

# Survival of postfledging Forster's terns in relation to mercury exposure in San Francisco Bay

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**Abstract** We examined factors influencing mercury concentrations in 90 fledgling Forster's terns (*Sterna forsteri*) and evaluated whether mercury influenced postfledging survival in San Francisco Bay, California. Mercury concentrations ( $\pm$ SE) in chicks 21–29 days old (just before fledging) were  $0.33 \pm 0.01 \mu\text{g g}^{-1}$  ww for blood and  $6.44 \pm 0.28 \mu\text{g g}^{-1}$  fw for breast feathers. Colony site had an overriding influence on fledgling contamination, however hatching date and age also affected blood, but not feather, mercury concentrations. Blood mercury concentrations decreased by 28% during the 50-day hatching period and increased with chick age by 30% during the last week prior to fledging. Using radio-telemetry, we calculated that cumulative survival during the 35-day postfledging time period was  $0.81 \pm 0.09$  (SE). Postfledging survival rates increased with size-adjusted mass, and cumulative survival probability was 61% lower for terns with the lowest, compared to the highest, observed masses. Conversely, survival was not influenced by blood mercury concentration, time since fledging, sex, or hatch date. Mercury concentrations in breast feathers of fledglings found dead at nesting colonies also were no different than those in live chicks. Our results indicate that colony site, hatching date, and age influenced mercury concentrations in fledgling Forster's terns, but that mercury did not influence postfledging survival.

**Keywords** Fledglings · Mercury · Postfledglings · Survival · Telemetry

## Introduction

Methyl mercury biomagnifies through aquatic food chains (Wiener et al. 2003) and elevated levels are common in wildlife foraging at high trophic positions in contaminated environments (Monteiro and Furness 1995; Henny et al. 2002; Evers et al. 2005). Dietary exposure to methyl mercury is problematic because it is a potent neurotoxin, and toxic effects on reproduction can occur at relatively low levels (Wolfe et al. 1998; Scheuhammer et al. 2007). In particular, methyl mercury can affect avian reproductive success by reducing hatching success (Heinz and Hoffman 2003; Albers et al. 2007; Heinz et al. 2008), and by altering chick behavior (Heinz 1975, 1979; Bouton et al. 1999), health (Spalding et al. 2000a; Kenow et al. 2007), growth (Spalding et al. 2000b; Longcore et al. 2007), and survival (Meyer et al. 1998; Heinz 1974; Finley and Stendell 1978; Ackerman et al. 2008a). Toxic endpoints for reproductive impairment mainly have been developed for egg hatchability (Wolfe et al. 1998; Heinz and Hoffman 2003; Scheuhammer et al. 2007; Heinz et al. 2008). Reduced chick survival due to mercury exposure also can be an important component contributing to reproductive impairment, but few studies have been able to detect effects of mercury on chick survival in the wild (Ackerman et al. 2008a).

Examining the effects of mercury exposure on chick survival is complicated due to high variability in mercury concentrations among chicks of differing ages (Karasov et al. 2007). Any effects of mercury exposure on chick survival are likely to occur shortly after hatching or during fledging when blood concentrations are at their highest

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levels. Blood mercury concentrations in chicks are relatively high immediately after hatching, due to in ovo exposure, then rapidly decline as chicks age and dilute their body burden of mercury through growth in size and depuration into growing feathers (Monteiro and Furness 2001; Fournier et al. 2002). Blood mercury concentrations then begin to increase just before and during fledging when body growth and feather production slows, while chicks continue to acquire mercury through their diets. This U-shaped pattern of blood mercury dilution followed by accretion as chicks age has been observed in several species (Spalding et al. 2000b; Kenow et al. 2003; Ackerman et al. 2007a). Therefore, juvenile birds may experience a period of higher risk to mercury toxicity shortly after hatching and again at the time of fledging when feather production ceases. The postfledging stage is thus hypothesized to be an especially sensitive period for survival of semi-altricial or semi-precocial birds with nidicolous young, which are fed and brooded by their parents during the nestling stage but must learn to fly and forage independently after fledging.

In this study, we examined the influence of mercury on survival of postfledging Forster's terns (*Sterna forsteri*). Forster's terns have semi-precocial young that are fed by their parents on nesting colonies until they fledge at about 28 days of age (McNicholl et al. 2001). Thereafter, postfledging terns are capable of flight and autonomous foraging. Forster's tern chicks exhibit elevated blood mercury concentrations just before and during fledging (Ackerman et al. 2007a) and may therefore experience increased risk of mortality due to mercury exposure. Forster's terns are an ideal species to examine the influence of mercury on postfledging survival because they forage at a high trophic level (McNicholl et al. 2001) in shallow-water wetlands along San Francisco Bay's margins (Ackerman et al. 2008b) where methyl mercury production is high (Marvin-DiPasquale et al. 2003). Moreover, Forster's terns are one of the most common piscivorous waterbirds breeding in San Francisco Bay, making them a good indicator of mercury exposure and effects to fledgling waterbirds.

## Methods

### Study site and species

We examined mercury contamination and survival of postfledging Forster's tern chicks in South San Francisco Bay, California (37.4° N, 122.0° W) at the Don Edwards San Francisco Bay National Wildlife Refuge. San Francisco Bay has a legacy of mercury contamination from both mercury mining and gold extraction in its tributaries, and evidence suggests that the bioavailability of methyl

mercury may increase within the estuary as current restoration plans will restore several thousand hectares of wetlands (Davis et al. 2003). In 2006, there were eight breeding colonies of Forster's terns, but this number has ranged from four to 14 colonies since 1982 (Strong et al. 2004; San Francisco Bay Bird Observatory, unpublished data). We studied Forster's terns at five of the eight colonies in 2006: Ponds A7, A8, A16, and New Chicago Marsh within the Alviso Salt Pond Complex, and Pond N7 within the Newark Salt Pond Complex.

### Colony monitoring

We monitored Forster's tern colonies weekly throughout the 2006 breeding season from nest initiation (early May) until the last tern chick fledged (late August). At each visit, we monitored nests to determine nest fate and hand-captured every chick on the nesting colony to measure their size. We banded chicks with stainless steel U.S. Geological Survey leg bands, weighed them with a spring scale ( $\pm 1.0$  g with a 100-g or 300-g Pesola® spring scale, Pesola Ag, Baar, Switzerland), and we measured exposed culmen length and short tarsus (tarsometatarsus bone) length with digital calipers ( $\pm 0.01$  mm with Fowler® electronic digital calipers, Newton, MA, USA) and flattened wing chord length with a wing board ( $\pm 1.0$  mm). For this study, we were specifically interested in only those chicks that were approaching fledging at about 28 days of age. We defined postfledging tern chicks as those that had fledged and were capable of flight ( $>28$  days of age), but still might have been fed periodically by their parents. We estimated each chick's age using a multiple regression equation developed from our 2005 morphometric data (mm) for South San Francisco Bay Forster's terns that included chicks with known hatching dates (chick age [in days] =  $[0.11 \times \text{wing chord}] + [1.11 \times \text{culmen}] - [0.018 \times \text{culmen}^2] + [1.34 \times \text{tarsus}] - [0.035 \times \text{tarsus}^2] - 22.15$ ;  $N = 472$ ,  $R^2 = 0.98$ ; J. T. Ackerman, unpublished data).

### Mercury sampling

For contaminant analyses, we collected blood and breast feathers from live chicks that were  $\geq 21$  days of age between 28 June and 17 August 2006 at colonies within Ponds A7 and N7. Whole blood was collected via the brachial vein using sterile and heparinized 25–27 gauge needles. The volume of blood collected (0.5–1.5 ml) was restricted to  $\leq 1\%$  of the chick's body mass. Whole blood was immediately transferred to polypropylene cryovials and held on dry ice until transfer to the laboratory for storage at  $-20^\circ\text{C}$  until analysis. We collected a drop of unheparinized blood from each chick to determine their sex using genetic analysis (Zoogen Services, Davis, CA, USA).

We also collected 5–10 breast feathers from each chick and stored them in Whirl-paks<sup>®</sup> (Nasco, Modesto, CA, USA) until laboratory analysis. Each chick was sampled only once for blood and feathers.

#### Radio-marking terns

We estimated survival of postfledging chicks using radio telemetry at the tern colony in Pond N7, which was the largest Forster's tern colony in San Francisco Bay during 2006 ( $N > 600$  nests; J. T. Ackerman, unpublished data). We radio-marked chicks on either 5 or 12 July 2006, when most chicks at Pond N7 were fledging. We selected chicks for radio-marking that were about 25-days of age to ensure that we marked chicks just before they fledged at about 28-days of age. We estimated hatching dates for each radio-marked chick via back-calculation using their estimated age at the date of capture. We used radio transmitters containing thermistor switches (Model BD-2T, Holohil Systems Ltd., Carp, ON, Canada [ $N = 21$ ]) or without thermistor switches (Model A2410 modified, Advanced Telemetry Systems Inc., Isanti, MN, USA [ $N = 9$ ]). Transmitters with thermistor switches were designed to improve detection of chick mortality because an increase or decrease in temperature given off by the chick resulted in a corresponding increase or decrease in signal pulse rate. We attached radio transmitters to the midline of a chick's mantle with sutures (Ethicon<sup>®</sup> Vicryl FS-2, 3-0, Ethicon Inc., Piscataway, NJ, USA) through front and rear channels, and secured them with 2–3 knots and cyanoacrylic glue (Loctite 422, Henkel Corp., Rocky Hill, CT, USA). A third suture was tied in the middle and over the top of the transmitter. Transmitters were  $\leq 1\%$  of chick body mass ( $\leq 1.1$  g;  $\leq 19$  mm long  $\times$   $\leq 8$  mm wide; 12-cm external whip antenna) to reduce the potential for transmitter effects on behavior or survival (e.g., Ackerman et al. 2004). We held birds in shaded and screen-lined poultry cages (model 5KTC, Murray McMurray Hatchery, Webster City, IA, USA) and returned them back to the site of capture within 3 h. Birds were captured and marked under California Department of Fish and Game Scientific Collection, Federal U.S. Fish and Wildlife Service, and U.S. Geological Survey Bird Banding Laboratory permits, and research was conducted under the guidelines of the U.S. Geological Survey, Western Ecological Research Center, Animal Care and Use Committee.

#### Radio-tracking terns

We tracked radio-marked postfledging terns from trucks and fixed-wing aircraft equipped with dual 4-element Yagi antenna systems (AVM Instrument Co., Colfax, CA, USA). Trucks had null-peak systems to accurately determine

bearings via triangulation (e.g., Takekawa et al. 2002; Ackerman et al. 2006), whereas aircraft had left-right systems to circle and pinpoint signals on either side of the plane (Gilmer et al. 1981). We used triangulation software (Location of a Signal, version 3.0.1, Ecological Software Solutions, Schwägälplstrasse 2, 9107 Urnäsch, Switzerland) to calculate Universal Transverse Mercator coordinates for each location. We located chicks daily by truck and twice weekly by aircraft from the time of radio attachment until their fate was determined (i.e., depredated, dead, or still alive at day 35). Overall, 15% of the 1,094 telemetry locations were collected by aircraft and 85% were collected by truck. Chicks that were not detected were searched for each day until found or until the transmitter was determined to have quit working. We also used an automated telemetry data logger system (AVM Instrument Co., Livermore, CA, USA) at the Pond N7 colony to continuously monitor whether radio-marked terns were present or absent from their natal colony. This system continuously scanned all 30 frequencies of radio-marked terns, with a cycle of about 20 min. When we believed the chick had died, we used hand-held Yagi antenna systems and receivers to find the transmitter and chick within 24 h.

#### Dead fledglings

In addition to sampling breast feathers from apparently healthy, live fledglings, we also sampled breast feathers for mercury analysis from salvaged chicks that were found dead on the colonies during routine monitoring activities. We only included fledglings that were between 21 and 29 days of age when they died as estimated by measuring their structural size and applying the age equation described above.

#### Mercury determination

We analyzed all blood samples for total mercury (U. S. Geological Survey, Davis Field Station Mercury Lab), since more than 95% of mercury in avian blood and feathers is methyl mercury (Thompson and Furness 1989; Fournier et al. 2002; Evers et al. 2005; Rimmer et al. 2005). Prior to analysis, we thawed samples to room temperature and ensured sample homogeneity by inverting the cryovials several times and thoroughly mixing the blood by stirring with a clean pipette tip. We pipetted 200  $\mu$ l of blood from each cryovial and weighed (to the nearest 0.0001 g, Ohaus Adventurer Balance, model AR0640, Ohaus Corporation, Pine Brook, NJ, USA) 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, CT, USA) as described in

Ackerman et al. (2007b, 2008b). 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, calibration checks, and matrix spikes, respectively, averaged ( $\pm$ SE)  $99.72 \pm 1.15\%$  ( $N = 57$ ),  $105.25 \pm 1.37\%$  ( $N = 40$ ), and  $101.67 \pm 1.01\%$  ( $N = 18$ ). Absolute relative percent difference for all duplicates and matrix spike duplicates, respectively, averaged ( $\pm$ SE)  $1.39 \pm 0.30\%$  ( $N = 19$ ) and  $0.91 \pm 0.20\%$  ( $N = 9$ ) for blood, and  $1.07 \pm 0.58\%$  ( $N = 16$ ) and  $2.05 \pm 0.51\%$  ( $N = 10$ ) for feathers.

### Statistical analysis

We analyzed (1) factors influencing mercury concentrations in postfledging tern blood and breast feathers, and (2) whether blood mercury concentrations at the time of fledging influenced subsequent survival rates. For each analysis, we used Akaike's Information Criterion (AIC) to select the best model from an a priori set of candidate models. We used a second-order AIC (AIC<sub>c</sub>) to correct for sample size and considered the model with the smallest AIC<sub>c</sub> to be the most parsimonious (Burnham and Anderson 1998; Anderson et al. 2000). We used the AIC<sub>c</sub> differences between the best model and the other candidate models ( $\Delta\text{AIC}_i = \text{AIC}_i - \text{minimum AIC}_c$ ) to determine the relative ranking of each model, and considered candidate models for biological importance when  $\Delta\text{AIC}_i \leq 2.0$  (Anderson et al. 2001). We calculated Akaike weights ( $w_i = \exp[-\Delta\text{AIC}_i/2] / \sum_j \exp[-\Delta\text{AIC}_j/2]$ ) to assess the weight of evidence that the selected model was actually the 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 assess the relative importance of each variable. Variables with an Akaike weight higher than expected by chance ( $>50\%$ ) in these balanced models were considered for biological importance.

To examine factors influencing mercury concentrations in postfledgings, we built a set of 15 candidate models based on potential effects of colony site, sex, age, and hatch date, and included a sixteenth null model (intercept and variance only) with no effects (Tables 1 and 2). We calculated values used in AIC analysis for each candidate model using ANOVA or ANCOVA with JMP<sup>®</sup> version 4.0.4 (Sall et al. 2001). We log<sub>e</sub>-transformed mercury concentrations (either wet weight for blood, hereafter ww, or fresh weight for feathers, hereafter fw). Unless otherwise noted, we reported geometric means  $\pm$  standard errors (SE) based on back-transformed least-squares means  $\pm$  SE derived from the most parsimonious model each for blood

and feathers. Standard errors of the geometric mean were calculated by the delta method (Williams et al. 2002).

Next, we examined whether blood mercury concentrations just prior to fledging influenced subsequent survival rates using the known fates modeling procedure in Program MARK (White and Burnham 1999). The known fates procedure is derived from the Kaplan–Meier estimator (Kaplan and Meier 1958), with modifications to allow for staggered entry of subjects into the study population (Pollock et al. 1989) and likelihood inference based on binomial probabilities (White and Burnham 1999). Known fates models assume a re-sight probability of one and that individuals which are censored from the dataset due to radio failure or emigration from the study area have the same survival probability as uncensored birds. Known fate models tend to yield very precise estimates of survival for radio telemetry studies when regular detections are made, as was the case for this study, even in situations where sample sizes are small.

We restricted our analysis to a 35-day postfledging period, as the transmitters were designed to transmit for about 40 days. To facilitate our analysis and meet model assumptions, we summarized encounter history data by 5-day intervals. We controlled for variable hatch dates by standardizing individual fates by bird age and assessed postfledging survival over seven intervals, from the age of 25–60 days post-hatch. We conducted a preliminary analysis to confirm that survival probability was independent of radio type (either Model BD-2T or Model A2410, described above). Our candidate model set was designed to evaluate variation in survival probability in relation to blood mercury concentration, size-adjusted mass at radio-marking (mass), sex, annual day (hatch date), and time since fledging (time). Although we attempted to control for hatching date by radio-marking tern chicks that were of similar age (25 day old) during a 7-day period, we included hatch date as a potential explanatory variable to validate our design. We also included size-adjusted mass at radio-marking in the survival analysis because mass often influences juvenile bird survival rates (Pelayo and Clark 2003; Traylor and Alisauskas 2006). To calculate the size-adjusted mass, we controlled for the effects of structural body size (also an index of age) on body mass by calculating the residuals from a regression of body mass on the first principal component (PC) of three structural measurements (i.e., flattened wing chord, short tarsus, and exposed culmen lengths). PC 1 accounted for 82%, 75%, and 30% of the variance in flattened wing chord, short tarsus, and exposed culmen, respectively. In our analysis, radio type was modeled as a group effect. Sex was coded as a binary categorical predictor (0 = female, 1 = male) and modeled as an individual covariate. Blood mercury concentration, mass, and hatch date were incorporated

**Table 1** Ranking of candidate models describing blood mercury concentrations in Forster's tern chicks near the time of fledging in San Francisco Bay, CA, USA during 2006

Model number	Model structure	<i>N</i>	<i>RSS</i> <sup>a</sup>	<i>k</i> <sup>b</sup>	$-\log_e$ -likelihood	<i>AICc</i> <sup>c</sup>	$\Delta$ <i>AICc</i> <sup>d</sup>	Akaike weight <sup>e</sup>
1	Site + hatch date	90	9.14	4	-102.91	-197.35	0.00	0.204
2	Site + age + hatch date	90	8.93	5	-103.95	-197.18	0.17	0.188
3	Site + age	90	9.18	4	-102.72	-196.98	0.37	0.169
4	Site + sex + hatch date	90	9.01	5	-103.56	-196.41	0.94	0.127
5	Site + sex + age + hatch date	90	8.82	6	-104.51	-196.00	1.35	0.104
6	Site + sex + age	90	9.06	5	-103.32	-195.92	1.43	0.100
7	Site	90	9.62	3	-100.63	-194.99	2.36	0.063
8	Site + sex	90	9.46	4	-101.39	-194.31	3.04	0.045
9	Hatch date	90	11.54	3	-92.44	-178.59	18.76	0.000
10	NULL (intercept + variance)	90	11.90	2	-91.04	-177.95	19.40	0.000
11	Age + hatch date	90	11.40	4	-92.99	-177.51	19.84	0.000
12	Sex + hatch date	90	11.43	4	-92.85	-177.23	20.12	0.000
13	Sex	90	11.83	3	-91.30	-176.32	21.03	0.000
14	Sex + age + hatch date	90	11.31	5	-93.35	-175.98	21.37	0.000
15	Age	90	11.90	3	-91.05	-175.82	21.53	0.000
16	Sex + age	90	11.83	4	-91.30	-174.13	23.22	0.000

<sup>a</sup> Residual sum of squares (RSS) 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)**Table 2** Ranking of candidate models describing mercury concentrations in breast feathers of Forster's tern chicks near the time of fledging in San Francisco Bay, CA, USA during 2006

Model number	Model structure	<i>n</i>	<i>RSS</i> <sup>a</sup>	<i>k</i> <sup>b</sup>	$-\log_e$ -likelihood	<i>AICc</i> <sup>c</sup>	$\Delta$ <i>AICc</i> <sup>d</sup>	Akaike weight <sup>e</sup>
1	Site	89	6.30	3	-117.87	-229.46	0.00	0.287
2	Site + hatch date	89	6.21	4	-118.48	-228.49	0.97	0.177
3	Site + sex	89	6.22	4	-118.44	-228.41	1.04	0.170
4	Site + sex + hatch date	89	6.12	5	-119.13	-227.54	1.91	0.110
5	Site + age	89	6.30	4	-117.88	-227.27	2.18	0.096
6	Site + age + hatch date	89	6.19	5	-118.61	-226.49	2.97	0.065
7	Site + sex + age	89	6.21	5	-118.45	-226.17	3.29	0.055
8	Site + sex + age + hatch date	89	6.11	6	-119.23	-225.43	4.02	0.038
9	Hatch date	89	11.05	3	-92.83	-179.37	50.08	0.000
10	Sex + hatch date	89	10.93	4	-93.32	-178.16	51.30	0.000
11	Age + hatch date	89	10.99	4	-93.07	-177.66	51.80	0.000
12	Sex + age + hatch date	89	10.88	5	-93.52	-176.31	53.14	0.000
13	Age	89	13.19	3	-84.94	-163.60	65.85	0.000
14	Sex + age	89	13.02	4	-85.53	-162.59	66.86	0.000
15	NULL (intercept + variance)	89	14.41	2	-81.01	-157.89	71.57	0.000
16	Sex	89	14.13	3	-81.88	-157.48	71.98	0.000

<sup>a</sup> Residual sum of squares (RSS) 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)

as continuous individual covariates and standardized ( $(x - \mu)/SD$ , where  $x$  is the raw score,  $\mu$  is the sample mean, and  $SD$  is standard deviation of the population) to ensure means were 0 with range  $-3$  to  $+3$ , thus allowing numerical optimization of the parameter estimation algorithm in Program MARK. A logit link function was used in calculations to bound real parameters between 0 and 1.

Our candidate set for postfledging survival included 15 models based on additive and multiplicative combinations of blood mercury concentration, mass, sex, hatch date, and three time dependencies, and we included a null model with no effects (Table 3). The most saturated model included all four covariates and contained full time dependency (Time<sub>7</sub>; Table 3, model 15). We also used a time invariant null model (Table 3, model 1; coded as 1,1,1,1,1,1,1) and three models (Time<sub>2</sub>, Time<sub>3</sub>, and Time<sub>7</sub>) designed to evaluate temporal variation in survival rate. Mortality of postfledging birds is typically greatest within the first week of fledging (Kershner et al. 2004; King et al. 2006; Berkeley et al. 2007; Salinas-Melgoza and Renton 2007), so we focused our models

assessing temporal variation in survival rate on this critical time period. The variable Time<sub>2</sub> contained two unique survival estimates, one for the first 10 days after fledging and a second for the remaining 25 days (Table 3, model 3; coded as 1,1,2,2,2,2,2). Time<sub>3</sub> contained three unique survival estimates, one for the first 5 days after fledging, a second for the next 5 days, and a third for the remaining 25 days (Table 3, model 11; coded as 1,2,3,3,3,3,3). Time<sub>7</sub> was fully time dependent and contained seven unique survival estimates for each 5-day time interval for the 35-day postfledging period (Table 3, model 14; coded as 1,2,3,4,5,6,7). Recognizing that our sample population of radio-marked terns was relatively small, we focused our candidate model set primarily on single variable models to evaluate covariate effects (Table 3, models 2–6, 11, and 14). A select group of multivariable models was used to evaluate additive and interactive combinations of the three variables we expected to exert the most influence on survival: blood mercury concentrations, size-adjusted mass at radio-marking, and Time<sub>2</sub> (Table 3, models 7–10, 12–13, and 15).

**Table 3** Ranking of candidate models describing postfledging Forster's tern chick survival in relation to potential explanatory variables including blood mercury concentrations in San Francisco Bay, CA, USA during 2006

Model number	Model structure <sup>a</sup>	<i>N</i>	<i>k</i> <sup>b</sup>	$-\log_e$ -likelihood	AICc <sup>c</sup>	$\Delta$ AICc <sup>d</sup>	Akaike weight <sup>e</sup>	Deviance <sup>f</sup>
1	NULL	30	1	-21.89	45.80	0.00	0.18	43.78
2	Mass	30	2	-21.19	46.46	0.66	0.13	42.38
3	Time <sub>2</sub>	30	2	-21.42	46.92	1.12	0.10	42.84
4	Hg	30	2	-21.55	47.18	1.38	0.09	43.10
5	Sex	30	2	-21.56	47.20	1.40	0.09	43.12
6	Date	30	2	-21.78	47.64	1.84	0.07	43.56
7	Mass + Time <sub>2</sub>	30	3	-20.87	47.90	2.10	0.06	41.74
8	Hg + Mass	30	3	-20.89	47.95	2.14	0.06	40.35
9	Hg + Mass + Time <sub>2</sub>	30	4	-19.86	47.99	2.19	0.06	39.71
10	Hg + Time <sub>2</sub>	30	3	-21.03	48.23	2.43	0.05	42.07
11	Time <sub>3</sub>	30	3	-21.28	48.72	2.91	0.04	42.55
12	Mass $\times$ Time <sub>2</sub>	30	4	-20.75	49.78	3.98	0.02	41.50
13	Hg $\times$ Time <sub>2</sub>	30	4	-20.84	49.96	4.16	0.02	41.69
14	Time <sub>7</sub>	30	7	-19.45	53.69	7.89	0.00	38.90
15	Hg + Mass + Date + Sex + Time <sub>7</sub>	30	11	-16.65	57.22	11.42	0.00	33.29

Daily survival probability was constrained to be equivalent over 5-day time intervals for a 35-day postfledging time period. Unless otherwise noted, no time dependency was incorporated into the Null or single variable models (coded as 1,1,1,1,1,1,1)

<sup>a</sup> Models are additive (+) or multiplicative ( $\times$ ) and variable codes are: NULL = no time dependency (coded as 1,1,1,1,1,1,1), Date = hatching date, Mass = size-adjusted body mass index, Hg = blood mercury concentration, Time<sub>2</sub> = two unique survival estimates (one for the first 10 days after fledging and the other for the remaining 25 days; coded as 1,1,2,2,2,2,2), Time<sub>3</sub> = three unique survival estimates (one for first 5 days after fledging, one for the next 5 days, and the other for the remaining 25 days; coded as 1,2,3,3,3,3,3), Time<sub>7</sub> = seven unique survival estimates for each of the 5-day time intervals (full time dependency; coded as 1,2,3,4,5,6,7)

<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)

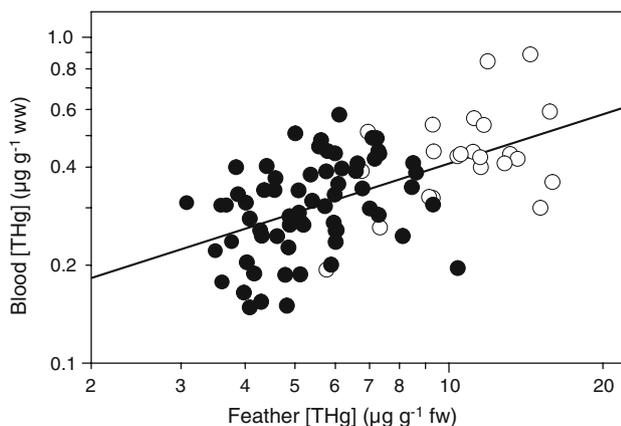
<sup>f</sup> Deviance is defined as the difference in  $-2 \log(\text{likelihood})$  of the current model and  $-2 \log(\text{likelihood})$  of the saturated model. The saturated model is the model with the number of parameters equal to the sample size

## Results

Although we monitored five of the eight tern colonies in 2006, few Forster's tern chicks reached fledging age at Ponds A8, A16, or New Chicago Marsh due to lower nesting densities and higher nest depredation rates than the other colonies. Of 893 tern chicks we monitored in 2006, only 9% were hatched at these three colonies combined, whereas 15% were hatched at the Pond A7 tern colony and 76% were hatched at the Pond N7 tern colony. Additionally, few chicks (<1%) reached the postfledging stage at Ponds A8, A16, or New Chicago Marsh. We therefore selected chicks that were nearing fledging ( $\geq 21$  days of age) within tern colonies at Pond A7 and N7 for our mercury sampling and radio-telemetry studies. We collected blood and breast feathers from 90 chicks in 2006; 23 chicks were sampled at Pond A7 (12 female and 11 male) and 67 chicks were sampled at Pond N7 (28 female and 39 male). Of these, we radio-marked 30 chicks (13 females and 17 males) just before they fledged at  $25 \pm 1.4$  (SD) days (range: 23–29 days) at the Pond N7 tern colony.

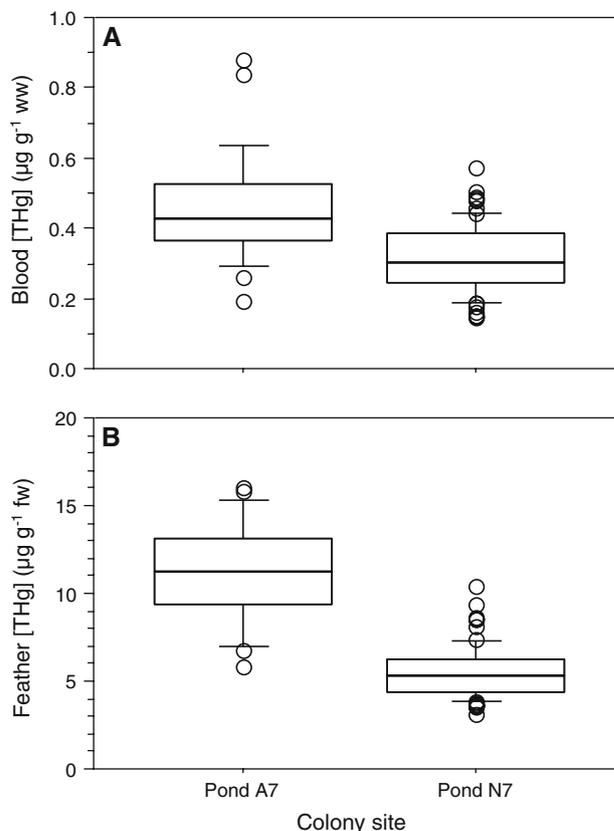
### Mercury concentrations in postfledging terns

The geometric mean (design-based) mercury concentrations of fledgling Forster's terns at  $25 \pm 1.5$  (SD) days of age were  $0.33 \pm 0.01 \mu\text{g g}^{-1}$  ww for blood ( $N = 90$ ) and  $6.44 \pm 0.28 \mu\text{g g}^{-1}$  fw for breast feathers ( $N = 89$ ). Mercury concentrations in fledgling tern blood was weakly correlated with breast feather mercury concentrations (linear regression:  $N = 89$ ,  $R^2 = 0.31$ ,  $P < 0.0001$ ; Fig. 1). The most parsimonious model explaining mercury

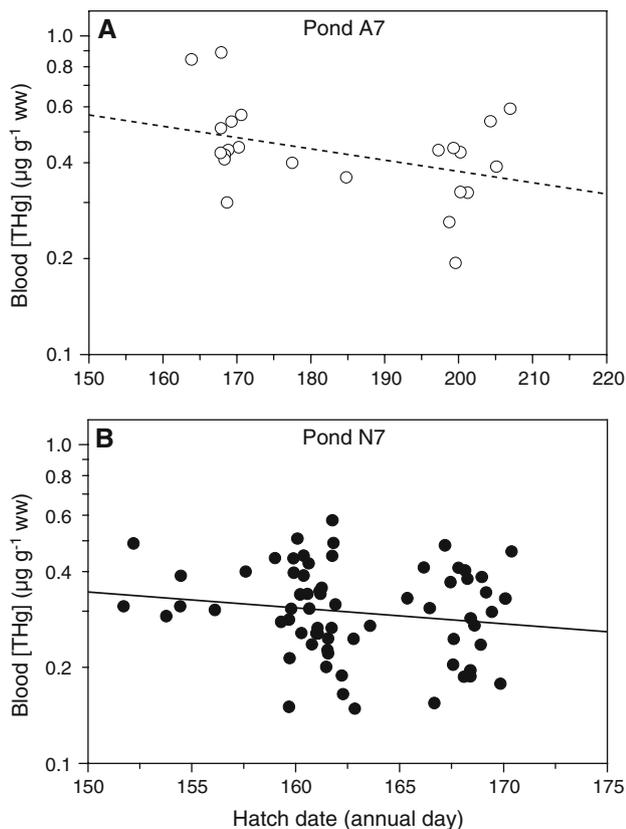


**Fig. 1** Blood mercury concentrations ( $\mu\text{g g}^{-1}$  wet weight [ww]) in fledgling Forster's terns were weakly correlated with breast feather mercury concentrations ( $\mu\text{g g}^{-1}$  fresh weight [fw]) in South San Francisco Bay, CA, USA during summer 2006 ( $N = 89$ ,  $R^2 = 0.31$ ,  $P < 0.0001$ ). Open circles are fledglings from Pond A7 ( $N = 23$ ) and closed circles are fledglings from Pond N7 ( $N = 66$ ). Both axes are on  $\log_{10}$ -scales

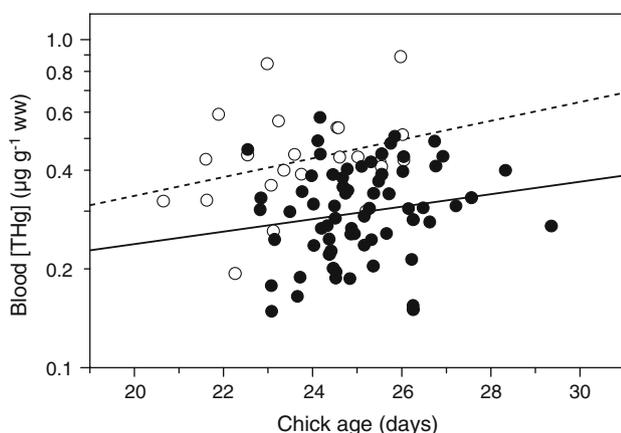
concentrations in postfledging tern blood contained both colony site and hatch date (Table 1). However, this model had an Akaike weight of only 0.20 and several other models, which all contained capture site, provided a comparable fit to the data (i.e.,  $\Delta\text{AICc} < 2.0$ ). We, therefore, used variable weights to assess the relative importance of each variable. Models containing colony site had a combined AIC weight of  $>99\%$ , compared to date (62%), age (56%), and sex (38%), indicating that colony site was the most important factor explaining blood mercury concentrations, but that date and, to some extent, age also contained some information. Blood mercury concentrations were higher in Pond A7 ( $0.49 \pm 0.04 \mu\text{g g}^{-1}$  ww) than in Pond N7 ( $0.29 \pm 0.01 \mu\text{g g}^{-1}$  ww; Fig. 2a), and tended to decline with hatching date and increase with age. Using the second best model which contained colony site, date, and age, we estimated blood mercury concentrations in postfledging terns decreased with hatching date by  $28 \pm 15\%$  during a 50-day (standardized) hatching period (Fig. 3) and increased slightly with age by  $30 \pm 24\%$  during the last week prior to fledging at 28 days (Fig. 4).



**Fig. 2** Box plots depicting total mercury concentrations ([THg]) in (a) blood ( $\mu\text{g g}^{-1}$  wet weight [ww]) and (b) breast feathers ( $\mu\text{g g}^{-1}$  fresh weight [fw]) of Forster's tern chicks nearing fledging in South San Francisco Bay, CA, USA during summer 2006. Sample sizes were (a)  $N = 23$  and (b)  $N = 23$  for fledglings in Pond A7 and (a)  $N = 67$  and (b)  $N = 66$  for fledglings in Pond N7



**Fig. 3** Blood mercury concentrations ( $\mu\text{g g}^{-1}$  wet weight [ww]) in fledglings decreased with hatch date (annual day) at the (a) Pond A7 (open circles and dashed line,  $N = 23$ ) and (b) Pond N7 (closed circles and solid line,  $N = 67$ ) Forster's tern colonies in South San Francisco Bay, CA, USA during summer of 2006. Both Y-axes are on  $\log_{10}$ -scales; x-axis scales differ



**Fig. 4** Blood mercury concentrations ( $\mu\text{g g}^{-1}$  wet weight [ww]) increased with fledgling age at the Pond A7 (open circles and dashed line,  $N = 23$ ) and Pond N7 (closed circles and solid line,  $N = 67$ ) Forster's tern colonies in South San Francisco Bay, CA, USA during summer of 2006. The Y-axis is on a  $\log_{10}$ -scale

Similarly, the best model explaining mercury concentrations in breast feathers contained only colony site (Table 2) and had an Akaike weight of 0.29. Several other

candidate models provided a reasonably good fit to the data, including colony site and date (0.18), site and sex (0.17), and site, date, and sex (0.11). Using evidence ratios, the model containing only colony site was 1.63, 1.69, and 2.60 times more likely than the next best models, respectively. Models containing colony site had a combined AIC weight of >99%, compared to date (39%), sex (37%), and age (26%); indicating colony site's overriding importance for explaining feather mercury concentrations. Similar to blood, feather mercury concentrations were nearly twice as high in Pond A7 ( $10.74 \pm 0.60 \mu\text{g g}^{-1}$  fw) than in Pond N7 ( $5.39 \pm 0.18 \mu\text{g g}^{-1}$  fw; Fig. 2b).

#### Postfledging tern survival

Mercury concentrations in radio-marked postfledging terns at Pond N7 ranged from  $0.19 \mu\text{g g}^{-1}$  ww to  $0.50 \mu\text{g g}^{-1}$  ww in blood and  $3.69 \mu\text{g g}^{-1}$  fw to  $10.45 \mu\text{g g}^{-1}$  fw in breast feathers. Five of 30 postfledging terns that we radio-marked subsequently died; including 17.6% (3 of 17) of males and 15.4% (2 of 13) of females. We recovered the dead terns and re-tested mercury concentrations in their breast feathers; there were no signs of depredation or other obvious causes of death. Mercury concentrations in breast feathers increased for four of the five terns (from  $3.69$  to  $4.25 \mu\text{g g}^{-1}$  fw in 7 days,  $4.60$  to  $5.31 \mu\text{g g}^{-1}$  fw in 10 days,  $5.60$  to  $6.65 \mu\text{g g}^{-1}$  fw in 20 days, and  $9.36$  to  $9.86 \mu\text{g g}^{-1}$  fw in 26 days) and decreased in one tern (from  $8.66$  to  $7.53 \mu\text{g g}^{-1}$  fw in 7 days) between the date they were sampled alive and when they were sampled dead.

In the first step of our survival analysis, we confirmed that survival rates were similar irrespective of radio type (*Null*:  $N = 30$ ,  $K = 1$ ,  $-\log_e$ -likelihood =  $-21.89$ ,  $\text{AICc} = 45.80$ ,  $\Delta\text{AICc} = 0.00$ , Akaike weight = 0.70, deviance = 43.78; *Radio type*:  $N = 30$ ,  $K = 2$ ,  $-\log_e$ -likelihood =  $-21.72$ ,  $\text{AICc} = 47.51$ ,  $\Delta\text{AICc} = 1.71$ , Akaike weight = 0.30, deviance = 43.43). Three of 21 (14.3%) terns fitted with Model BD-2T transmitters died compared to two of nine (22.2%) terns fitted with Model A2410 transmitters. On the basis of these results, we did not include it as an explanatory variable in subsequent analyses.

The most parsimonious model explaining postfledging tern survival was the null model with no effects (Table 3). However, this best fitting model had an Akaike weight of only 0.18, and five other single variable models fit the data reasonably well (i.e.,  $\Delta\text{AICc} \leq 2.0$ ). Conversely, models containing multiple variables or interactions including covariates with a time component had a poorer fit to the data. We further examined each variable's potential effect on postfledging tern survival using coefficient (beta) estimates derived from the best model where the variable of interest was included; thus, coefficient estimates were derived from models 2–6 (Table 3). Coefficient estimates

( $\pm$ SE) indicated that there were relatively small to no effects of blood mercury concentration ( $0.396 \pm 0.505$ ),  $\text{Time}_2$  ( $-0.887 \pm 0.929$ ), sex ( $0.742 \pm 0.928$ ), or hatch date ( $-0.212 \pm 0.466$ ) on postfledging tern survival rates because standard errors were relatively large when compared to their coefficient estimates. Conversely, the coefficient estimate ( $\pm$ SE) for size-adjusted mass ( $0.565 \pm 0.467$ ) indicated that survival rates of postfledging terns increased with relative mass at the time of fledging, although the effect was relatively weak.

To more fully examine the effect of size-adjusted mass on predicted postfledging tern survival rates, we utilized the user-specified individual covariate feature in Program MARK. Using the best-fitting model that included size-adjusted mass as a variable (Table 3, model 2), we input size-adjusted mass at a range of values from the minimum ( $-40$  g residual mass) to the maximum ( $+25$  g residual mass) observed values. We found a 2.7% difference in daily survival rates between the lowest and highest observed size-adjusted masses. Overall, the cumulative 35-day survival probability was  $61.0 \pm 48.3\%$  (SE) lower for terns with the lowest observed masses than for terns with the highest observed masses.

Cumulative survival during the 35-day postfledging time period was  $0.809 \pm 0.085$  (SE; Fig. 5). Using model averaged (all models considered) parameter estimates for each 5-day time interval, daily survival rates were 0.992 during the first 5-day time interval, 0.993 during the second time interval, and 0.995 during each of the final five 5-day time intervals. Although daily survival rates increased slightly with age, the effect of time on survival was relatively small compared to the effect of mass since the coefficient

estimate's SE was larger relative to its mean and mass was a more important model than  $\text{Time}_2$  in the AIC analysis.

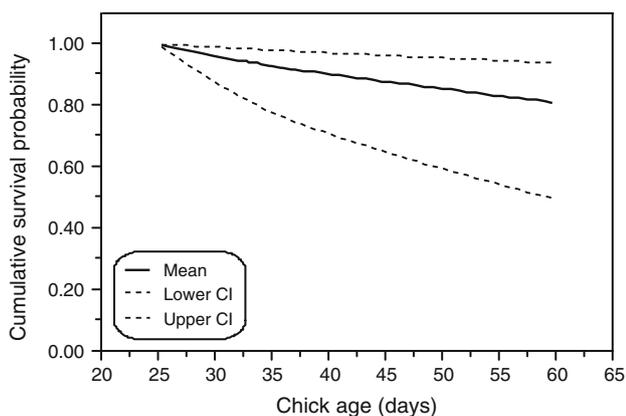
#### Mercury concentrations in dead fledgling terns

We compared the best model explaining factors influencing mercury concentrations in fledgling tern breast feathers (Table 2, model 1: Site) to a second model incorporating the tern's fate in addition to this same variable (Site + Fate). For this analysis, we included 19 additional fledgling tern chicks that were found dead to our main dataset of alive fledgling chicks ( $N = 89$ ) and included a fate column as either sampled dead or alive. The addition of the fate variable did not improve the model's fit (Site:  $N = 108$ ,  $RSS = 6.30$ ,  $K = 3$ ,  $-\log_e$ -likelihood =  $-153.48$ ,  $AIC_c = -300.73$ ,  $\Delta AIC_c = 0.00$ , Akaike weight = 0.25; Site + Fate:  $N = 108$ ,  $RSS = 7.11$ ,  $K = 4$ ,  $-\log_e$ -likelihood =  $-146.95$ ,  $AIC_c = -285.51$ ,  $\Delta AIC_c = 15.23$ , Akaike weight  $< 0.01$ ). Mercury concentrations in breast feathers of terns found dead ( $7.46 \pm 0.48 \mu\text{g g}^{-1}$  fw) near the age of fledging were no different than levels in randomly sampled live terns of similar age ( $7.60 \pm 0.24 \mu\text{g g}^{-1}$  fw).

#### Discussion

The geometric mean mercury concentrations of fledgling Forster's terns at 25-day of age in San Francisco Bay were  $0.33 \mu\text{g g}^{-1}$  ww for blood and  $6.44 \mu\text{g g}^{-1}$  fw for breast feathers. These blood mercury concentrations are similar to, and feather mercury concentrations are considerably higher than, those reported for other tern species sampled as juveniles (reviews by Sepúlveda et al. 1999; Kojadinovic et al. 2007). For example, the next highest reported average mercury concentrations in juvenile tern feathers were about  $4.4 \mu\text{g g}^{-1}$  fw for common terns (*Sterna hirundo*) in New Jersey (Burger and Gochfeld 1997) and  $3.1 \mu\text{g g}^{-1}$  fw for common terns in Massachusetts (Burger et al. 1994). Few other piscivorous birds sampled as juveniles contain feather mercury concentrations as high as Forster's tern chicks in San Francisco Bay, but great egret (*Ardea albus*), common loon (*Gavia immer*), and bald eagle (*Haliaeetus leucocephalus*) feather mercury concentrations have been documented to be higher in some areas (reviews by Burger et al. 1994; Sepúlveda et al. 1999; Kojadinovic et al. 2007).

Mercury concentrations in blood and feathers of fledgling Forster's terns were mostly influenced by colony site. Fledgling mercury concentrations in Pond A7 (Alviso salt pond complex) were about 1.7 and 2.0 times higher in blood and breast feathers, respectively, than fledglings raised in Pond N7 (Newark salt pond complex). Roughly 15% of the 893 chicks raised in South San Francisco Bay in 2006 hatched at this higher mercury site and 76% hatched



**Fig. 5** Cumulative survival probability (with confidence intervals [CI]) for juvenile Forster's terns during the 35-day postfledging time period at the Pond N7 tern colony in South San Francisco Bay, CA, USA during summer 2006. Survival rates were estimated by radio-marking 30 Forster's terns just before they fledged at  $25 \pm 1.4$  (SD) days of age, and tracking them daily for 35 subsequent days

at the Pond N7 colony. We observed similar differences between these same general areas in American avocet (*Recurvirostra americana*) chick and adult mercury concentrations (Ackerman et al. 2007b, 2008a). We also found that site was the most important factor explaining blood mercury concentrations of pre-breeding adult Forster's terns in San Francisco Bay and that terns exhibited fairly high site fidelity relative to their mobility (Ackerman et al. 2008b). Considering that Forster's tern parents likely foraged near their nest sites, higher mercury concentrations in fledglings being raised at Pond A7 are not surprising due to their proximity to Alviso Slough, which connects the Guadalupe River watershed and the historic New Almaden mercury mine, a major source of mercury in the region, to the San Francisco Bay (Conaway et al. 2004).

Although colony site had an overriding influence on fledgling mercury concentrations, hatching date and age also affected blood, but probably not feather, mercury concentrations. Blood mercury concentrations in fledglings declined with hatch date by 28% during the 50-day (standardized) hatching period. In contrast, we found that blood mercury concentrations more than tripled in adult Forster's terns during the 45-day pre-breeding season in San Francisco Bay (Ackerman et al. 2008b). This apparent discrepancy is likely due to adults rapidly accumulating mercury upon arrival in San Francisco Bay to breed, compared with their wintering areas where they were presumably exposed to lower mercury levels. Fledgling mercury concentrations, on the other hand, are more likely to be responsive to changes in dietary mercury exposure because much of their maternally derived mercury present in ovo has been diluted by their rapid growth or depurated during feather production (Monteiro and Furness 2001; Fournier et al. 2002; Kenow et al. 2003). Indeed, Forster's tern chick blood mercury concentrations rapidly decline after hatching and older chicks that are approaching fledging have relatively low mercury concentrations (Ackerman et al. 2007a). Dietary mercury exposure at this late chick age may not be diluted by growth or depurated into feathers since chick growth and feather production slow at the time of fledging. Accordingly, we found that blood mercury concentrations increased with age by 30% during the last week prior to fledging at 28-days. The decline of fledgling mercury concentrations with hatching date therefore may be caused by changes in prey composition, size, or mercury contamination during the breeding season.

We did not find support for an influence of mercury on postfledging survival, despite observing a 2.6- and 2.8-fold range in mercury concentrations observed in radio-marked tern blood and feathers, respectively. It is possible that mercury does affect postfledging survival at higher concentrations than we observed in our sample of radio-marked terns. For example, 9% and 16% of all the fledglings we

sampled had blood or breast feather mercury concentrations, respectively, that were higher than those of the most contaminated chick that we happened to radio-mark. If mercury effects survival only at these highest concentrations, then a much larger sample of radio-marked terns would be necessary to detect such an effect. Few studies have been able to detect an effect of mercury on juvenile bird survival. Elsewhere, we did not find an effect of mercury on survival of radio-marked American avocet and black-necked stilt (*Himantopus mexicanus*) chicks from hatching to fledging in San Francisco Bay, although we did find that newly hatched chicks found dead near nesting sites had higher mercury concentrations than similar-aged live chicks sampled randomly (Ackerman et al. 2008a). Sepúlveda et al. (1999) also used radio-telemetry and did not detect an effect of natural or manipulated levels of mercury on postfledging survival of great egrets (*Ardea albus*) in Southern Florida. Using mark-resight methodology for common loons (*Gavia immer*) breeding in Wisconsin, Meyer et al. (1998) found that chick production was lower at lakes where chick blood mercury concentrations were higher, but Merrill et al. (2005) did not find an effect of mercury exposure on chick survival. In contrast, laboratory studies have more consistently demonstrated that methyl mercury exposure can reduce chick survival (Heinz 1974; Finley and Stendell 1978; Heinz and Hoffman 1998; but see Kenow et al. 2003), as well as chick growth (Spalding et al. 2000b) and health (Spalding et al. 2000a; Kenow et al. 2007).

Few studies have estimated postfledging survival in terns or examined factors that influence survival. Cumulative survival of postfledging Forster's terns was 81% during the 5-week time period in San Francisco Bay. Similarly, postfledging survival of radio-marked black-fronted terns (*Sterna albobriata*) in New Zealand was 80% during a 4-week period after fledging (Keedwell 2003). Using mark-resight methods, annual postfledging survival was estimated to be 53–57% for roseate terns (*Sterna dougallii*) in Connecticut (Spendelov et al. 2002) and 86% for royal terns (*Thalasseus maximus*) in Southern California (Collins and Doherty 2006). Mortality rates are generally highest for postfledging birds within the first week after fledging (Keedwell 2003; Berkeley et al. 2007; Salinas-Melgoza and Renton 2007). Although daily survival rates were lower during the first 10-days after fledging than the subsequent 25-days, time was not an important variable influencing postfledging survival rates for Forster's terns. Hatch date and sex also had no influence on postfledging survival rates. However, we did not expect hatch date to be an important determinant of survival in our case because we designed our study to assess the effect of mercury on survival, and we specifically controlled for hatch date's potential effect by radio-marking fledgling terns that were >21-days of age during only a 7-day time

period. Earlier hatched chicks often have higher survival during the hatching to fledging (Arnold et al. 2006; Mehl and Alisauskas 2007) and postfledging time periods in birds (Lindén et al. 1992; Harris et al. 2007).

In contrast, we found that size-adjusted mass affected postfledging survival of Forster's terns. The probability of survival during the 35-day postfledging time period was 61% lower for terns with the lowest, compared to the highest, observed masses. Mass and body condition often are positively related to postfledging survival in birds (Krementz et al. 1989; Lindén et al. 1992) and also with survival of tern chicks from hatching to fledging (roseate terns, Nisbet et al. 1999; sandwich terns [*Sterna sandvicensis*], Stienen and Brenninkmeijer 2002). Mercury exposure in ovo or soon after hatching can influence chick growth rates and fledging mass. For example, captive great egret nestlings that were fed a diet containing elevated mercury levels had reduced appetites and body condition (Spalding et al. 2000b). Mass growth rate, but not asymptotic weight, of tree swallow (*Tachycineta bicolor*) nestlings was negatively related to feather mercury concentrations in the wild (Longcore et al. 2007). In contrast, a captive common loon study that dosed chicks with mercury via their diet did not detect an effect of mercury on chick growth rates (Kenow et al. 2003). Thus, although mercury was not related to postfledging Forster's tern survival, it may influence chicks earlier in life. Our future research will examine effects of mercury on growth and survival of Forster's tern chicks from hatching to fledging.

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