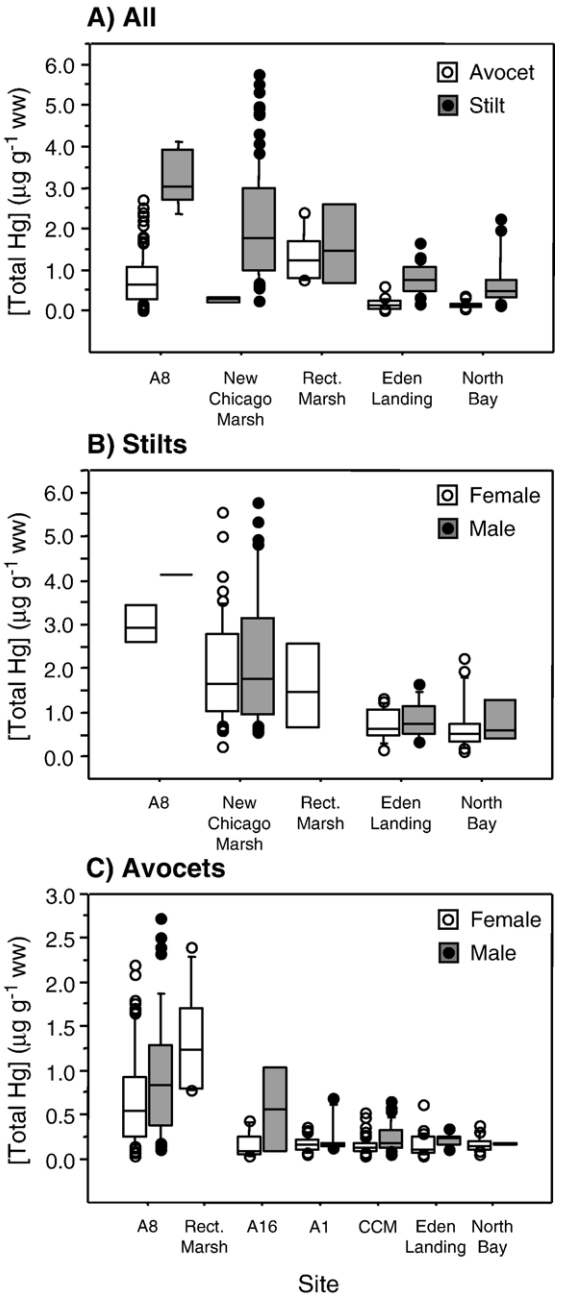

Fig. 2. Blood mercury concentrations (µg g^{-1} wet weight, ww) of American avocets and black-necked stilts among sites in San Francisco Bay, California, U.S.A. during spring 2005 and 2006. A) Blood mercury concentrations in black-necked stilts (sample size for A8 = 5, New Chicago Marsh = 96, Rectangle Marsh = 3, Eden Landing Ecological Reserve = 33, and North Bay = 21) and American avocets (sample size for A8 = 117, New Chicago Marsh = 2, Rectangle Marsh = 7, Eden Landing Ecological Reserve = 43, and North Bay = 22) at several sites. B) Blood mercury concentrations in black-necked stilt females (sample size for A8 = 4, New Chicago Marsh = 53, Rectangle Marsh = 3, Eden Landing Ecological Reserve = 22, and North Bay = 17) and males (sample size for A8 = 1, New Chicago Marsh = 43, Rectangle Marsh = 0, Eden Landing Ecological Reserve = 10, and North Bay = 4). C) Blood mercury concentrations in American avocet females (sample size for A8 = 75, Rectangle Marsh = 7, A16 = 8, A1 = 29, Coyote Creek Marsh [CCM] = 101, Eden Landing Ecological Reserve = 37, and North Bay = 19) and males (sample size for A8 = 42, Rectangle Marsh = 0, A16 = 2, A1 = 10, Coyote Creek Marsh [CCM] = 32, Eden Landing Ecological Reserve = 6, and North Bay = 3).

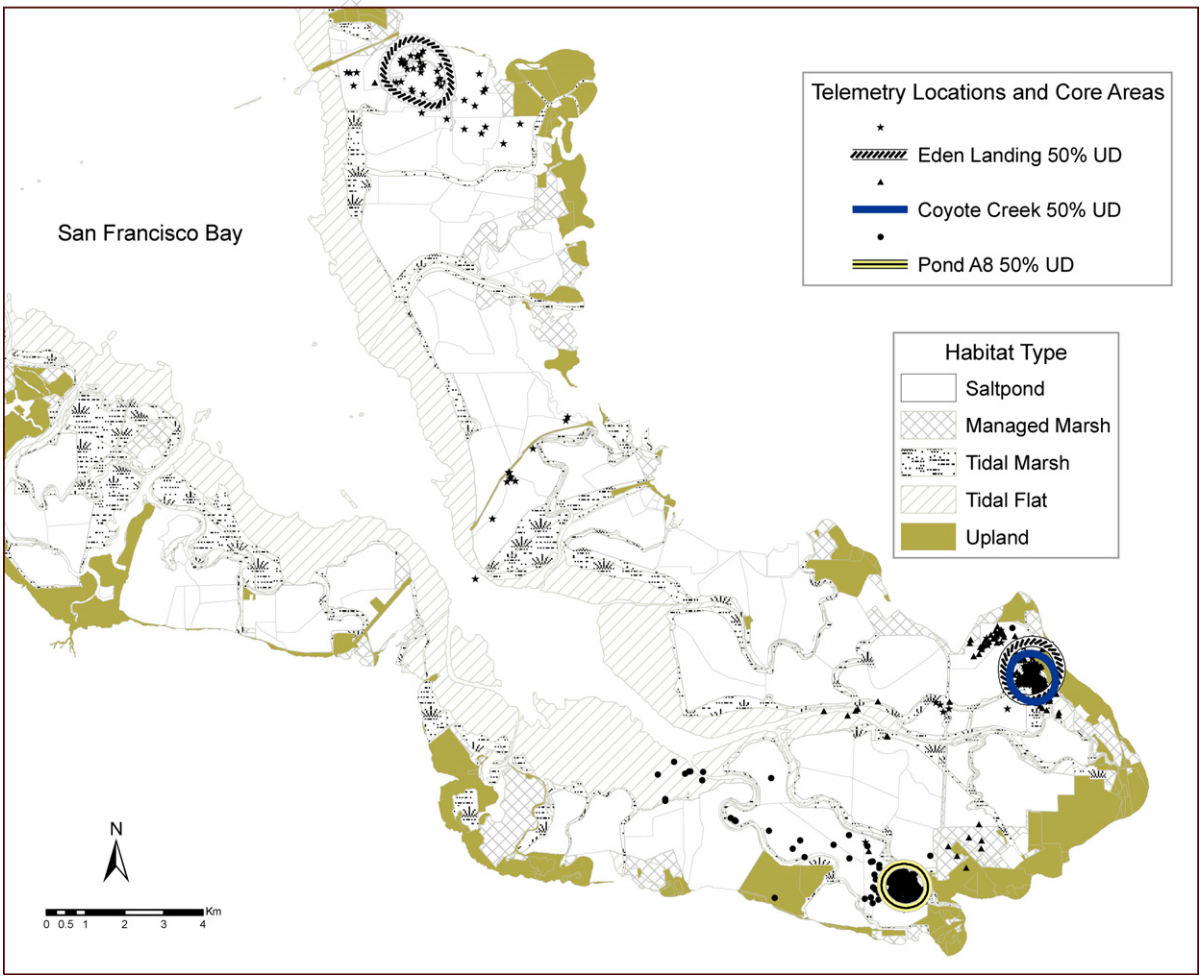

Fig. 3. Core use areas and telemetry locations of American avocet females radio-marked within A8 (N=254), Coyote Creek Marsh (N=287), and Eden Landing Ecological Reserve (N=116) sites in San Francisco Bay, California, U.S.A. during spring 2005.

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 (Burnham and Anderson, 1998; Anderson et al., 2000). 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.

To understand differences in observed mercury concentrations in birds among capture sites, we used radio telemetry to examine foraging areas and space use. These data were used to assess whether birds captured at specific sites remained within the local capture pond or foraged elsewhere. We defined population range size for each site as the size of the overall distribution of radio-marked avocets or stilts originating from that site (e.g., Adams et al., 2004; Ackerman et al., 2006). To calculate the population range of pre-breeding birds for each species and site, we used all telemetry locations from birds that were captured at a specific site each year. For example, we radio-marked 27 avocets at pond A8 during three capture events in 2006 and we used all telemetry locations originating from these avocets, regardless of whether or not they stayed in pond A8, from the date of their capture to 15 April (when breeding begins) to calculate the population range size and extent. We waited 24 h after marking before we began tracking to allow for behavioral adjustments to transmitters. We used only those locations that were separated by >1 h to reduce any potential autocorrelation among locations (White and Garrott, 1990; Haig et al., 2002), and most locations (99%) were separated by >3 h. We also excluded any locations with error-polygon sizes >3 ha (11% of locations). We estimated the size of radio-

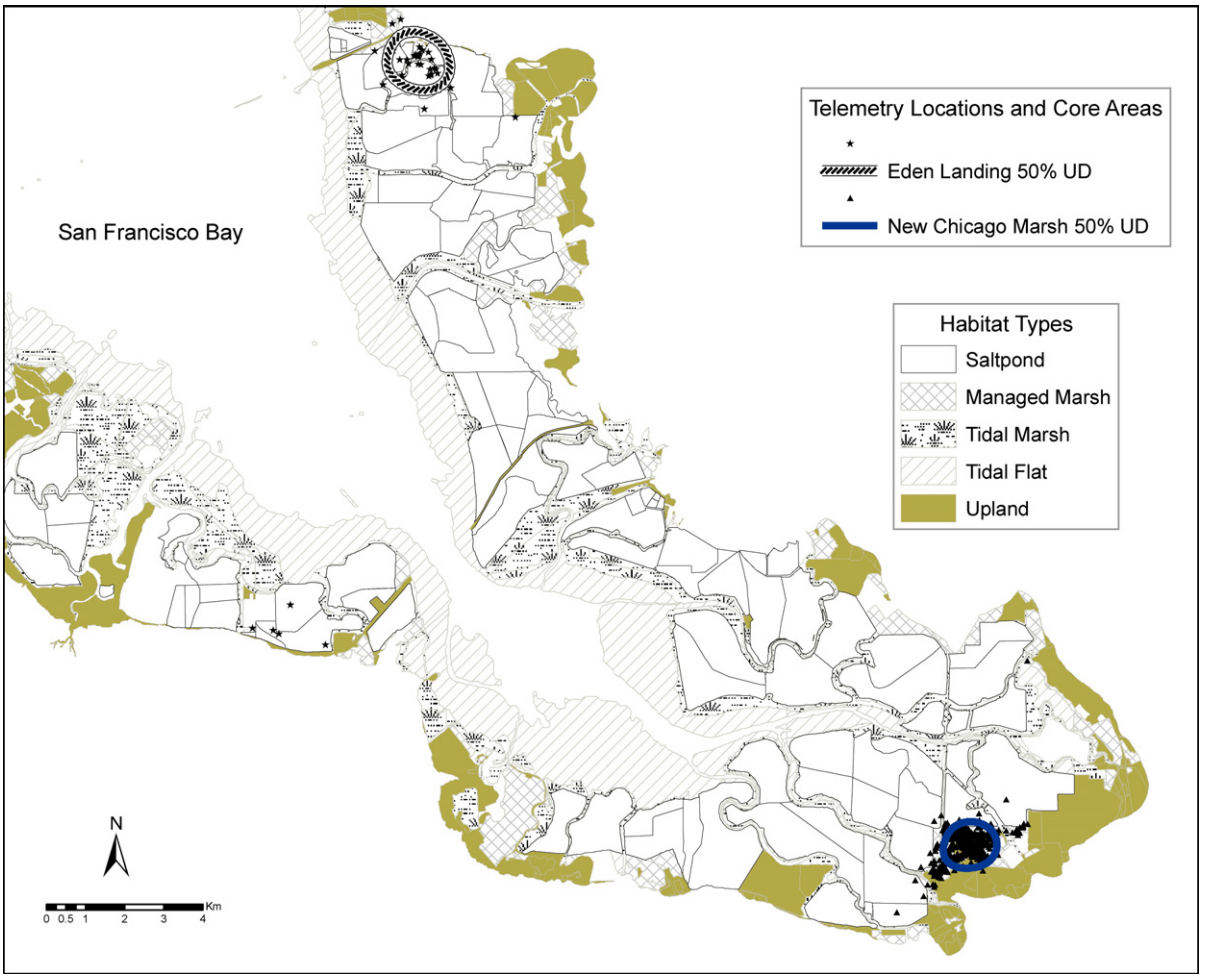

Fig. 4. Core use areas and telemetry locations of black-necked stilts radio-marked within New Chicago Marsh (N=474) and Eden Landing Ecological Reserve (N=43) sites in San Francisco Bay, California, U.S.A. during spring 2005.

marked bird's population range and core use area in ArcGIS version 9.1 (ESRI, 1996; ESRI Inc., Redlands, California, U.S.A.) using Hawth's Analysis Tools for ArcGIS Version 3.26 (Beyer, 2004). We used the fixed-kernel method with the default smoothing parameter selection (h value) to calculate 50% (hereafter core use area) and 95% (hereafter population range size) utilization distributions (Hooge et al., 2001). Depending on species and site, 62–80% of all telemetry locations were located within the 50% utilization distribution. Kernel methods are considered superior to minimum convex polygons because they estimate the intensity of use within an animal's home range (Kernohan et al., 2001) and omit large areas that are not used by the animal (White and Garrott, 1990).

After determining 50% and 95% utilization distributions, we overlaid Bay Area EcoAtlas habitat coverages (version 1.50b, SFEI, 1998) and quantified the proportion of habitat types used by each group of birds, including salt ponds (active and former salt evaporation ponds), managed marshes (diked and managed marshes), tidal marshes (high, mid, and low elevation tidal marshes and muted tidal marshes), tidal flats (shallow water tidal flats and beaches), sloughs (major channels and ditches), lagoons (lagoons and storage treatment ponds), and uplands (developed and undeveloped fill, farmed and grazed baylands, and other uplands). We radio-marked and calculated population ranges for avocets in ponds A8, Coyote Creek Marsh, and Eden Landing Ecological Reserve in 2005 and in salt ponds A8, A16, Coyote Creek Marsh, and Eden Landing Ecological Reserve in 2006, and for stilts in New Chicago Marsh, Eden Landing Ecological Reserve, and North Bay in 2005 and in ponds A8, New

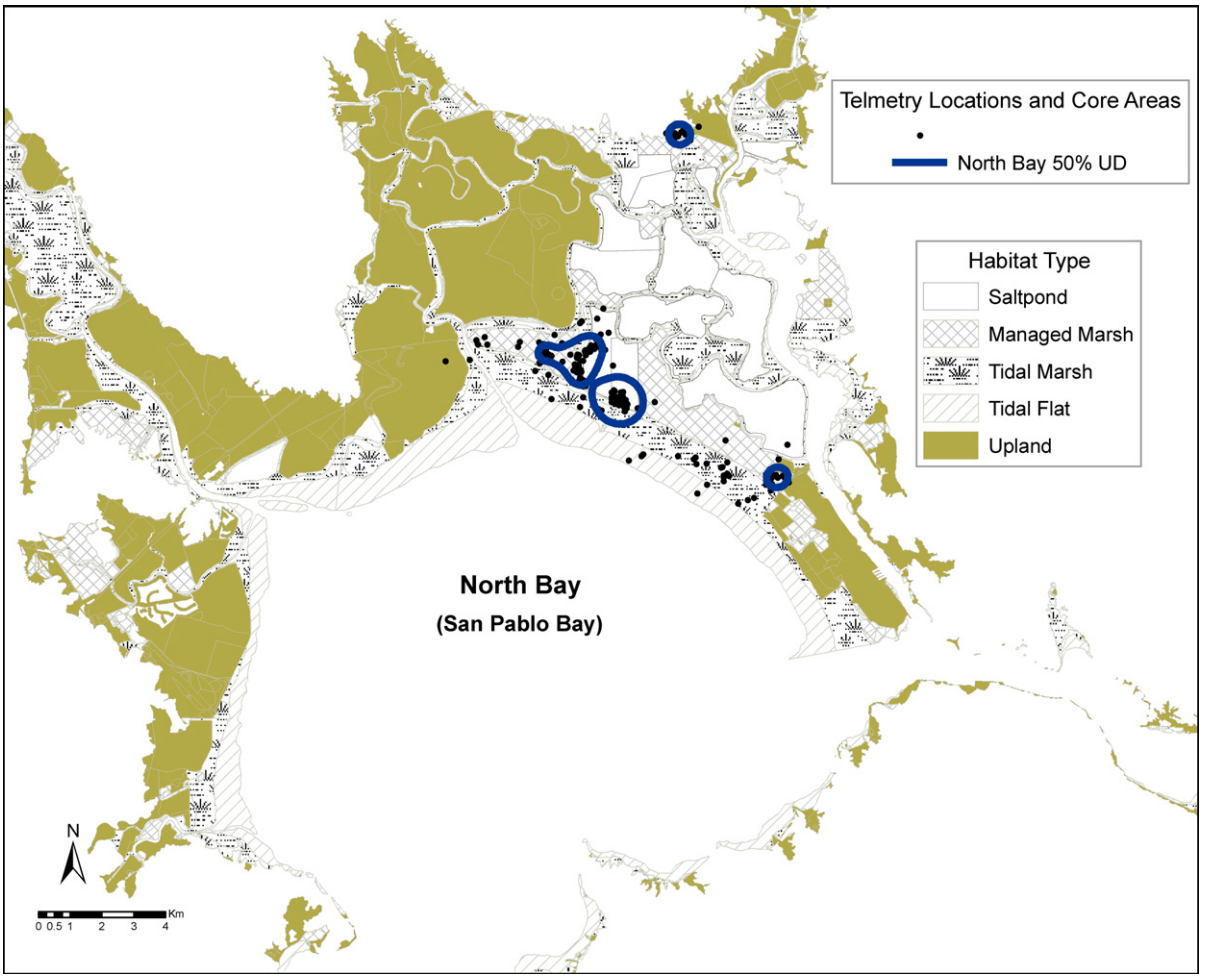

Fig. 5. Core use areas and telemetry locations of black-necked stilts radio-marked within the North Bay (N=230) site in San Francisco Bay, California, U.S.A. during spring 2005.

Chicago Marsh, and Eden Landing Ecological Reserve in 2006.

3. Results

3.1. Mercury concentrations in birds

We captured or collected 373 avocets and 157 stilts during the pre-breeding seasons in 2005 and 2006. The most parsimonious model explaining differences in mercury concentrations among birds contained species, capture site, and sex, and had an Akaike weight of 0.50 (Table 1). Three other models containing these variables and either capture date, year, or capture date and year also provided a reasonably good fit to the data. However, the log-likelihood values for these three alternate models (−640.58 to −640.85) were very similar to the best model (−640.44), indicating that the addition of the date and year variables neither improved nor hurt the fit of the best model. Furthermore, models containing the variables species, site, and sex had a combined AIC weight of >99%, indicating their overriding importance for explaining differences in mercury concentrations among birds; excluding any one of these variables would have caused a large reduction in model fit.

We used variable weights to assess the order of importance for each variable and found that site (1.0), species (1.0), and sex (0.99) were the most important followed by capture date (0.30) and year (0.30). We could not differentiate the top three variables because they had similar weights, therefore we used the other models in the candidate set to rank their relative importance. For example, using only the single variable models, the variable with the lowest ΔAIC_c was capture site, followed by species, sex, date, and year (Table 1). These results indicate that capture site was the most

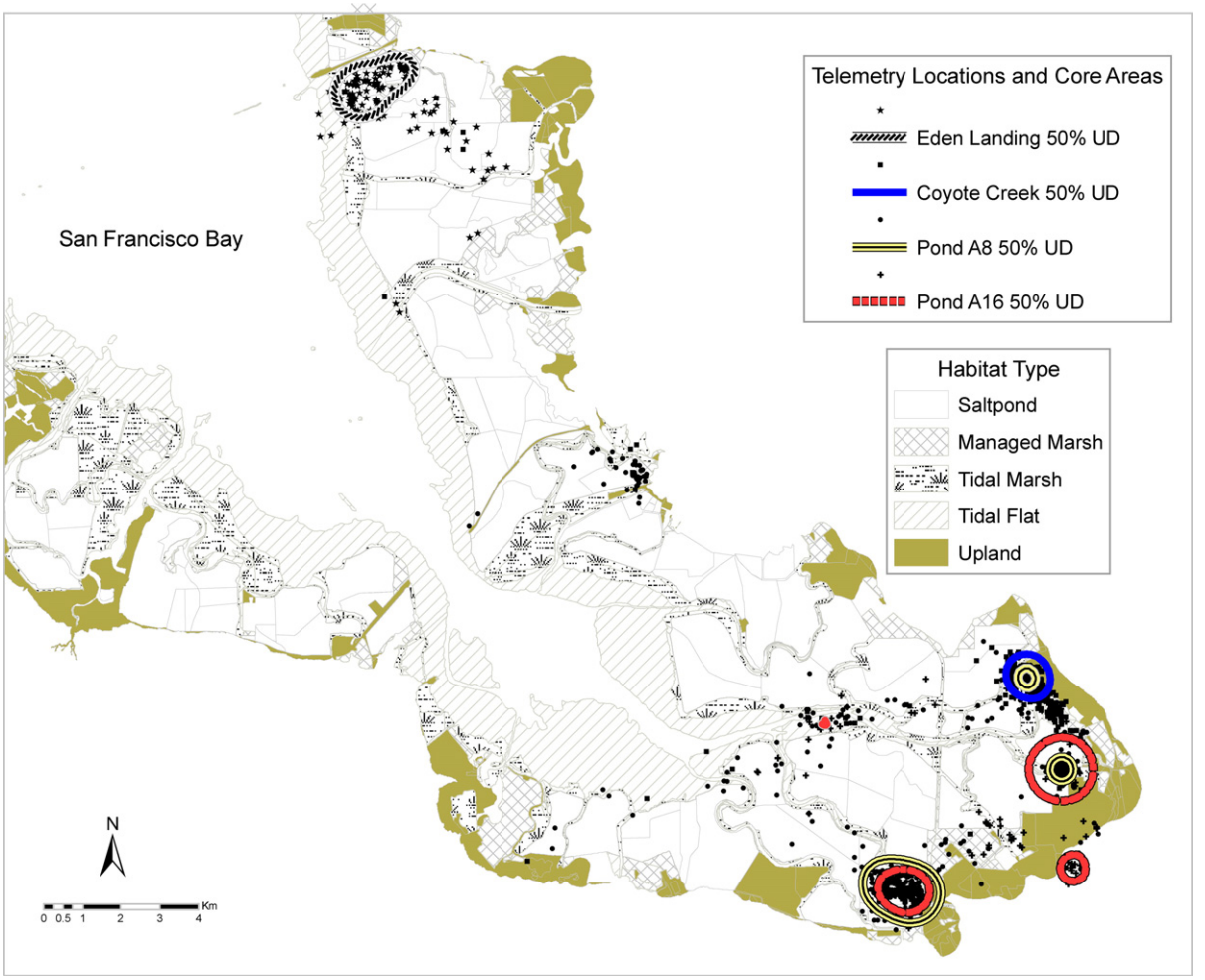

Fig. 6. Core use areas and telemetry locations of American avocet females radio-marked within A8 (N=651), A16 (N=185), Coyote Creek Marsh (N=777), and Eden Landing Ecological Reserve (N=134) sites in San Francisco Bay, California, U.S.A. during spring 2006.

important variable predicting mercury concentrations in birds, followed by species and sex.

Mercury concentrations were highest for both species in the southern San Francisco Bay at the Alviso salt pond complex (A8, A16, Rectangle Marsh, and New Chicago Marsh; Fig. 2). Most notably, salt pond A8 and Rectangle Marsh had the highest mercury concentrations for avocets (0.58±0.04 μg g^{-1} ww and 1.47±0.40 μg g^{-1} ww, respectively), and A8 and New Chicago Marsh had the highest mercury concentrations for stilts (3.31±0.96 μg g^{-1} ww and 1.72±0.11 μg g^{-1} ww, respectively). In contrast, the lowest mercury concentrations for each species were found in North Bay (stilts: 0.56±0.08 μg g^{-1} ww; avocets 0.16±0.03 μg g^{-1} ww) and in the South-Central Bay at the Eden Landing Ecological Reserve (stilts: 0.69±0.08 μg g^{-1} ww; avocets: 0.15±0.02 μg g^{-1} ww; Fig. 2). Mercury concentrations also were higher in stilts (1.09±0.10 μg g^{-1} ww) than in avocets (0.25±0.01 μg g^{-1} ww) at every site where they co-occurred (Fig. 2A) and males (stilts: 1.32±0.17 μg g^{-1} ww; avocets: 0.32±0.03 μg g^{-1} ww) generally had higher mercury concentrations than females (stilts: 1.15±0.12 μg g^{-1} ww; avocets: 0.21±0.02 μg g^{-1} ww; Fig. 2B, C).

3.2. Telemetry and space use of birds

To understand site differences in mercury concentrations, we radio-marked and tracked 115 avocets and 94 stilts and obtained 2393 and 1928 telemetry locations, respectively. Radio-marked birds generally remained near their capture site (Figs. 3–7). For example, 60% and 48% of avocet core use areas for A8 and Coyote Creek Marsh, respectively, were within the pond site of

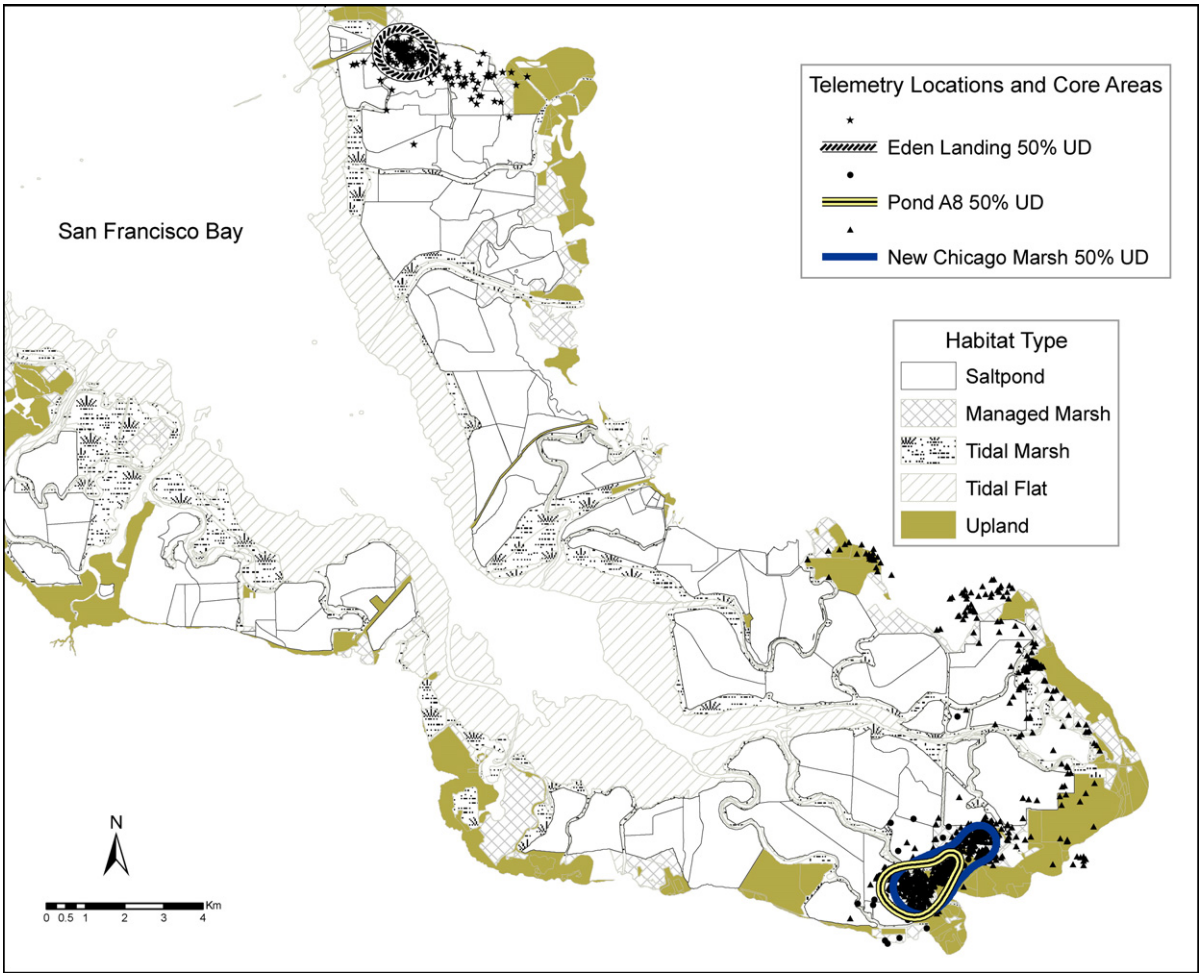

Fig. 7. Core use areas and telemetry locations of black-necked stilts radio-marked within New Chicago Marsh (N=905), A8 (N=83), and Eden Landing Ecological Reserve (N=195) sites in San Francisco Bay, California, U.S.A. during spring 2006.

capture (Table 2). Similarly, 75% and 40% of stilt core use areas for New Chicago Marsh and A8, respectively, were within the pond site of capture. The exception was avocets captured at A16, where 0% of the core use area was within the pond site of capture. Instead, avocets captured at A16 had multiple core use areas located near Coyote Creek Marsh and A8 (Fig. 6), and their mercury concentrations were correspondingly intermediate to avocets captured at those sites (Fig. 2C).

Avocets generally used salt pond habitats, tidal marshes, tidal flats, and managed marshes, but capture site influenced space use due to high site fidelity (Table 2). For example, avocets radio-marked at A8 and Eden Landing Ecological Reserve were mainly located in salt ponds, whereas avocets radio-marked in Coyote Creek Marsh were mainly located within tidal marshes and tidal flats that were adjacent to the capture site. Stilts also often used salt pond habitats, but they tended to use managed marshes, such as New Chicago Marsh, more than avocets (Table 2).

4. Discussion

Mercury concentrations in the blood of pre-breeding avocets and stilts differed among sites in San Francisco Bay. In particular, birds captured at sites in the southernmost portion of the Bay had the highest mercury concentrations, especially within salt pond A8 and New Chicago Marsh. These sites also have high levels of mercury derived from contaminated sediments due to their proximity to Alviso Slough, the discharge point for the Guadalupe River watershed, which contains the historic New Almaden mercury mine (Beutel and Abu-Saba, 2004; Conaway et al., 2004). Pond A8 and New Chicago Marsh have some of the largest breeding populations of avocets (minimum estimate in A8 was

Table 2
Population range sizes and percent use of habitat types within 50% and 95% utilization distributions (UD) of pre-breeding American avocets and black-necked stilts radio-marked at each site during spring 2005 and 2006 in San Francisco Bay, California, U.S.A

Site [b]	Number of radio-marked birds	Number of telemetry locations	Population range size (ha)	Percentage of UD within capture site (%)	Habitat type [a]						
					Salt pond (%)	Managed marsh (%)	Tidal marsh (%)	Tidal flat (%)	Slough (%)	Lagoon (%)	Upland (%)
American avocets: 50% UD											
A8	45	905	207.3	60	75	1	8	8	1	0	7
A16	6	185	331.1	0	43	21	16	6	0	9	4
Eden Landing	18	245	304.3	80	83	3	6	5	0	0	3
Coyote Creek Marsh	46	1058	108.4	48	8	11	44	38	0	0	0
American avocets: 95% UD											
A8	45	905	2300.3	10	52	6	12	16	3	2	10
A16	6	185	2384.5	1	39	13	16	10	2	9	11
Eden Landing	18	245	1770.5	71	74	5	7	10	0	0	4
Coyote Creek Marsh	46	1058	873.2	12	19	15	36	25	1	2	1
Black-necked stilts: 50% UD											
A8	5	83	212.1	40	58	28	8	3	0	0	4
Eden Landing	15	235	143.7	100	79	14	3	0	2	0	2
New Chicago Marsh	66	1380	211.0	75	18	73	3	1	0	0	5
North Bay	8	230	436.5	100	35	39	20	0	3	2	1
Black-necked stilts: 95% UD											
A8	5	83	957.3	16	51	30	5	1	1	1	9
Eden Landing	15	235	955.7	82	67	12	3	1	0	2	14
New Chicago Marsh	66	1380	1264.3	27	33	35	8	3	1	2	18
North Bay	8	230	2470.1	100	16	27	38	9	1	1	8

[a] Similar habitat types are grouped into categories as follows: salt ponds (includes active and inactive salt evaporation ponds), managed marshes (includes diked and managed marshes), tidal marshes (includes high, mid, and low elevation tidal marshes and muted tidal marshes), tidal flats (includes shallow water bay, tidal flats, and beaches), sloughs (includes major channels and ditches), lagoons (includes lagoons and storage treatment ponds), and uplands (includes developed and undeveloped fill, farmed and grazed baylands, and other uplands). GIS habitat coverages are from the Bay Area EcoAtlas (version 1.50b, SFEI 1998).

[b] Data are pooled for 2005 and 2006, except for sites where we had one year of data (only 2006 data for American avocets at site A16, only 2006 data for black-necked stilts at site A8, and only 2005 data for black-necked stilts at site North Bay). Thus, the total number of radio-marked birds and the total number of telemetry locations at each site includes 2005 and 2006 data, and the population range size, percentage of UD within capture site, and the percent use of each habitat type are averaged for 2005 and 2006.

188 nests in 2005 and 208 in 2006) and stilts (minimum estimate in New Chicago Marsh was 101 nests in 2005 and 309 in 2006) within the entire San Francisco Bay (J. T. Ackerman, U. S. Geological Survey, unpublished data). Thus, a large proportion of breeding shorebirds are nesting in areas with the highest mercury levels. Using radio telemetry, we confirmed that birds remained near their capture site during the pre-breeding season (late February to mid April), indicating that differences in bird mercury concentrations among sites were probably due to differences in foraging areas and dietary mercury uptake.

We also found that mercury concentrations in stilts were higher than those in avocets captured at the same sites. Although avocets and stilts (Recurvirostridae) are often associated together and forage on similar foods, their use of micro-habitats and possibly aquatic prey types can differ (Hamilton, 1975; Robinson et al., 1997, 1999). For example, we found that avocets tended to use salt ponds and tidal flats more often than stilts, whereas stilts tended to use managed marshes more often than avocets. Furthermore, within the same sites, avocets tended to use the more open water and mudflat habitats whereas stilts used the more vegetated areas (Rintoul

et al., 2003). Such differences in micro-habitat selection may lead to different mercury exposure levels. The higher mercury concentrations in stilts may also indicate a higher trophic level feeding by stilts than avocets since stilts appear to be more likely to feed on fish (Robinson et al., 1997, 1999), whereas avocets in San Francisco Bay appear to consume mainly aquatic invertebrates (Anderson, 1970).

In both species, pre-breeding males had higher mercury concentrations than pre-breeding females; average mercury concentrations were 1.8 and 1.3 times higher in males than females in avocets and stilts, respectively. It is unlikely that sex differences in mercury concentrations of avocets and stilts were due to sexual size dimorphism because sexes differed in size by <0.5% (J. T. Ackerman, U. S. Geological Survey, unpublished data). Sex differences in mercury concentrations could be due to foraging strategies (consumption rates or prey size selection), but differences might also have been caused by females depurating methyl mercury into eggs the prior breeding season. Mercury concentrations are generally not found to differ between sexes when tissues representing accumulation during the non-breeding season are analyzed (Burger, 1995; Thompson et al., 1991; Burger and Gochfeld, 1992), but males typically have higher mercury concentrations than females during the breeding season in common loons (*Gavia immer*; Evers et al., 1998; Scheuhammer et al., 1998; Burgess et al., 2005), gulls (Braune and Gaskin 1987; Lewis et al., 1993), American white pelicans (*Pelecanus erythrorhyncos*; Donaldson and Braune, 1999), and Forster's terns (*Sterna forsteri*; authors, unpublished data). Lewis et al. (1993) calculated that female herring gulls (*Larus argentatus*) depurated about 15–24% of their body burden of mercury into their clutch. These data indicate that females depurate methyl mercury into eggs, but it is unclear whether such a large reduction in female mercury concentration (43% for avocets and 25% for stilts) could occur solely due to depuration into eggs and if it could still be detected nearly 10 months later, just prior to the subsequent breeding season, as we observed in our study. Most likely, sex differences in mercury concentrations in the blood of pre-breeding birds were due to factors other than egg depuration, such as differences in foraging strategies or physiology (e.g., Burgess et al., 2005; Evers et al., 2005).

Sensitivity to methyl mercury toxicity is known to vary among species (Scheuhammer, 1987; Wiener et al., 2003b; Scheuhammer et al., 2007) and toxicity thresholds for avocets and stilts have not been established. Furthermore, few studies have established mercury toxicity thresholds for bird blood. Henny et al. (2002) found little evidence for histological damage in adult snowy egrets (*Egretta thula*), black-crowned night-herons (*Nycticorax nycticorax*), and double-crested cormorants (*Phalacrocorax auritus*) with blood mercury concentrations of 5.9 $\mu g\ g^{-1}$ ww, 6.6 $\mu g\ g^{-1}$ ww, and 17.1 $\mu g\ g^{-1}$ ww, respectively. However, Evers et al. (submitted for publication) found that common loons with blood mercury concentrations >3.0 $\mu g\ g^{-1}$ ww produced 40% fewer offspring than loons with only 1.0 $\mu g\ g^{-1}$ ww. Although it is unknown whether loon toxicity levels are appropriate for avocets and stilts, we estimated that 17% of stilts, but no avocets, had blood mercury concentrations >3.0 $\mu g\ g^{-1}$ ww and were potentially at risk to impaired reproduction. The number of stilts at risk to mercury toxicity were especially prevalent in South San Francisco Bay, particularly in salt pond A8 (60%) and New Chicago Marsh (24%). Considering that avocets and stilts primarily eat aquatic invertebrates and seeds (Anderson, 1970; Robinson et al., 1997; Robinson et al., 1999), it seems likely that waterbirds feeding on higher trophic level prey, such as fish-eating terns, are even more at risk to mercury contamination in San Francisco Bay.

Currently, management agencies are implementing large-scale plans to restore or enhance wetland habitats along San Francisco Bay's margins (Goals Project, 1999). Restoration activities could increase the contamination of the aquatic biota within the estuary by accelerating microbial conversion of legacy inorganic mercury to methyl mercury, the form which is highly toxic and most bioavailable to wildlife and humans (reviews by Davis et al., 2003; Wiener et al., 2003a). This might be especially problematic for San Francisco Bay waterbirds because a large proportion of the breeding populations of several waterbird species (e.g., shorebirds, rails, gulls, and terns) nest in the South Bay where much of the restoration of former salt evaporation ponds into tidal marsh will occur. Our results suggest that continued monitoring of mercury levels in breeding waterbirds within San Francisco Bay is warranted.

Acknowledgments

This research was funded by the CALFED Bay-Delta Program's Ecosystem Restoration Program (grant number ERP-02D-C12) with additional support from the USGS Western Ecological Research Center. We thank Angela Rex, Sarah Stoner-Duncan, Joe Northrup, Brooke Hill, Kristen Dybala, Stacy Moskal, John Henderson, Cathy Johnson, Ross Wilming, Lindsay Dembosz, Emily Eppinger, Mychal Truwe, River Gates, Lani Stinson, Cheryl Strong, Eli French, and Maliheh Nakhai for field

assistance, Robin Keister, Sarah Spring, and Liz Bowen for lab analyses, and Julie Yee for statistical advice. We also thank Clyde Morris, Joy Albertson, Mendel Stewart, Joelle Buffa, Eric Mruz, and the staff at the Don Edwards San Francisco Bay National Wildlife Refuge (U.S. Fish and Wildlife Service; Special Use Permits 11640-2005-002 and 11640-2006-006), John Krause and the staff of the Eden Landing Ecological Reserve (California Department of Fish and Game), Tom Huffman, Larry Wyckoff, Carl Wilcox, Karen Taylor, and the staff of the Napa-Sonoma Marsh Wildlife Area (California Department of Fish and Game), Lew Allen and the Can Duck Club, Mark Herzog, and Nicole Athearn for logistical support. Early versions of the manuscript were improved by discussions and comments from Mary Ellen Mueller, Mark Ricca, Josh Vest, Roger Hothem, Chuck Henny, and an anonymous reviewer. The use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U. S. Government.

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