THE PULSE OF THE ESTUARY

2008

Monitoring and Managing Water Quality in the San Francisco Estuary

MERCURY: Water Quality Enemy Number One

A Report of the Regional Monitoring Program for Water Quality in the San Francisco Estuary

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Mercury Bioaccumulation and Effects on Birds in San Francisco Bay

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Black-necked stilts. Photograph by Josh Ackerman.

HIGHLIGHTS

- San Francisco Bay is an important wintering and breeding ground for more than 1 million waterbirds annually
- Mercury concentrations are highest in birds that eat fish and that reside in the Lower South Bay
- When Forster's terns arrive in the Bay in spring to breed, mercury concentrations in their blood increase by four-fold in a six week period
- Based on mercury concentrations in blood, nearly 60% of all breeding Forster's terns sampled in the Bay are at high risk of toxic effects
- One important piece of evidence of impairment of reproduction in Forster's terns is that average mercury concentrations in failed-to-hatch eggs were statistically significantly higher than in randomly selected eggs
- Avian eggs represent an ideal matrix for assessing bioaccumulation because they are indicative of short-term, localized exposure and are central to predicting risk in multiple lifestages

San Francisco Bay: An Avian Haven

San Francisco Bay is the largest estuary on the West Coast and serves as an important wintering and breeding ground for more than 1 million waterbirds annually. Although the Bay has lost approximately 80% of its tidal wetland habitat, the remaining habitat mosaic, including open bay, tidal mudflats, tidal marsh, diked marsh, and salt ponds, supports a diverse and abundant community of waterbirds. Currently, the Bay is undergoing large-scale wetland restoration and enhancements, including the South Bay Salt Pond Restoration Project, as well as smaller wetland enhancements throughout the Bay.

Unfortunately, the Bay is also highly contaminated with mercury, due primarily to a legacy of gold mining in the Sierra Nevada and mercury mining in the Coast Range. There is concern that wetland restoration may enhance conditions that stimulate the bacterial conversion of legacy mercury to the toxic and bioaccumulative form, methylmercury. Mercury accumulates to high concentrations at the top of the food web, and avian reproduction is particularly sensitive to the toxic effects of mercury. Consequently, several waterbird species are suspected to be experiencing deleterious effects due to mercury exposure, and this situation may worsen as wetland restoration moves forward.

Recent extensive research by the US Geological Survey (USGS) has examined mercury exposure and bioaccumulation in waterbirds, as well as mercury effects on avian reproduction. This work has been funded by CALFED, the Regional Monitoring Program, and USGS. These results are important not only for elucidating the overall risk of mercury to waterbird populations within the Bay, but also for facilitating management actions and development of restoration targets by establishing mercury toxicity thresholds for birds breeding in San Francisco Bay.

Patterns of Mercury Exposure in Waterbirds

Mercury concentrations differ among waterbird species, reflecting variation in diet and foraging habitats among species. Mercury concentrations in birds that eat fish are substantially higher than those in shorebirds which primarily consume aquatic invertebrates (insects and crustaceans). For example, average mercury levels in the blood of fish-eating Forster's terns and Caspian terns from locations throughout San Francisco Bay were 1.41 and 1.37 ppm, respectively, whereas black-necked stilts and American avocets (two invertebrate-eating species) had average concentrations of 0.99 ppm and 0.30 ppm, respectively (Ackerman et al. 2007a).

Sampling location and date are also important factors influencing mercury concentrations in waterbirds (Ackerman et al 2007b; Ackerman et al. 2008b). In fact, location was the single most important factor in determining blood mercury concentrations in pre-breeding adult stilts and avocets (Ackerman et al. 2007b), and among the most important factors in pre-breeding Forster's terns (Ackerman et al. 2008b). Waterbird exposure to mercury appears to follow different spatial patterns in different regions of the Bay: lower South Bay (south of the Dumbarton Bridge), upper South Bay (Dumbarton Bridge to San Mateo Bridge), and Napa Marsh. For each species, blood mercury concentrations were generally highest in lower South Bay, intermediate in Napa Marsh, and lowest in upper South Bay (Figure 1).

Blood mercury concentrations were generally highest in lower South Bay, intermediate in Napa Marsh, and lowest in upper South Bay

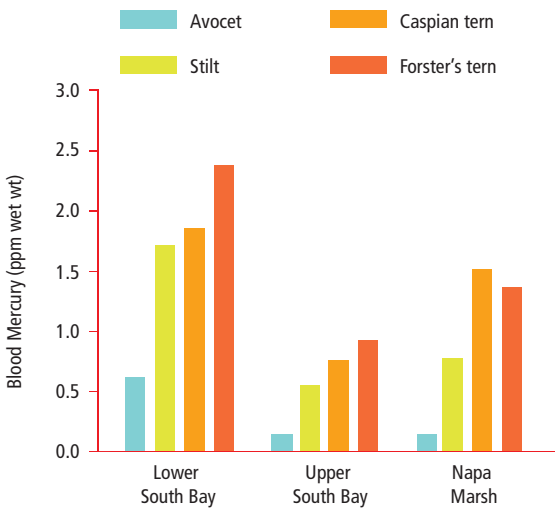
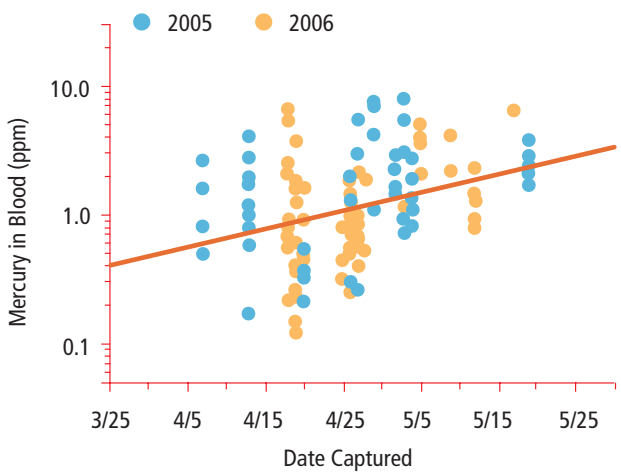


FIGURE 1
Mercury concentrations were highest in blood of Forster's terns and Caspian terns across all study regions, whereas concentrations in stilts were moderate, and those in avocets were generally lowest. Concentrations were substantially higher in all birds from the lower South Bay than in those from upper South Bay or Napa Marsh.

Although birds are highly mobile, following bird movements with tiny radio transmitters (radiotelemetry) coupled with measurements of site-specific mercury concentrations suggest that waterbirds have relatively high site fidelity, making them excellent indicators of mercury exposure in specific locations. In fact, radiotelemetry data showed that avocets, stilts, and Forster's terns generally remained within the wetland where the birds were captured.

Date of sampling also can be an important factor influencing mercury concentrations in waterbirds in San Francisco Bay, particularly for migratory species that spend a portion of the year outside of the Bay. Forster's terns overwinter mainly outside of the Bay (though exact wintering locations are currently unknown) and arrive in early March, prior to breeding, with relatively low mercury concentrations (approximately 0.5 ppm) in their blood. Yet, by mid-May when nest initiation begins, blood mercury concentrations increase by over four-fold to 2.0 ppm (Figure 2).



Footnote: Note log scale of graph. Total mercury reported on a wet weight basis. Linear regression line shown. From Ackerman et al. 2008b.

This dramatic increase in mercury concentrations after arrival in the Bay, over a period of about six weeks, coincides with nest initiation. Thus, mercury concentrations in Forster's terns become particularly elevated during the egg-formation stage when mercury circulating in the bloodstream is often deposited into eggs. Moreover, mercury concentrations in breeding Forster's terns were observed to increase even more during and after nesting, indicating that terns continued to accumulate mercury in the Bay at a very fast rate during a sensitive time-frame in the breeding cycle (Figure 3).

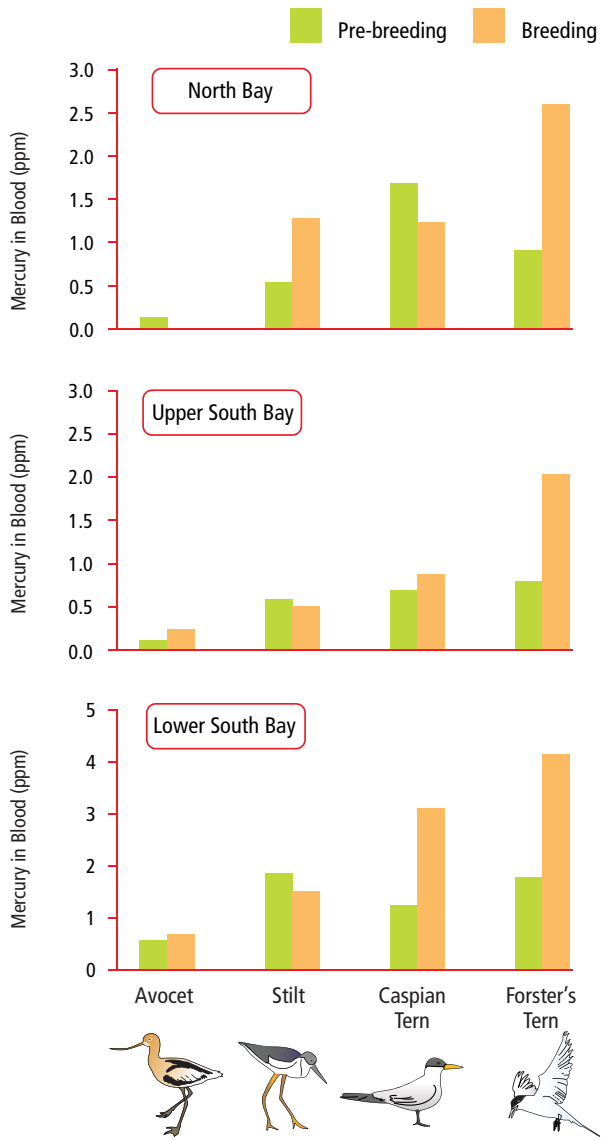
In contrast to terns, sampling date was of little importance in determining mercury levels in adult pre-breeding stilts and avocets, nor were there any clear temporal trends between pre-breeding adults and breeding adults across regions (Figure 3). This finding is likely because stilts and avocets overwinter in the Bay where they are exposed to elevated mercury concentrations year-round. These results suggest that resident shorebirds such as avocets and stilts may be effective indicators of year-round mercury accumulation in the Bay.

FIGURE 2
Mercury concentrations in blood of pre-breeding Forster's terns increase at later dates of capture, indicating that concentrations increase with time spent in the Bay. Concentrations increase by about 4-fold over a 6-week time period from when they arrive in the Bay to when they begin breeding.

The Influence of Diet and Foraging Habitat

Although some locations clearly have higher mercury exposure than others, the foraging ecology of each species also has an important influence on mercury bioaccumulation. Two important factors include trophic level (position in the food web) and foraging habitat. Both Forster's terns and Caspian terns primarily forage on fish (higher in the food web), whereas the prey of stilts and avocets is dominated by insects and crustaceans (lower in the food web). Because mercury biomagnifies, increasing in concentration with each successive step up the food chain, it is not surprising that terns also have higher mercury concentrations than avocets and stilts.

Tern mercury concentrations also are highly dependent on their diet at each colony. For example, we have used fish delivered to colonies by mates and parents to quantify colony-specific tern diets at several sites in the Bay. The results indicate that tern diet varies considerably among colonies, and predominant prey fish include both water column (e.g., Mississippi silverside, three-spine stickleback) and bottom-dwelling (e.g., long-jawed mudsucker, yellowfin goby) fish (Figure 4). Thus, tern mercury concentrations depend not only on spatial variation in mercury contamination but also on prey preferences and foraging range. As a result, individual fish species can be poor indicators of mercury concentrations in the eggs of fish-eating birds (Ackerman et al. 2007a).



Footnote: Note different scales. Total mercury reported on a wet weight basis.

FIGURE 3

Mercury concentrations in blood of pre-breeding and breeding American avocets, black-necked stilts, Caspian terns, and Forster's terns in three regions of San Francisco Bay. Forster's terns show dramatic increases between pre-breeding and breeding time periods in all three regions, suggesting that they forage in sites of particularly high exposure in the Bay.

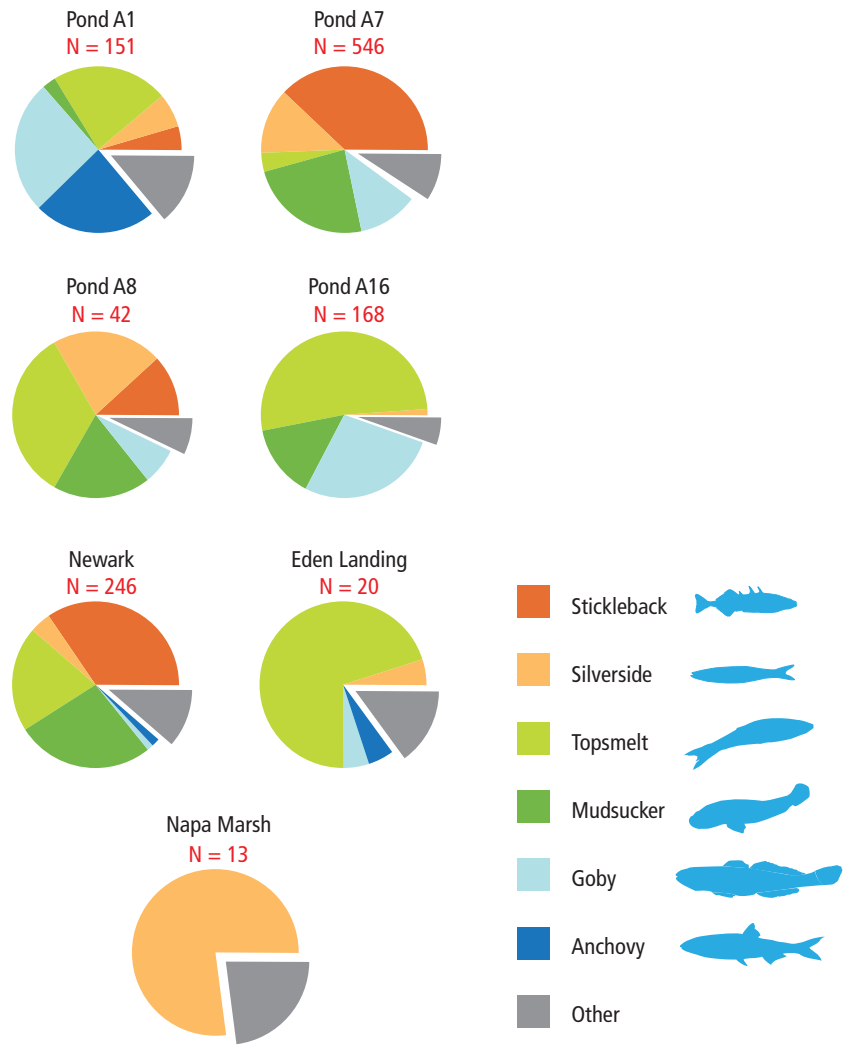


FIGURE 4

Diet composition of Forster's terns varies substantially among several colonies in San Francisco Bay. These results indicate that terns are likely very opportunistic foragers, and that no single fish species serves as a good indicator of tern diet in the Bay.

Interestingly, stilts have substantially higher mercury concentrations than avocets, even though they are often co-located and forage in similar areas on similar species (invertebrates). These results suggest that in some circumstances trophic level may have less of an influence on mercury bioaccumulation than other factors. In fact, chemical tracers (carbon isotopes) indicate that stilts and avocets forage in substantially different micro-habitats. Our radiotelemetry data support this interpretation, and indicate that stilts feed in salt marsh habitat more than avocets, whereas avocets feed more in tidal flats and tidal marsh than stilts (Ackerman et al. 2007b). These results suggest that foraging habitat is an important consideration when evaluating potential risk of mercury to waterbirds

Although these results indicate substantial risk to waterbirds such as terns in San Francisco Bay, it is important to evaluate this interpretation cautiously

Forster's Tern. Photograph by Josh Ackerman.

Evidence for Significant Risks

As discussed above, risk of mercury to birds in San Francisco Bay varies with trophic level, foraging habitat, and location. Another important factor is species-specific sensitivity to mercury. Based on risk thresholds developed for other bird species (Evers et al. 2004, Heinz 1974), Forster's terns appear to be at highest risk in the Bay to the deleterious effects of mercury on avian reproduction (Figure 5).

Based on mercury concentrations in blood, nearly 60% of all breeding Forster's terns sampled in the San Francisco Bay were at high to extra-high risk of toxic effects (Ackerman et al. 2007a), and the entire remaining population was considered to still be at moderate risk. Interestingly, a much smaller proportion of the Caspian tern population (10%) is considered to be at high to extra-high risk, despite also being fish-eaters. Although 5% of stilts sampled were at high to extra-high risk, most breeding stilts were at moderate and low risk to mercury, and all avocets were at low to moderate risk.

Although these results indicate substantial risk to waterbirds such as terns in San Francisco Bay, it is important to evaluate this interpretation cautiously. The risk categories were derived from toxicity endpoints from other species (common loons and mallards), as well as from studies done in the lab (Heinz et al. 2008). Sensitivity to mercury is known to differ among species, and results from lab studies are often difficult to apply in the field. Recent work comparing the effects of mercury on hatchability in 26 species has shown that sensitivities can vary by up to 10-fold. For example, the LC50 (concentration at which 50% of the eggs exposed died) for common terns, a species closely related to Forster's terns, was 4.35 ppm dry weight (Heinz et al. 2008). Unfortunately, 82% of all Forster's tern eggs sampled in San Francisco Bay exceeded this level, suggesting that mercury levels in this San Francisco Bay biosentinel species may exceed levels of concern. However, the methylmercury injected into eggs for the lab studies is thought to be substantially more toxic than mercury naturally deposited into an egg by a mother bird. It is therefore difficult to base management decisions on these laboratory studies. Thus, there is a need to evaluate the actual toxicity of mercury to species breeding in the Bay to determine whether mercury is having an impact on bird populations, as well as to enhance the utility of monitoring results. Currently, USGS scientists are working on establishing better toxicity thresholds for birds breeding in San Francisco Bay. These thresholds will be established for egg hatchability, but other toxicity endpoints such as chick growth and survival may also be evaluated.

Is Mercury Impairing Waterbird Reproduction?

Mercury can impair waterbird reproduction in several ways, including altering adult nesting behavior, reducing egg hatchability, and reducing chick growth, health, and survival. Egg hatchability is generally thought to be the most sensitive stage, and may have the largest impact on reproduction. There is evidence that hatchability in Forster's terns may be impaired by mercury in the Bay. One compelling piece of evidence is that average mercury concentrations in failed-to-hatch eggs were significantly higher than those in random eggs sampled from successful nests, and in abandoned eggs (Figure 6).

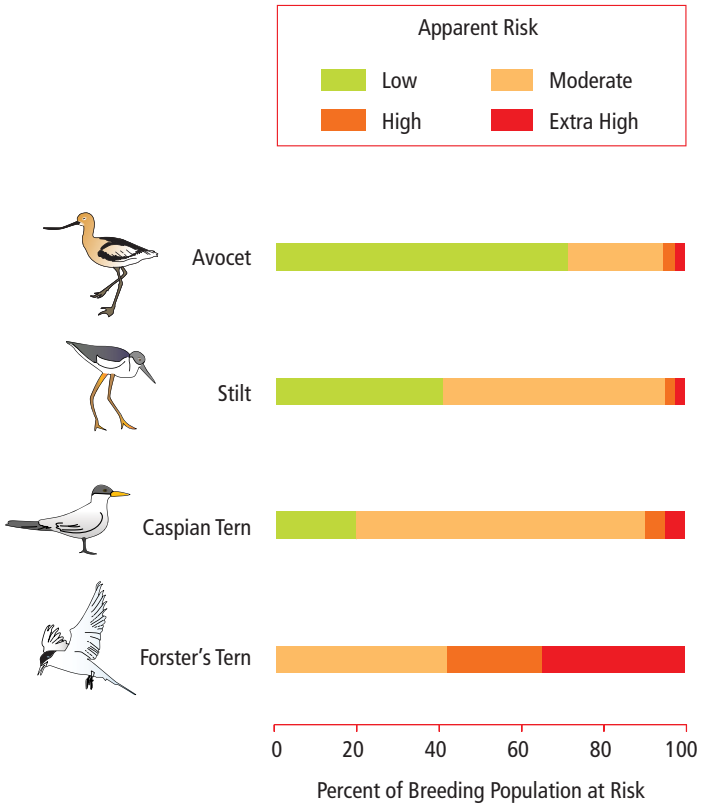


FIGURE 5
Percent of population of breeding birds at risk from mercury exposure in San Francisco Bay. These risk evaluations indicate Forster's terns are at substantially higher risk from mercury than other waterbird species. In fact, nearly 60% of Forster's terns breeding in the Bay have mercury concentrations in their blood that are at or above high risk thresholds developed for other bird species. In contrast, Caspian terns and stilts are at moderate risk, and avocets are generally at low risk.

Tern chick. Photograph by Josh Ackerman.

Footnote: Total mercury on a dry weight basis.

FIGURE 6
Mercury concentrations in failed-to-hatch egg of Forster's terns were statistically significantly higher than those in abandoned eggs and random eggs sampled from successful nests. This suggests that mercury is impairing hatchability of Forster's tern eggs in San Francisco Bay.

However, defining a threshold for mercury impairment of egg hatchability is confounded by many factors that make interpreting egg mercury concentrations difficult. Both predation and prey availability are important variables influencing natural hatchability and nest success in waterbirds in the Bay, and the relative impact of each factor can vary considerably among sites and years. Moreover, these factors may also interact with mercury in subtle ways to further complicate threshold development. For example, sites with heavy predator impacts and low mercury would bias threshold estimates low, whereas sites with high rates of depredation and elevated mercury may bias estimates high. To account for the effects of these factors in relation to hatchability and mercury concentrations, thresholds must be developed using information gathered over several years and across multiple sites. The Regional Monitoring Program is currently funding a USGS study to further define hatchability thresholds and interactions with selenium for Forster's terns in the Bay.

After an egg hatches, mercury may still influence subsequent chick growth and survival. Blood mercury concentrations are highest in chicks just after hatching, when they are still influenced by mercury exposure from the egg. Concentrations then decline rapidly with age as the mercury is shunted into growing feathers and diluted by body growth. When feather growth and body growth slow just before and after fledging, mercury concentrations begin to increase again (Figure 7).

Thus, the timeframes just after hatching and at fledging are especially sensitive periods when chicks are at elevated risk from mercury. These critical time periods are important developmentally, as chicks avoid predators, acquire the necessary nutrients for rapid growth, and learn to forage and fly independently. As a neurotoxin, methylmercury may have important impacts on chick behavior that can influence the likelihood of mortality. Mercury concentrations in down feathers sampled from black-necked stilt chicks found dead within a colony in San Francisco Bay were significantly higher than those from similarly-aged, apparently healthy, live chicks (Figure 8). Avocet chicks on the other hand, which have substantially lower mercury concentrations overall, showed no differences in mercury concentrations in down feathers of dead and live chicks (Figure 8).

Stilt chick. Photograph by Josh Ackerman.

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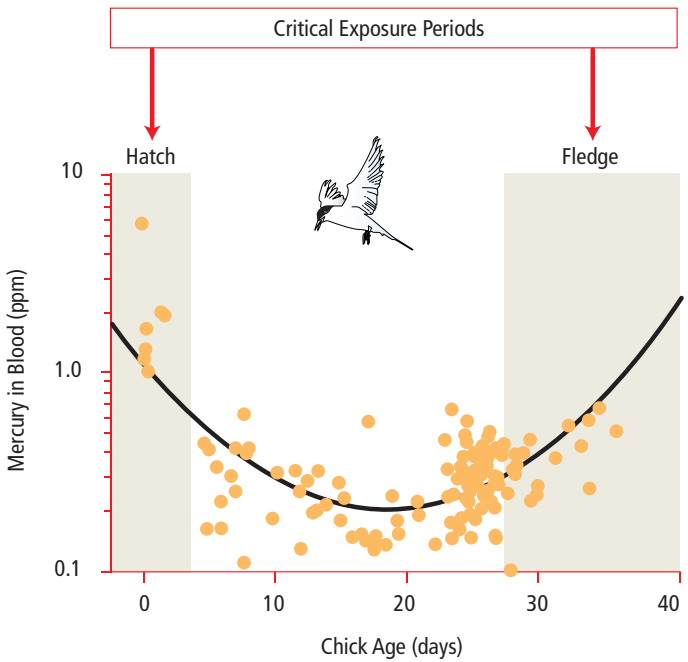

Footnote: Note log scale of graph. Total mercury on a wet weight basis. Polynomial regression line shown.

Footnote: Total mercury reported on a fresh weight basis. From Ackerman et al. 2008a.

FIGURE 7
Mercury concentrations in blood of Forster's tern chicks are highest immediately after hatching and just before fledging. These critical exposure periods are also critical stages of development.

FIGURE 8
Mercury concentrations in down feathers of recently-hatched stilt chicks that were found dead were significantly higher than in randomly-sampled live chicks, suggesting that mercury may reduce stilt hatchling survival. In avocet chicks, mercury concentrations were substantially lower overall, and there were no differences between alive and dead chicks.

Future Directions and Management Implications

Recent research has shown that waterbirds in San Francisco Bay appear to be at elevated risk of reproductive impairment from mercury. Important regions (e.g., lower South Bay and Napa Marsh) and habitats (e.g., diked salt marshes, tidal marshes) for enhanced mercury accumulation also have been identified, helping to assess likely impacts to waterbirds and other sensitive wildlife. Additionally, steps have been taken to quantify actual risks to waterbird reproduction in the Bay.

Future efforts in evaluating deleterious effects of mercury to waterbirds should include:

- continued development of appropriate egg hatchability thresholds for the highest risk species;
- evaluation of toxicity thresholds for growth and survival of chicks; and
- evaluation of the cumulative effects of mercury and other contaminants, such as selenium, PCBs, and PBDEs, on waterbird reproduction.

These steps will provide critical information to managers that will serve as a scientifically defensible foundation for thresholds that can be applied to minimize risk to waterbirds. Additionally, the results from this research will be essential for guiding site selection for waterbird habitat enhancement relative to mercury risk, as well as for evaluating the effects of restoration activities on methylmercury production and subsequent bioaccumulation in waterbirds.

Waterbirds are ideal Bay biosentinels for measuring the actual bioaccumulation of mercury into sensitive species, and for interpreting observed concentrations relative to likelihood of effects. Eggs in particular represent an ideal matrix for assessing toxicologically relevant bioaccumulation because they are indicative of short-term, localized exposure, and are central to predicting risk in multiple lifestages (Figure 9).

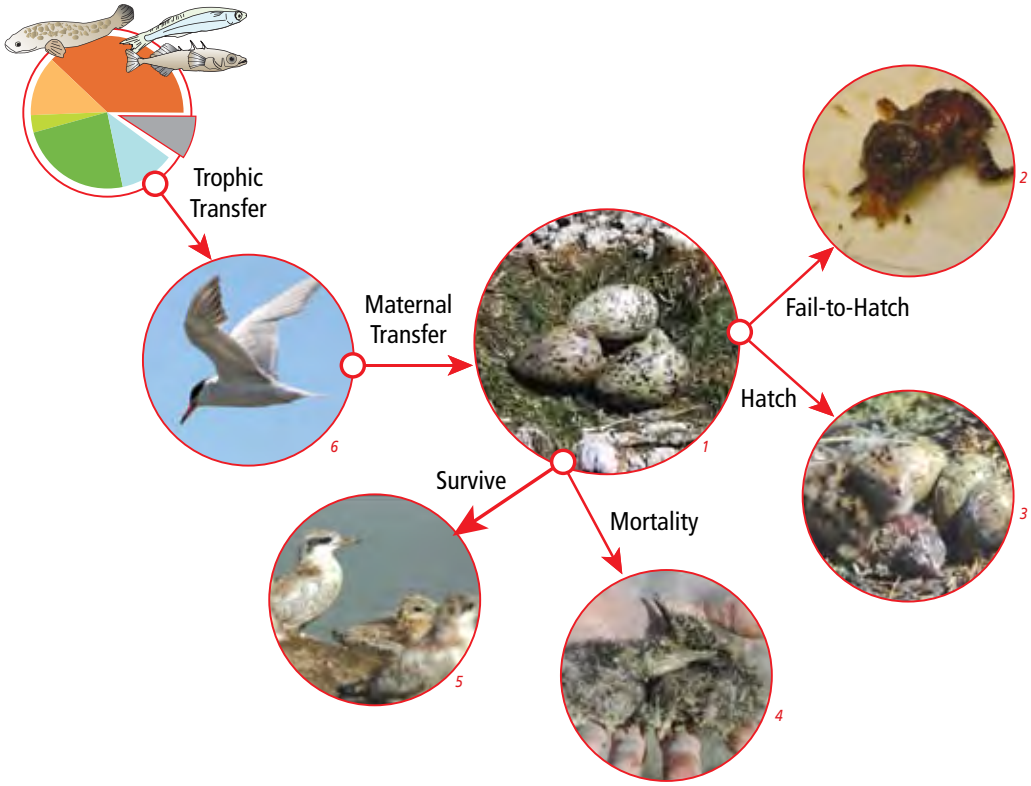

FIGURE 9
Conceptual model illustrating the utility of eggs as a monitoring tool for multiple lifestages, providing a measure of exposure and effects in adults, chicks, and eggs in a single tissue monitoring matrix.

Photographs 1, 2, 3, 4, and 5 by Josh Ackerman
Photograph 6 by Linda Wanczyk.