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Prepared for the California State Water Resources Control Board,
Surface Water Ambient Monitoring Program

Estimating Exposure of Piscivorous Birds and Sport Fish to Mercury in California Lakes Using Prey Fish Monitoring—A Predictive Tool for Managers

Open–File Report 2015–1106

U.S. Department of the Interior
U.S. Geological Survey

SWAMP

Cover: Photograph showing Clark's grebe sitting on a nest at Thermalito Afterbay, California. Photograph taken by Alex Hartman in 2012.

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SALLY JEWELL, Secretary

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
hectare (ha)	0.003861	square mile (mi^2)
	Volume	
liter (L)	0.264172	gallon (gal)
milliliter (mL)	0.0333814	ounce, fluid (fl. oz)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32.$$

Abbreviations and Acronyms

dw	dry weight
ww	wet weight
fww	fresh wet weight
Hg	mercury
THg	total mercury
MeHg	methylmercury
µg/g	micrograms per gram

Estimating Exposure to Piscivorous Birds and Sport Fish to Mercury in California Lakes Using Prey Fish Monitoring—A Predictive Tool for Managers

By Joshua T. Ackerman[1], C. Alex Hartman[1], Collin A. Eagles-Smith[1], Mark P. Herzog[1], Jay Davis[2], Gary Ichikawa[3], and Autumn Bonnema[3]

Executive Summary

Background

- Numerous water bodies in California are listed under the Clean Water Act as being impaired by mercury (Hg) contamination. The Surface Water Ambient Monitoring Program, via the Bioaccumulation Oversight Group, has recently completed statewide surveys of contaminants in sport fish tissue from California lakes, rivers, and coastal waters. This effort focused on human health issues, but did not include beneficial uses by wildlife.
- We developed a tool for estimating wildlife and sport fish risk due to Hg exposure based on Hg concentrations in prey fish. This tool can be used to predict Hg concentrations in grebe blood, grebe eggs, and sport fish, thus facilitating a feasible alternative for estimating wildlife exposure to Hg when more comprehensive wildlife sampling is not feasible.

Methods

- We used western grebes (*Aechmophorus occidentalis*) and Clark's grebes (*Aechmophorus clarkii*) as indicators of wildlife exposure to Hg in California lakes. Specifically, we sampled grebes, prey fish, and sport fish simultaneously at up to 25 lakes throughout California during the spring and summer of 2012 and 2013, seasons when breeding birds are particularly vulnerable to Hg-induced reproductive impairment.
- We sampled and analyzed total mercury (THg) concentrations in tissue from 354 grebes at 25 lakes, 101 grebe eggs at 7 lakes, 505 prey fish of 14 species at 25 lakes, and 230 sport fish of 5 species at 24 lakes.
- We used linear mixed-effect models, Akaike's Information Criterion, and model-averaging to evaluate which variables influenced THg concentrations in grebe blood, grebe eggs, and sport fish. For each of these tissues, we built a set of candidate models based on potential predictor variables describing the (1) specific tissue, (2) lake attributes, and (3) THg concentrations in prey fish.

[1]U.S. Geological Survey.
[2]San Francisco Estuary Institute.
[3]California Department of Fish and Wildlife.

Factors Influencing Mercury in Grebes and Sport Fish

- Data strongly supported the influence of THg concentrations in prey fish on THg concentrations in grebe blood, grebe eggs, and sport fish.
- The most parsimonious model describing THg concentrations in grebe blood included THg concentrations in prey fish, grebe species, grebe sex, wing molt index, and lake perimeter. Specifically, predicted THg concentrations in grebe blood increased by 824 percent (from 0.26 to 2.37 micrograms per gram [µg/g] wet weight [ww]) over the observed range of THg concentrations in prey fish among lakes (0.03±0.01 to 0.70±0.18 µg/g dry weight [dw]).
- The most parsimonious model describing THg concentrations in grebe eggs included THg concentrations in prey fish, date, and lake perimeter, but date and lake perimeter contributed little to explaining THg concentrations in grebe eggs. Similar to THg concentrations in grebe blood, predicted THg concentrations in grebe eggs increased by 500 percent (from 0.04 to 0.24 µg/g fresh wet weight [fww]) over the observed range of THg concentrations in prey fish among lakes (0.03±0.01 to 0.70±0.18 µg/g dw).
- The most parsimonious model describing THg concentrations in sport fish included THg concentrations in prey fish, sport fish species, sport fish length, lake elevation, lake area, and a sport fish species × total length interaction, but lake area had only a marginal effect. Specifically, predicted THg concentrations in sport fish increased by 1,023 percent (from 0.20 to 2.21 µg/g dw) over the observed range of THg concentrations in prey fish among lakes (0.03±0.01 to 0.70±0.18 µg/g dw).

Predictive Tool for Managers

- We built predictive equations for each tissue type using model-averaged coefficients from our full candidate model set (a total of 3,456 models for grebe blood, 384 models for grebe eggs, and 480 models for sport fish).
- We then built a predictive tool for use by natural resource managers using these predictive equations (see Microsoft® Excel file entitled "USGS Wildlife and Sport Fish Risk Estimator Tool Final.xlsx," available at http://www.werc.usgs.gov/mercuryriskinlakes).
- Tool users will enter THg concentrations in prey fish, date sampled, and the specific lake's attributes; our tool will then predict THg concentrations in grebe blood, grebe eggs, and sport fish.
- Furthermore, our tool uses these estimated values to assess the relative risk to the animal by comparing the estimated THg concentrations to published toxicity benchmarks.

Management Questions

We also addressed three specific management questions and discussed the tool's broader application for estimating risk to wildlife in California lakes and reservoirs:

1. Does methylmercury pose significant risks to aquatic life in a representative sample of California lakes and reservoirs?
2. Can a correlational approach be applied on a statewide basis to estimate risks to birds?
3. What are appropriate water-quality monitoring requirements to address methylmercury exposure in wildlife?

Introduction

Numerous water bodies in California are listed under the Clean Water Act as being impaired due to mercury (Hg) contamination. The Surface Water Ambient Monitoring Program (SWAMP), via the Bioaccumulation Oversight Group (BOG), has recently completed statewide surveys of contaminants in sport fish tissue from more than 250 lakes and rivers in California and throughout coastal waters (Davis and others, 2010, 2012). This effort focused on human health issues but did not include beneficial uses by wildlife. Many piscivorous birds such as grebes, terns, cormorants, and mergansers eat fish smaller than those that were sampled by BOG, and sport fish Hg concentrations are not always indicative of wildlife exposure to Hg; therefore, the BOG surveys could not address whether wildlife were at risk due to Hg-induced reproductive impairment in these lakes.

We used western grebes (*Aechmophorus occidentalis*) and Clark's grebes (*Aechmophorus clarkii*) as our index of wildlife exposure to Hg in California lakes. Grebes are widely distributed in lakes throughout California and, as piscivorous waterbirds, are near the top of the food chain in lakes. Additionally, grebes become flightless after they arrive at their summer locations. Thus, grebes are useful representatives for wildlife risk from local, lake-specific contaminant exposure. Grebes also breed at many lakes throughout California, making them susceptible to impaired reproduction due to local Hg contamination.

We developed a tool for estimating wildlife and sport fish risk from Hg exposure based on Hg concentrations in prey fish. This quantitative tool can be used to predict Hg concentrations in grebe blood, grebe eggs, and sport fish, thus facilitating a feasible alternative for adequately estimating wildlife exposure when more comprehensive wildlife sampling is not possible. Specifically, we sampled grebes, prey fish, and sport fish simultaneously at 25 lakes throughout California during the spring and summer of 2012 and 2013 when breeding birds are particularly vulnerable to Hg-induced reproductive impairment. We selected lakes based on a combination of factors, including lakes

(1) from southern and northern California,
(2) of various sizes, shapes, and elevations,
(3) with a range of sport fish Hg exposure levels (Davis and others, 2010),
(4) where largemouth bass (*Micropterus salmoides*) was the primary sport fish, and
(5) with a history of use by grebes.

Using these factors ensured that our results are representative of a broad range of lakes and reservoirs in California and are comparable to prior BOG studies.

Specifically, we addressed three management questions:

1. Does methylmercury pose significant risks to aquatic life in a representative sample of California lakes and reservoirs?
2. Can a correlational approach be applied on a statewide basis to estimate risks to birds?
3. What are appropriate water-quality monitoring requirements to address methylmercury exposure in wildlife?

Methods

Grebe Sampling

We conducted this study at 25 lakes and reservoirs (hereafter termed *lakes*) throughout California during 2012 and 2013 (fig. 1). To sample grebes, sport fish, and prey fish during the summer breeding season at all 25 lakes, we sampled 13 lakes in 2012 and 12 lakes in 2013 from April through October (table 1). We captured an average of 14 grebes per lake (range: 2–38 grebes) with night-lighting techniques (King and others, 1994; Whitworth and others, 1997). Briefly, we shined a high-powered spotlight at grebes, which sometimes can disorient the bird long enough for capture with a long-handled net from a moving boat. We held birds in individual animal crates lined with towels (Plastic Pet Carrier, C Specialties, Inc., Indianapolis, Indiana, USA) until processing, and we released them near the site of capture. Clark's grebes and western grebes were differentiated by plumage. We weighed each grebe with a digital bench scale (Ohaus ES6R, Ohaus Corporation, Parsippany, New York, USA) or spring scale (Pesola Spring Scales, Pesola Ag, Baar, Switzerland). We measured the distance from the back of the bird's head to the tip of the culmen, short tarsus length (tarsometatarus bone), and culmen depth at the proximal end of the nares with digital calipers (Fowler electronic digital calipers, Newton, Massachusetts, USA). We measured flattened wing length with a wing board. We described wing molt by classifying each of the 10 primary feathers on the right wing with a value from 0 through 5—0 represented an old feather grown the prior year; 1 represented a missing feather or a new feather that had not yet emerged from the feather quill; 2 represented a new feather less than one-third the length of a fully grown feather; 3 represented a new feather between one-third and two-thirds the length of a fully grown feather; 4 represented a new feather greater than two-thirds the length of a fully grown feather; and 5 represented a new, fully grown feather. We banded each bird with stainless steel U.S. Geological Survey leg bands to identify recaptures. We then collected whole blood (≤ 3.0 mL) from each bird via the brachial or jugular vein with heparinized 23–26-gauge needles and a syringe. Whole blood was immediately transferred to polypropylene cryovials, held on wet ice while in the boat, and then transferred to a liquid nitrogen storage chamber within 6 hours of collection. Blood was then transferred to the laboratory for storage at -20 °C until mercury analysis. We also collected a drop of blood from each grebe to determine sex through genetic analysis (Zoogen Services, Davis, California, USA).

We collected a mean of 14 grebe eggs (range: 6–23 eggs) at 7 of the 25 lakes where we sampled grebe blood (table 2). We randomly collected one egg from each nest. When possible, we identified whether the egg was that of a western grebe or a Clark's grebe by observing the incubating bird prior to collection and we classified each collected egg as either randomly sampled from an active nest (random egg) or salvaged from a nest that had been abandoned before our visit (abandoned egg). Because the parents were no longer present at abandoned nests, abandoned eggs could not be identified to species of *Aechmophorus* grebe. We floated eggs to determine embryo age (Ackerman and Eagles-Smith, 2010) and estimated nest initiation date by subtracting the clutch size and embryo age from the date the nest was visited.

We stored eggs on wet ice in the field and transferred them to a refrigerator until dissection. During egg dissection, we measured length and breadth of each egg to the nearest 0.01 mm with digital calipers (Fowler, Newton, Massachusetts, USA) and measured total egg weight to the nearest 0.01 g on a digital balance (Ohaus Adventurer Pro, Ohaus Corporation, Pine Brook, New Jersey, USA). We then cut an approximately 20 mm diameter hole in the top (air-cell end) of each egg using clean, stainless steel scissors and removed the embryo and any remaining contents into a sterile 125 mL jar with stainless steel forceps. We then stored the egg contents at -20 °C until mercury determination.

Fish Sampling

Within an average of 11 days from the date of grebe blood sampling (range: 19 days before to 79 days after grebe sampling), we returned to each of the 25 lakes to sample prey fish and sport fish at the locations where grebes were sampled. Fish were captured via electrofishing boat (Smith-Root, Vancouver, Washington, USA) and dip nets. We collected small fish in the size range (mean: 58 mm standard length, range: 18–123 mm) that grebes commonly consume (Lawrence, 1950). Efforts were made to sample the same species across all lakes; when this was not possible, we sampled fish that overlapped in trophic guild (table 3). We sampled 10 individuals from each of two prey fish species from each lake, for a total of 20 prey fish per lake, with four exceptions—at three lakes we sampled 25 prey fish (10 each of two species and 5 of a third species at two lakes; and 10, 8, and 7 for each of three species at one lake) and at one lake we sampled only 10 prey fish of a single species. In total, we sampled 505 prey fish of 14 species from 25 lakes (table 4). For sport fish, we collected the most common species (table 5) at each lake, within the size range commonly consumed by humans (mean: 397 mm total length; range: 178–726 mm). We sampled 10 individuals from the most common sport fish species in each lake, with three exceptions—at two lakes we sampled only 8 sport fish and at one lake we were only able to collect 4 sport fish of 2 different species. In total, we sampled 230 sport fish of 5 species from 24 lakes (Tule Lake was not sampled for sport fish; table 6). We stored fish on wet ice in the field until processing. During fish processing, we weighed each fish with a digital balance (prey fish: Smart Weigh Pro Pocket Scale, Smart Weigh, Nanuet, New York, USA; sport fish: Angyo Portable Electronic Scale, Angyo, China) and measured standard length (prey fish) or total length (sport fish) with a fish board. Thereafter, fish were stored on dry ice until they were transferred to a freezer (-20 °C), where they were stored until mercury determination.

Mercury Determination

We used total mercury (THg) concentrations as an index of methylmercury (MeHg) concentrations because most of the Hg in fish and birds is in the more toxic MeHg form (Wiener and others, 2003; Ackerman and others, 2013). THg concentrations were determined on a Milestone DMA-80 Direct Mercury Analyzer (Milestone, Monroe, Connecticut, USA) or a Nippon MA-3000 Direct Mercury Analyzer (Nippon Instruments North America, College Station, Texas, USA) following Environmental Protection Agency Method 7473 (U.S. Environmental Protection Agency, 2000), using an integrated sequence of drying, thermal decomposition, catalytic conversion, and then amalgamation, followed by atomic absorption spectroscopy. THg concentrations were determined at three different laboratories depending on tissue type:

1. Bird eggs were analyzed at the U.S. Geological Survey, Dixon Field Station Environmental Mercury Laboratory (Dixon, California),
2. Bird blood was analyzed at the U.S. Geological Survey, Corvallis Field Station Environmental Mercury Laboratory (Corvallis, Oregon), and
3. Fish were analyzed at Moss Landing Marine Laboratories (Moss Landing, California).

Before THg analysis, tissues were processed in the following manner. We determined THg concentrations in whole blood, egg contents (without the eggshell), whole-body prey fish, and muscle fillets of sport fish. For bird blood, we determined THg concentrations on a wet-weight basis. We thawed blood to room temperature, then homogenized it in a vortexer before weighing the blood for THg determination. For bird eggs, we dried the entire egg contents at 50 °C for 48–72 h until completely dried, reweighed egg contents to determine moisture content, and then homogenized the dried egg contents to a powder in a grinder with stainless steel blades. For prey fish, whole fish were washed in deionized water and manually scrubbed to remove any debris from the fish surface, dried at

50 °C for approximately 48 h until completely dried, reweighed to determine moisture content, and then homogenized to a fine powder with a porcelain mortar and pestle. For sport fish, we filleted the fish and used a small aliquot of muscle to determine THg concentrations on a wet-weight basis.

We report THg concentrations on a dry-weight (dw) basis for prey fish and sport fish, on a wet weight (ww) basis for bird blood, and on a fresh wet-weight basis (fww) for eggs. THg concentrations in sport fish were estimated on a dry-weight basis from individual-specific moisture content values and wet-weight THg concentrations. THg concentrations in eggs were estimated on a fresh wet weight basis using individual-specific moisture content of egg contents and egg morphometrics following the methods of Ackerman and others (2013). Moisture content (mean±SE) was 75.9±0.14 percent in bird blood (2013 only; n=149; range: 71.2−80.8 percent), 75.5±0.14 percent in bird eggs (n=101; range: 71.7−77.9 percent), 75.8±0.11 percent in prey fish (n=505; range: 50.4−87.5 percent), and 78.3±0.15 percent in sport fish (n=230; range: 69.7−85.2 percent). For comparison with toxicity benchmarks developed on a wet weight basis, we also calculated wet-weight THg concentrations for prey fish based on individual moisture content.

Quality assurance measures included analyses of at least two certified reference materials (either dogfish muscle tissue [DORM], dogfish liver [DOLT], or lobster hepatopancreas [TORT] certified by the National Research Council of Canada, Ottawa, Canada), two system and method blanks, three continuing calibration verifications, two duplicates, and two spiked duplicates per batch. Recoveries (mean±SD) for blood samples were 99.2±0.4 percent (n=34) for certified reference materials, 99.2 ±0.5 percent (n=52) for calibration verifications, and 101.7 ±1.0 percent (n=26) for matrix spikes. Absolute relative percent difference for blood samples averaged 4.7±1.1 percent (n=22) for duplicates and 4.6±1.4 percent (n=13) for matrix spike duplicates. Recoveries (mean±SD) for egg samples were 100.0±4.3 percent (n=28) for certified reference materials, 98.1±2.2 percent (n=32) for calibration verifications, and 99.0±1.8 percent (n=24) for matrix spikes. Absolute relative percent difference for egg samples averaged 3.1±1.7 percent (n=21) for duplicates and 1.3±1.0 percent (n=12) for matrix spike duplicates. Recoveries (mean±SD) for prey fish samples were 96.3±4.8 percent (n=27) for certified reference materials, 97.0±6.6 percent (n=10) for calibration verifications, and 96.2±11.4 percent (n=54) for matrix spikes. Absolute relative percent difference for prey fish averaged 8.0±6.5 percent (n=27) for duplicates and 4.1±3.8 percent (n=27) for matrix spike duplicates. Recoveries (mean±SD) for sport fish samples were 95.0±5.9 percent (n=16) for certified reference materials, 96.1±7.0 percent (n=57) for calibration verifications, and 97.7±8.1 percent (n=32) for matrix spikes. Absolute relative percent difference for sport fish averaged 5.6±6.0 percent (n=16) for duplicates and 4.9±3.3 percent (n=16) for matrix spike duplicates.

Statistical Methods

Mercury by Lake

In the first stage of our analyses, we used linear mixed-effect models to estimate least squares mean THg concentrations in grebe blood, grebe eggs, prey fish, and sport fish for each lake. To do so, we developed a separate model for each tissue type that incorporated several variables that we could not completely control during field sampling. These potential sampling biases included species and sex of grebes (blood), species and type of grebe eggs collected (random or abandoned eggs), and species and length of fish. For grebe blood, $\log_e$-transformed THg concentration (µg/g ww) was the dependent variable, species (western grebe or Clark's grebe) and sex (male or female) were fixed effects, and lake was a random effect. For grebe eggs, $\log_e$-transformed THg concentration (µg/g fww) was the dependent variable, species (western grebe, Clark's grebe, or unknown) and egg collection type (random or abandoned) were fixed effects, and lake was a random effect. For prey fish, $\log_e$-transformed THg

concentrations (µg/g dw) was the dependent variable; species, standard length, and species × length interaction were fixed effects; and lake was a random effect. The sport fish model was similar to the prey fish model, except that total length was used instead of standard length. For all four response variables, least squares means were estimated for each lake from the mixed-effect models using Best Linear Unbiased Predictors in JMP® software (version 11.2.0; SAS Institute, Inc., Cary, North Carolina, USA). The least squares mean THg concentrations in prey fish for each lake were then used as a covariate in the next analyses describing factors influencing THg concentrations in grebe blood, grebe eggs, and sport fish. Lastly, the least squares mean THg concentrations in grebe blood, grebe eggs, and sport fish for each lake were used in linear regression analyses to assess the relationships among these three tissues.

Factors Influencing Mercury in Grebes and Sport Fish

In the next stage of our analyses, we used linear mixed-effect models to examine which variables influenced THg concentrations in grebe blood, grebe eggs, and sport fish. For each of these tissues, we built a set of candidate models based on potential predictor variables describing the (1) specific tissue, (2) lake attributes, and (3) THg concentrations in prey fish. For each of the three tissue types, the model structure was similar except for the variables describing the specific tissue.

For grebe blood, the potential tissue-specific predictor variables included species (western grebe or Clark's grebe), sex (male or female), bird mass, body condition index, linear (wing molt) and quadratic (wing molt^2) terms for wing molt score, and linear (date) and quadratic (date^2) terms for sampling date. We did not allow bird mass and body condition to occur in the same model. Year was not included because each lake was sampled in only 1 of the 2 years. The body condition index was estimated as an individual's residual mass divided by its mass, where an individual's residual mass was calculated as the residual from a linear regression model of bird mass and structural body size. Structural body size of birds was calculated using a principal components analysis (PCA) of three structural body size measurements (length in millimeters of back of head to tip of culmen, short tarsus, and culmen depth) for each grebe species and sex. The PCA indicated that structural body size measurements were correlated as expected, and the first principal component (PC1) accounted for 54 percent (male) and 50 percent (female) of the morphological variation in western grebes and 56 percent (male) and 51 percent (female) of the morphological variation in Clark's grebes. Eigenvector weights of PC1 were positive and ranged from 0.41 to 0.67 (male) and 0.47 to 0.64 (female) for western grebes and from 0.50 to 0.63 (male) and 0.55 to 0.59 (female) for Clark's grebes. Wing molt was calculated as the mean value of molt classification for each of the 10 primary feathers. Finally, date was standardized as the difference between the day of year the bird was captured and the median day of year for all captured birds (median day of year was 181 for June 29 in 2012 and June 30 in 2013).

For grebe eggs, the potential tissue-specific predictor variables included species (western grebe, Clark's grebe, or unknown *Aechmophorus* grebe), egg collection type (random or abandoned), date, and date^2. Again, date was standardized as the difference between the day of year the nest was initiated and the median day of year for all nests initiated (median day of year was 211). For sport fish, the potential tissue-specific predictor variables included taxa (largemouth bass [*Micropterus salmoides*], smallmouth bass [*Micropterus dolomieu*], rainbow trout [*Oncorhynchus mykiss*], brown trout [*Salmo trutta*], and Eagle Lake rainbow trout [a subspecies of rainbow trout; *Oncorhynchus mykiss aquilarum*]), total length, and species × total length interaction. Date was standardized as the difference between day of year the sport fish were captured and the median day of year for all captured sport fish (median day of year was 204).

For each of the three tissue types, the candidate model set included several lake-specific variables, including lake area (hectares), lake perimeter (kilometers), lake shape index, and elevation (meters). For each lake, we obtained the lake attribute data (table 7) from the U.S. Geological Survey National Hydrography Dataset (http://nhd.usgs.gov) and the California Department of Fish and Wildlife (ftp://ftp.dfg.ca.gov/BDB/GIS/California_Lakes). The lake shape index was calculated using the following equation where a larger shape index indicates a lake with more shoreline relative to the lake's size (McGarigal, 2014):

$$Lake\ Shape\ Index = \frac{0.25 \times Perimeter\ (m)}{\sqrt{Lake\ Area\ (m^2)}}$$

Lastly, we evaluated the influence of both lake-specific least squares mean $\log_e$-transformed THg concentrations in prey fish and lake-specific geometric mean $\log_e$-transformed THg concentrations in prey fish on THg concentrations in grebe blood, grebe eggs, and sport fish, with the rule that both least squares mean and geometric mean THg concentrations in prey fish could not be included in the same model. For each of the three tissue types, models including least squares mean THg concentrations in prey fish, which statistically accounted for prey-fish length and species, performed substantially better than models including geometric mean THg concentrations in prey fish. The best model that included least squares mean THg concentrations in prey fish was 5.9, 6.8, and 30.3 times more likely than the best model that included geometric mean THg concentrations in prey fish for grebe blood, grebe eggs, and sport fish, respectively (all $\Delta AICc > 3.55$). Therefore, geometric mean THg concentrations in prey fish was removed as a potential variable in the final candidate model sets.

For each of the three tissue types, our final candidate model set included all additive combinations of variables (except where previously noted) and a null model (a total of 3,456 models for grebe blood, 384 for grebe eggs, and 480 for sport fish). In each model, $\log_e$-transformed THg concentration was the dependent variable and lake was included as a random effect. We evaluated models using second-order Akaike Information Criterion (AIC*c*) and considered the model with the smallest AIC*c* to be the most parsimonious (Burnham and Anderson, 2002). We used AIC_c differences between the best model and each of the other candidate models (ΔAIC*c*) to determine the relative ranking of each model. For biological importance, we considered models for which $\Delta AICc \leq 2$. We used Akaike weights (w_i) to examine the weight of evidence that the selected model was the best model within the set of candidate models. We used evidence ratios to compare the relative weight of support between models. We also assessed the relative importance of each variable by summing Akaike weights across models that incorporated the same variable. Because the variables were not completely balanced in the candidate model set, and therefore had different prior variable weights, we further adjusted this relative variable importance by comparing the difference in final (or posterior) relative variable weight with its initial (or prior) weighting. Prior weighting represents the expected variable weight if all models in the candidate model set were equally weighted and was calculated as the proportion of models within the candidate model set in which a given variable was present. Adjusted relative variable importance was thus calculated as the log-odds ratio of the posterior and prior variable weights. Adjusted relative variable importance values that exceeded 0 had posterior weights that were greater than was expected by their prior weighting and were considered to be important, and values less than 0 had posterior weights that were less than was expected by their prior weighting and were considered to be unimportant. The adjusted relative variable importance equation was described as follows:

$$\text{Adjusted Relative Variable Importance} = \log\left[\frac{\left(\frac{P}{1-P}\right)}{\left(\frac{P_0}{1-P_0}\right)}\right]$$

where,

$$P = \text{Posterior Variable Weight}$$
$$P_0 = \text{Prior Variable Weight}$$

For brevity in the tables, we present only the set of best models that were within $\Delta AICc \leq 2$, the null model, and each model that was similar to the best model except one of the variables in the best model was removed. When examining effects of a specific variable, we estimated conditional model-averaged coefficients by only model-averaging across models where the variable was present, to better reflect the true relationship of THg concentrations with that variable. However, all other results were based on model-averaged predictions and standard errors from the full candidate model set. We report back-transformed least squares means and estimated standard errors using the delta method (Seber, 1982).

All data in this report are available to be accessed with the authors' permission via the California Environmental Data Exchange Network (CEDEN).

Results and Discussion

Mercury Concentrations among Lakes

We captured 354 grebes at 25 lakes and determined their THg concentrations in blood; 71 percent were western grebes and 29 percent were Clark's grebes, and 48 percent were female and 52 percent were male (table 1). THg concentrations in grebe blood differed between species ($F_{1,331.3}$=13.35, p<0.001) and sexes ($F_{1,328.5}$=12.58, p<0.001; fig. 2). Least squares mean THg concentrations in grebe blood ranged from 0.16±0.02 µg/g ww at Big Lake to 5.16±0.61 µg/g ww at Lake Berryessa (fig. 3).

We collected 101 grebe eggs at seven lakes and analyzed them for THg concentrations (table 2); 62 percent were western grebes, 15 percent were Clark's grebes, and 23 percent were unknown *Aechmophorus* grebes. THg concentrations in grebe eggs did not differ between species ($F_{2,92.31}$=0.64, p=0.53) or egg collection status ($F_{1,92.06}$=2.10, p=0.15). Least squares mean THg concentrations in grebe eggs ranged from 0.03±0.01 µg/g fww at Big Lake to 0.15±0.02 µg/g fww at Clear Lake (fig. 3). (**Note:** Although we analyzed another 23 abandoned grebe eggs for THg concentrations and uploaded these data into the CEDEN database, we eventually excluded these eggs from statistical analyses because we could not adequately account for sibling eggs collected from the same nest because the correctly structured statistical model with nest number as a random effect [to account for potential pseudoreplication of the same parent] would not converge.)

We analyzed THg concentrations in 505 prey fish of 14 species from 25 lakes: 30 percent bluegill (*Lepomis macrochirus*), 22 percent Mississippi silverside (*Menidia audens*), 14 percent threadfin shad (*Dorosoma petenense*), 8 percent golden shiner (*Notemigonus crysoleucas*), 5 percent Sacramento perch (*Archoplites interruptus*), 4 percent tui chub (*Gila bicolor*), 4 percent Sacramento sucker (*Catostomus occidentalis*), and 2 percent each of blue chub (*Gila coerulea*), hitch (*Lavinia exilicauda*), largemouth bass, pumpkinseed (*Lepomis gibbosus*), redear sunfish (*Lepomis microlophus*), smallmouth bass, and Tahoe sucker (*Catostomus tahoensis*) (tables 3 and 4). THg concentrations in prey fish differed among species ($F_{13,374.7}$=9.90, p<0.0001) while accounting for standard length ($F_{1,455.1}$=2.86, p=0.09), and there was a significant species × standard length interaction ($F_{13,459.1}$=11.13, p<0.0001). Least squares mean THg concentrations were highest in blue chub (0.25±0.14 µg/g dw), hitch (0.24±0.07 µg/g dw), and silverside (0.23±0.05 µg/g dw), and lowest in smallmouth bass (0.04±0.02 µg/g dw; fig. 4). Least squares mean THg concentrations in prey fish ranged from 0.03±0.01 µg/g dw at Eagle Lake to 0.70±0.18 µg/g dw at Bridgeport Reservoir (fig. 3).

We analyzed THg concentrations in 230 sport fish of 5 species from 24 lakes—68 percent largemouth bass, 17 percent rainbow trout, 5 percent smallmouth bass, 5 percent brown trout, and 4 percent Eagle Lake rainbow trout (tables 5 and 6). THg concentrations in sport fish differed among species ($F_{4,27.52}$=9.02, p<0.0001) and increased with total length ($F_{1,208.4}$=30.05, p<0.0001), while accounting for the potential species × total length interaction ($F_{4,210.5}$=1.77, p=0.14). Least squares mean THg concentrations were highest in smallmouth bass (2.33±1.10 µg/g dw) and lowest in Eagle Lake rainbow trout (0.10±0.07 µg/g dw; fig. 4). Least squares mean THg concentrations in sport fish ranged from 0.20±0.06 µg/g dw at Perris Reservoir to 2.12±0.63 µg/g dw at Lake Berryessa (fig. 3).

Factors Influencing Mercury in Grebe Blood

The most parsimonious model describing THg concentrations in grebe blood included least squares mean THg concentrations in prey fish, grebe species, grebe sex, wing molt index, and lake perimeter (table 8). Fifteen other models were within $\Delta AICc \leq 2.0$, and all included the variables least squares mean THg concentrations in prey fish, grebe species, and grebe sex. In fact, all models containing these three variables had a cumulative Akaike weight of 0.97, indicating their importance.

The other variables that appeared with these three primary variables in models within $\Delta AIC_c \leq 2.0$ included date, date^2, wing molt index^2, grebe body condition index, lake shape index, and lake area. However, these additional variables did not improve model fit and were considered to be uninformative parameters (Arnold, 2010). We estimated the relative importance of individual variables and found that the data strongly supported the effects of least squares mean THg concentrations in prey fish (adjusted relative variable importance = 14.4), species (5.8), and sex (3.5), with some support for lake perimeter (1.2). In contrast, the adjusted relative variable importance for the remaining variables were all less than 0.

To further determine the importance of variables in the best model, we compared the best model to the same model structure but omitted one of the variables. Using this evidence ratio approach, we estimated that the best model that included least squares mean THg concentrations in prey fish was 2.47×10^6 times more likely than the same model without the effect of least squares mean THg concentrations in prey fish. Similarly, the best model was 428 times more likely than the same model without grebe sex, 318 times more likely than the same model without grebe species, 5.5 times more likely than the same model without lake perimeter, and only 1.03 times more likely than the same model without wing molt index. The null model (with lake as a random effect) was not supported (ΔAIC_c = 53.08; w_i = 0.00), and the best model was 3.36×10^{11} times more likely than the null model. Model-averaged estimates of each variable's beta coefficients are presented in the equations in section, "Predictive Equations."

The conditional model-averaged coefficients indicated that each 1.0 µg/g dw (approximately 0.24 µg/g ww) increase in THg concentrations in prey fish results in a 103 percent increase in THg concentrations in grebe blood. Predicted THg concentrations in grebe blood increased by 824 percent[1] (from 0.26 to 2.37 µg/g ww) over the observed range of THg concentrations in prey fish among lakes (0.03±0.01 µg/g dw at Eagle Lake to 0.70±0.18 µg/g dw at Bridgeport Reservoir; fig. 5). Least squares mean THg concentrations in blood were 27 percent higher in Clark's grebes (0.78±0.10 µg/g ww) than in western grebes (0.61±0.07 µg/g ww), and 22 percent higher in males (0.77±0.10 µg/g ww) than in females (0.63±0.08 µg/g ww). Lastly, conditional model-averaged coefficients indicated that THg concentrations in grebe blood increased by 0.5 percent with each 1 km increase in lake perimeter.

Factors Influencing Mercury in Grebe Eggs

The most parsimonious model describing THg concentrations in grebe eggs included least squares mean THg concentrations in prey fish, date, and lake perimeter (table 9). Fifteen other models were within ΔAIC_c less than or equal to 2.0. The other variables that appeared in models within $\Delta AIC_c \leq 2.0$ included lake area, lake shape index, egg collection type, and date^2, but these additional variables were considered to be uninformative parameters (Arnold, 2010). We estimated the relative importance of individual variables and found that the data supported only the effects of least squares mean THg concentrations in prey fish (adjusted relative variable importance = 1.9) because the adjusted relative variable importance for the remaining variables were all less than 0.

Using evidence ratios, we estimated that the best model, which included least squares mean THg concentrations in prey fish, was 40 times more likely than the same model without the effect of THg concentrations in prey fish. Similarly, the best model was only 1.4 times more likely than the same model without lake perimeter and 1.3 times more likely than the same model without date. The null model (with lake as a random effect) was not supported (ΔAIC_c = 8.63; w_i = 0.00), and the best model was 74.7 times more likely than the null model.

[1] All percentages were calculated using unrounded Hg concentrations, and will therefore differ slightly with those that might be calculated by readers using the rounded mean values presented.

Similar to THg concentrations in grebe blood, conditional model-averaged coefficients indicated that each 1.0 µg/g dw increase in THg concentrations in prey fish results in a 92 percent increase in THg concentrations in grebe eggs. Predicted THg concentrations in grebe eggs increased by 500 percent (from 0.04 to 0.24 µg/g fww) over the observed range of THg concentrations in prey fish among lakes (fig. 5).

Factors Influencing Mercury in Sport Fish

The most parsimonious model describing THg concentrations in sport fish included least squares mean THg concentrations in prey fish, sport fish species, sport fish total length, lake elevation, lake area, and a sport fish species × total length interaction (table 10). Five other models were within $\Delta AICc \leq 2.0$, and all included the variables least squares mean THg concentrations in prey fish, sport fish species, sport fish length, and a sport fish species × total length interaction. In fact, all models containing these variables had a cumulative Akaike weight of 0.89. The other variables that appeared with these primary variables in models within $\Delta AICc \leq 2.0$ included lake perimeter, lake shape, and date, but these additional variables were considered to be uninformative parameters (Arnold, 2010). We estimated the relative importance of individual variables and found that the data strongly supported the effects of sport fish total length (adjusted relative variable importance >36), least squares mean THg concentrations in prey fish (8.3), lake elevation (4.1), sport fish species (2.0), and sport fish species × total length interaction (3.5), with a little support for lake area (0.2). In contrast, the adjusted relative variable importance for the remaining variables were all less than 0.

Using evidence ratios, we estimated that the best model, which included least squares mean THg concentrations in prey fish, was 1.71×10^5 times more likely than the same model without the effect of THg concentrations in prey fish. Similarly, the best model was 4.18×10^{28} times more likely than the same model without sport fish length and the sport fish species × length interaction, 49.1 times more likely than the same model without lake elevation, 44.9 times more likely than the same model without the sport fish species × length interaction, 17.3 times more likely than the same model without sport fish species and the sport fish species × length interaction, and only 1.2 times more likely than the same model without lake area. The null model (with lake as a random effect) was not supported ($\Delta AICc = 181.19$; $w_i = 0.00$), and the best model was 2.21×10^{39} times more likely than the null model.

The conditional model-averaged coefficients indicated that each 1.0 µg/g dw increase in THg concentrations in prey fish results in a 116 percent increase in THg concentrations in sport fish. Predicted THg concentrations in sport fish increased by 1,023 percent (from 0.20 to 2.21 µg/g dw) over the observed range of THg concentrations in prey fish among lakes (fig. 5). With each 10 cm increase in total length of sport fish, conditional model-averaged coefficients indicated that THg concentrations in sport fish increased by 239 percent for Eagle Lake rainbow trout, 102 percent for largemouth bass, 93 percent for rainbow trout, 80 percent for smallmouth bass, and 21 percent for brown trout. Least squares mean THg concentrations in sport fish were highest in smallmouth bass (1.97±0.67 µg/g dw), followed by largemouth bass (1.30±0.19 µg/g dw), rainbow trout (0.55±0.18 µg/g dw), Eagle Lake rainbow trout (0.45±0.29 µg/g dw), and brown trout (0.38±0.15 µg/g dw). Lastly, conditional model-averaged coefficients indicated that THg concentrations in sport fish decreased by 28 percent with each 0.5 km increase in the lake's elevation.

Predictive Equations

Grebe Blood

THg concentrations in grebe blood (µg/g ww) can be estimated using model-averaged coefficients from our full candidate model set:

$$\ln(BloodTHg_{Grebe}) = \beta_0 + 0.706\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.000408(DayofYear - 181) - 0.0000258(DayofYear - 181)^2 + 0.00416(LakePerimeter_{km}) - 0.00000270(LakeArea_{ha}) - 0.0496(LakeShapeIndex) - 0.0000250(LakeElevation_m)$$

where,

β_0 is a species and sex-specific coefficient that incorporates the potential effects of bird mass, body condition, and wing molt score.

To uniquely predict THg concentrations by grebe species and sex, β_0 can be estimated using one of these four equations:

Western grebe females:

$$\beta_0 = 0.811 + 0.0000216(Mass) - 0.0698(Molt) + 0.00897(Molt^2) - 0.0151(BodyCondition)$$

Western grebe males:

$$\beta_0 = 1.01 + 0.0000216(Mass) - 0.0698(Molt) + 0.00897(Molt^2) - 0.0151(BodyCondition)$$

Clark's grebe females:

$$\beta_0 = 1.05 + 0.0000216(Mass) - 0.0698(Molt) + 0.00897(Molt^2) - 0.0151(BodyCondition)$$

Clark's grebe males:

$$\beta_0 = 1.24 + 0.0000216(Mass) - 0.0698(Molt) + 0.00897(Molt^2) - 0.0151(BodyCondition)$$

To estimate β_0 coefficient, we used species and sex-specific means, or the mode in the case of wing molt score, for each equation. Mean mass of western grebes was 1,055 g for females and 1,311 g for males. Mean mass of Clark's grebes was 1,021 g for females and 1,271 g for males. Mean body condition index of western grebes was -0.0156 for females and -0.0119 for males. Mean body condition index of Clark's grebes was -0.0109 for females and -0.00734 for males. Given the highly skewed nature of wing molt scores (87 percent of all grebes were captured prior to molt and therefore had a wing molt score of 0), we used the mode of molt score (0) for model prediction. Using these values, β_0 was estimated to be 0.834 for female western grebes, 1.04 for male western grebes, 1.07 for female Clark's grebes, and 1.27 for male Clark's grebes.

Often, model users will have no knowledge about the species and sex composition of grebes within the lake of interest. Therefore, we can simplify this equation even further by assuming equal composition of grebes among species and sexes, and the four specific β_0 coefficients can be replaced with the average grebe β_0 coefficient of 1.05.

Thus, the final equation to predict THg concentrations in grebe blood is:

$$\ln(BloodTHg_{AverageGrebe}) = 1.05 + 0.706(\ln(\overline{THg}_{preyfish})) + 0.000408(DayofYear - 181) - 0.0000258(DayofYear - 181)^2 + 0.00416(LakePerimeter_{km}) - 0.00000270(LakeArea_{ha}) - 0.0496(LakeShapeIndex) - 0.0000250(LakeElevation_m)$$

Lastly, to estimate THg concentrations in grebe blood, this model equation can be exponentiated to remove the $\log_e$-transformation used during modeling:

$$BloodTHg_{AverageGrebe} = 2.87e^{(0.706(\ln(\overline{THg}_{preyfish}))+0.000408(DayofYear-181)-0.0000258(DayofYear-181)^2+0.00416(LakePerimeter_{km}) -0.00000270(LakeArea_{ha})-0.0496(LakeShapeIndex)-0.0000250(LakeElevation_m))}$$

where,

$\overline{THg}_{preyfish}$ is the least squares mean THg concentration in prey fish, which accounts for the length and species of prey fish.

Figure 6 displays this model-averaged prediction of THg concentrations in grebe blood over the observed range of THg concentrations in individual prey fish. The panels in figure 6 show the differences among grebe species and sexes for the modeled-averaged means (top left panel) and the 95-percent confidence limits around this mean for each grebe species and sex.

When lake data are not available, we can further simplify these equations by using median values for date and mean values for lake attributes. When we do so, the equations to predict THg concentrations in grebe blood are:

$$\ln(BloodTHg_{AverageGrebe}) = 1.11 + 0.706(\ln(\overline{THg}_{preyfish}))$$
$$\ln(BloodTHg_{AverageFemaleWesternGrebe}) = 0.895 + 0.706(\ln(\overline{THg}_{preyfish}))$$
$$\ln(BloodTHg_{AverageMaleWesternGrebe}) = 1.10 + 0.706(\ln(\overline{THg}_{preyfish}))$$
$$\ln(BloodTHg_{AverageFemaleClark'sGrebe}) = 1.13 + 0.706(\ln(\overline{THg}_{preyfish}))$$
$$\ln(BloodTHg_{AverageMaleClark'sGrebe}) = 1.33 + 0.706(\ln(\overline{THg}_{preyfish}))$$

Grebe Eggs

For predicting THg concentrations in grebe eggs (µg/g fww), we implemented a similar approach and predicted models for each unique combination of grebe species (western grebe, Clark's grebe, and unknown) and egg collection type (random and abandoned). The egg-specific coefficients in the model (β_0) were species, egg collection type, and nest initiation date. We assumed equal composition of Clark's grebes' and western grebes' eggs as well as random and abandoned eggs. Lastly, we used the median nest initiation date for all eggs collected (median day of year was 211). Thus, the final equation to predict THg concentrations in grebe eggs is:

$$\begin{aligned}\ln\left(EggTHg_{fww;\,AverageGrebe}\right) &= -1.49 + 0.569\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.00197\left(LakePerimeter_{km}\right) \\ &+ 0.00000846\left(LakeArea_{ha}\right) + 0.0421\left(LakeShapeIndex\right) \\ &- 0.00000977\left(LakeElevation\right)\end{aligned}$$

Figure 7 displays this model-averaged prediction of THg concentrations in grebe eggs over the observed range of THg concentrations in individual prey fish. The panels in figure 7 show the differences among grebe species and egg type for the modeled-averaged means (top left panel), and the 95-percent confidence limits around this mean. Because there was no difference in model predictions by grebe species and egg collection type, the regression lines are indistinguishable and we therefore show only the 95-percent confidence limits around this mean for randomly sampled western grebe eggs as an example.

When lake data are not available, we can further simplify these equations by using median values for date and mean values for lake attributes. When we do so, the equation to predict THg concentrations in grebe eggs is:

$$\ln\left(EggTHg_{fww;\,AverageGrebe}\right) = -1.21 + 0.569\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$

Sport Fish

For predicting THg concentrations in sport fish (µg/g dw), we again implemented a similar approach and predicted models for each species of sport fish. The final equations to predict THg concentrations in sport fish are:

$$\begin{aligned}\ln\left(SportFishTHg_{AverageSportfish}\right) &= -0.630 + 0.00621\left(TotalLength_{mm}\right) \\ &+ 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.0000205\left(LakeArea_{ha}\right) \\ &- 0.000658\left(LakeElevation_{m}\right) - 0.000140\left(LakePerimeter_{km}\right) \\ &- 0.0202\left(LakeShapeIndex\right) + 0.000309\left(DayofYear - 204\right) \\ &+ 0.00000161\left(DayofYear - 204\right)^2\end{aligned}$$

$$\begin{aligned}\ln\left(SportFishTHg_{LargemouthBass}\right) &= -0.237 + 0.00649\left(TotalLength_{mm}\right) \\ &+ 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.0000205\left(LakeArea_{ha}\right) \\ &- 0.000658\left(LakeElevation_{m}\right) - 0.000140\left(LakePerimeter_{km}\right) \\ &- 0.0202\left(LakeShapeIndex\right) + 0.000309\left(DayofYear - 204\right) \\ &+ 0.00000161\left(DayofYear - 204\right)^2\end{aligned}$$

$$\ln(SportFishTHg_{SmallmouthBass}) = 0.557 + 0.00544(TotalLength_{mm}) + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.0000205(LakeArea_{ha}) - 0.000658(LakeElevation_{m}) - 0.000140(LakePerimeter_{km}) - 0.0202(LakeShapeIndex) + 0.000309(DayofYear - 204) + 0.00000161(DayofYear - 204)^2$$

$$\ln(SportFishTHg_{RainbowTrout}) = -0.865 + 0.00608(TotalLength_{mm}) + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.0000205(LakeArea_{ha}) - 0.000658(LakeElevation_{m}) - 0.000140(LakePerimeter_{km}) - 0.0202(LakeShapeIndex) + 0.000309(DayofYear - 204) + 0.00000161(DayofYear - 204)^2$$

$$\ln(SportFishTHg_{BrownTrout}) = 0.437 + 0.00192(TotalLength_{mm}) + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.0000205(LakeArea_{ha}) - 0.000658(LakeElevation_{m}) - 0.000140(LakePerimeter_{km}) - 0.0202(LakeShapeIndex) + 0.000309(DayofYear - 204) + 0.00000161(DayofYear - 204)^2$$

$$\ln\left(SportFishTHg_{EagleLakeRainbowTrout}\right) = -3.04 + 0.0111(TotalLength_{mm}) + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right) + 0.0000205(LakeArea_{ha}) - 0.000658(LakeElevation_{m}) - 0.000140(LakePerimeter_{km}) - 0.0202(LakeShapeIndex) + 0.000309(DayofYear - 204) + 0.00000161(DayofYear - 204)^2$$

Figure 8 displays this model-averaged prediction of THg concentrations in sport fish over the observed range of THg concentrations in individual prey fish. The panels in figure 8 show the differences among species of sport fish for the modeled-averaged means (top left panel) and the 95-percent confidence limits around this mean for each species of sport fish.

Lastly, figure 9 displays these same model-averaged predictions simultaneously for mean THg concentrations in grebe blood, grebe eggs, and sport fish over the observed range of THg concentrations in individual prey fish. For this figure, the different panels show only the differences between types of animal tissue, without the variance associated with the estimates.

When lake data are not available, we can further simplify these equations by using median values for date, 350 mm for total length, and mean values for lake attributes. When we do so, the equations to predict THg concentrations in sport fish are:

$$\ln\left(SportFishTHg_{AverageSportfish}\right) = 1.06 + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$
$$\ln\left(SportFishTHg_{LargemouthBass}\right) = 1.56 + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$
$$\ln(SportFishTHg_{SmallmouthBass}) = 1.98 + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$
$$\ln(SportFishTHg_{RainbowTrout}) = 0.783 + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$
$$\ln(SportFishTHg_{BrownTrout}) = 0.631 + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$
$$\ln\left(SportFishTHg_{EagleLakeRainbowTrout}\right) = 0.370 + 0.768\left(\ln\left(\overline{THg}_{preyfish}\right)\right)$$

Predictive Model's Fit

We compared model-averaged predictions to our individual raw THg concentrations and found generally good agreement between predicted and observed data (fig. 10). Predicted THg concentrations were correlated with raw THg concentrations observed in grebe blood (R^2 = 0.61, n=353; fig. 10 top panel), grebe eggs (R^2 = 0.47, n=101; fig. 10 bottom panel), and sport fish (R^2 = 0.83, n=230; fig. 10 middle panel), Generally, the model performed better at intermediate THg concentrations (sport fish: 0.1–7.0 µg/g dw; grebe blood: 0.1–3.0 µg/g ww; grebe eggs: 0.04–0.2 µg/g fww) and poorer at very low or high THg concentrations where model-averaging tended to predict THg concentrations closer to the mean. This tendency for predictions to regress toward the mean indicates that individuals with very high THg concentrations will be underestimated, and individuals with very low THg concentrations will be overestimated. However, because we are using mean THg concentrations in prey fish at each lake rather than individuals to estimate risk to birds and sports fish, these errors will likely be minor.

Management Application—Predictive Tool for Resource Managers

Using the equations developed above, we built a predictive tool for use by natural resource managers (see Excel file entitled "USGS Wildlife and Sport Fish Risk Estimator Tool Final.xlsx" available at http://www.werc.usgs.gov/mercuryriskinlakes). Users can follow the guidelines in the tool's worksheet entitled "Tutorial." Tool users will need to enter THg concentrations in prey fish, date sampled, and the specific lake's attributes, and our tool will then predict THg concentrations in grebe blood, grebe eggs, and sport fish. Furthermore, our tool uses these estimated values to assess the relative risk to the animal by comparing the estimated THg concentrations to published toxicity benchmarks. Figure 11 illustrates the tool using THg concentrations in prey fish and physical attributes from Lake Berryessa as a high-Hg lake example. Figure 12 illustrates the tool using THg concentrations in prey fish and physical attributes from Big Lake as a low-Hg example.

The specific steps for using the tool are as follows.

1. First, the user would enter THg concentrations in prey fish at the lake of interest in microgram per gram dry weight. We suggest determining THg concentrations in prey fish on a whole-body and dry-weight basis, but entering values on a wet-weight basis and also entering moisture content is acceptable.
2. Second, the user enters the date the prey fish were sampled, as the number of days since January 1 of each year.
3. Third, the user would enter the specific lake's attributes, including lake area in hectares, lake perimeter in kilometers, and the lake's elevation in meters. These lake variables are available in the tool's worksheet entitled "Lake Attribute Data." We have included lake attribute data for 4,316 lakes in California; if lake data are not included in the worksheet, the user will need to obtain those data independently. The tool will calculate the lake's shape index from the lake area and perimeter data.
4. Fourth, the user would enter the desired total length in millimeters for the sport fish THg estimate. The specific values entered should fall within the general range of the fish and lake data used to generate the model (table 11), and these metadata are included in the tool's worksheet entitled "Appropriate Data Ranges." Additionally, we recommend that users only use the prediction for the sport fish species that inhabit the specific lake.

The tool then estimates the THg concentrations in grebe blood (including an average grebe, or by species and sex), grebe eggs (combining grebe species and type of eggs), and sport fish (by species), and assesses the relative risk of mercury to wildlife and sport fish if they were to consume prey fish from the specific lake. Table 12 shows the toxicity benchmarks and associated citations used to generate the relative risk estimates.

For bird blood, toxicity benchmarks across multiple taxa, and grebes specifically, are still lacking. However, benchmarks for deleterious effects of Hg on reproduction have been developed for common loon (*Gavia immer*) blood (Evers and others, 2004): less than 1.0 µg/g ww is considered low risk, 1.0–3.0 µg/g ww is considered medium risk, 3.0–4.0 µg/g ww is considered high risk, and greater than 4.0 µg/g ww is considered extra-high risk. These values are similar to toxicity benchmarks derived by Depew and others (2012) for dietary MeHg exposure to common loons. Depew and others (2012) derived three benchmarks—0.1 µg/g ww in prey fish is the threshold for adverse behavioral impacts in adult loons, 0.18 µg/g ww in prey fish corresponds to significant reproductive impairment in loons, and 0.4 µg/g ww in prey fish corresponds to complete reproductive failure in loons. For example, Burgess and Meyer (2008) found that maximum loon productivity was reduced by 50 percent when THg concentrations were 4.3 µg/g ww in loon blood and 0.21 µg/g ww in prey fish. Using Burgess and Meyer's (2008) equation, maximum loon productivity would be reduced by approximately 13, 36, and 47 percent when THg concentrations in loon blood were at the 1.0, 3.0, and 4.0 µg/g ww risk benchmarks we used in this study.

Sensitivity of avian embryos to Hg can differ widely among species (Heinz and others, 2009). For example, Heinz and others (2009) classified 26 bird species according to their sensitivity to Hg toxicity and found that species that were highly sensitive to Hg toxicity had median lethal concentrations (LC_{50}) at less than 0.25 µg/g ww of injected Hg. However, MeHg injected directly into eggs is more toxic than maternally deposited MeHg (Heinz and others, 2009), thus it is unclear how an LC_{50} estimated from egg-injection studies relates to potential toxicity in the wild. Egg THg concentrations greater than 0.50 µg/g fww have long been considered a concentration at which bird reproduction can be impaired (review by Wiener and others, 2003). Lastly, we chose 0.65 µg/g fww as an exposure concentration at which birds are at extra-high risk of reproductive impairment, because multiple studies have documented effects near this value. For example, we estimated a sublethal threshold of 8.51 µg/g dw in liver, where waterbirds begin to demethylate the toxic form of Hg (MeHg) into inorganic Hg for four species breeding in California (Eagles-Smith and others, 2009; Ackerman and others, 2014). This liver THg threshold of 8.51 µg/g dw corresponds to an egg THg concentration of 0.65 µg/g fww (Ackerman and others, 2014). Based on the preceding, we used the following Hg toxicity benchmarks for identifying risk of impaired reproduction to grebe eggs—less than 0.25 µg/g fww was considered low risk, 0.25–0.50 µg/g fww was considered medium risk, 0.50–0.65 µg/g fww was considered high risk, and greater than 0.65 µg/g fww was considered extra-high risk of impaired reproduction.

For sport fish, we used a no-observed-effects-residue (NOER) of 0.20 µg/g ww (Beckvar and others, 2005) and a lowest-observed-effects-residue (LOER) of 0.30 µg/g ww (Sandheinrich and others, 2011). The NOER threshold identifies the Hg concentration in fish tissues below which fish should not experience deleterious effects of Hg exposure on reproduction, growth, or survival. In contrast, the LOER threshold indicates the Hg concentration above which sublethal endpoints of Hg exposure, including alterations to reproductive health, have been documented in laboratory and field studies of freshwater fish. We therefore used the following Hg toxicity benchmarks for identifying risk to sport fish—less than 0.20 µg/g ww was considered low risk, 0.20–0.30 µg/g ww was considered medium risk, 0.30–0.40 µg/g ww was considered high risk, and greater than 0.40 µg/g ww was considered extra-high risk.

Mercury Correlations between Grebe Blood, Grebe Eggs, and Sport Fish

Although the goal of this study was to use THg concentrations in prey fish to estimate THg concentrations in predators (grebe blood, grebe eggs, and sport fish), it is informative to know how well THg concentrations in grebe blood, grebe eggs, and sport fish were related. Examination of least squares mean THg concentrations indicated that grebe blood was related to sport fish (n=24 lakes, R^2=0.59, $F_{1,22}$=31.79, p<0.0001; fig. 13 top panel), grebe eggs were related to sport fish (n=6 lakes, R^2=0.67, $F_{1,4}$=8.17, p=0.05; fig. 13 middle panel), and grebe eggs were strongly related to grebe blood (n=7 lakes, R^2=0.93, $F_{1,5}$=71.43, p<0.001; fig. 13 bottom panel).

Equations for these relationships are as follows:

$$\ln\left(Blood\overline{THg}_{grebe;\frac{\mu g}{g}ww}\right) = 0.03 + 0.966\left(\ln\left(\overline{THg}_{sportfish;\frac{\mu g}{g}dw}\right)\right)$$

$$\ln\left(Egg\overline{THg}_{grebe;\frac{\mu g}{g}fww}\right) = -1.97 + 0.720\left(\ln\left(\overline{THg}_{sportfish;\frac{\mu g}{g}dw}\right)\right)$$

$$\ln\left(Egg\overline{THg}_{grebe;\frac{\mu g}{g}fww}\right) = -1.94 + 0.883\left(\ln\left(Blood\overline{THg}_{grebe;\frac{\mu g}{g}ww}\right)\right)$$

Conclusions and Management Implications

In this study, we specifically addressed three main management questions with broad applicability throughout the State.

(1) Does methylmercury pose significant risks to aquatic life in a representative sample of California lakes and reservoirs?

Overall, Hg exceeded 1.0 µg/g ww in blood in 28 percent of grebes, a blood-Hg level that generally puts birds at elevated risk of potential impairment (table 1). In particular, THg concentrations exceeded 1.0 µg/g ww in blood in more than 40 percent of all grebes sampled in 9 of the 25 lakes; these included Lake Berryessa, Topaz Lake, Crowley Lake, Lake Hennessey, Bridgeport Reservoir, East Park Reservoir, Lake Mendocino, Lake San Antonio, and Lake Casitas. This study did not specifically focus on the potential effects of these high Hg concentrations on grebes. However, elsewhere, we estimated a sublethal threshold of 8.51 µg/g dw in liver (equivalent to 1.3 µg/g ww in blood) where waterbirds begin to demethylate the toxic form of Hg (MeHg) into inorganic Hg for four species breeding in California (Eagles-Smith and others, 2009; Ackerman and others, 2014). No eggs exceeded 0.5 µg/g fww at the seven lakes where they were sampled. However, eggs were sampled from lakes that were at the low end of the observed THg concentrations in grebe blood and fish among all lakes in this study (fig. 3). Thus, the potential exists for Hg impairment of grebes and other piscivorous wildlife in many California lakes.

Hg concentrations in sport fish also were elevated; Hg concentrations exceeded 0.30 µg/g ww in 48 percent of sport fish where sublethal endpoints of Hg exposure have been documented in laboratory and field studies of fish (Sandheinrich and others, 2011). Hg concentrations exceeded 0.30 µg/g ww in at least 1 sportfish in 18 of the 24 lakes sampled. Furthermore, THg concentrations exceeded 0.30 µg/g ww in more than 50 percent of all sport fish sampled in 13 of the 24 lakes; these included Black Butte Reservoir, Clear Lake, Lake Berryessa, Lake Casitas, Lake Hennessey, Lake Mendocino, Lake Success, Lake Cuchuma, Thermalito Afterbay, Lake San Antonio, East Park Reservoir, Crowley Lake, and Topaz Lake. A more comprehensive study specifically monitoring Hg concentrations in sport fish sampled from 250 California lakes is available in Davis and others (2010).

(2) Can a correlational approach be applied on a statewide basis to estimate risks to birds?

We found strong relationships between Hg concentrations in piscivorous wildlife (represented by western grebes and Clark's grebes) and prey fish among California lakes. Similarly, Hg concentrations in prey fish were a strong predictor of Hg concentrations in sport fish. Using a model-averaging approach, we were able to develop equations to predict Hg concentrations in bird blood, bird eggs, and sport fish using Hg concentrations in prey fish, sampling date, and lake attributes. We then applied these equations to develop a tool for natural resource managers and regulators to use for predicting lake-specific risk of Hg to wildlife and sport fish. This tool, which can be downloaded for use at: http://www.werc.usgs.gov/mercuryriskinlakes, can be effectively used to estimate Hg risk to piscivorous wildlife on a statewide basis among California lakes and reservoirs, within the applicable data ranges of this study. These appropriate data ranges for our model's application are available in the tool's worksheet entitled "Appropriate Data Ranges." Because we specifically designed our study to cover a broad range of lake elevations, sizes, and shapes and Hg exposure levels throughout the State, our tool is fairly robust to the different environmental conditions common to California. However, it is important to note that this tool is directly applicable only to western grebes and Clark's grebes, and should be used with caution if predicting risk to other piscivorous bird species. Differences among wildlife species, such as prey selection and bioenergetics, likely would result in different MeHg biomagnification rates, and additional study would be needed to appropriately estimate Hg concentrations in other wildlife taxa. A few other studies have found correlations between THg concentrations in bird blood and THg concentrations in prey fish, particularly for common loons breeding on lakes in the northeast (Scheuhammer and others, 1998; Champoux and others, 2006; Burgess and Meyer, 2008; Yu and others, 2011; Hosseini and others, 2013).

We also provided equations to predict THg concentrations in grebe blood from THg concentrations in sport fish for occasions when sport fish data are the only data available at a particular lake. However, the equations to predict THg concentrations in grebe blood using THg concentrations in prey fish are more robust than those using sport fish, and the prey fish models should be used when possible.

(3) What are appropriate water-quality monitoring requirements to address methylmercury exposure in wildlife?

We found that risk to piscivorous wildlife can be effectively estimated using THg concentrations in prey fish and associated lake and sampling date variables. However, the modeling and associated tool has its limitations. Whereas we used *Aechmophorus* grebes as our index of risk to piscivorous wildlife, species differences in Hg exposure, as well as pronounced differences in sensitivity to Hg among species (Heinz and others, 2009), should be considered when using such a generalized tool. Other species of wildlife that use California lakes, such as osprey, mergansers, kingfisher, and occasionally terns, might have even higher (or lower) Hg concentrations. For example, using Lake Berryessa data,

we estimated that THg concentrations could differ from 3.08 µg/g ww for female western grebes to 4.76 µg/g ww for male Clark's grebes. Such differences in Hg concentrations between species and sexes are real, and are further influenced by other bird-specific variables such as body condition, sampling date, and molt status. Because these bird-specific values are often unknown without direct sampling, we used mean values in our predictive models and in the tool's development. Therefore, while this tool can be highly useful to estimate levels of risk, there is still no substitute for direct sampling of birds and other wildlife for more precise estimates of Hg exposure.

Furthermore, least squares mean THg concentrations in prey fish were substantially better than geometric mean THg concentrations in prey fish at predicting THg concentrations in grebe blood, grebe eggs, and sport fish. The least squares mean THg concentrations in prey fish statistically accounted for inherent sampling biases in prey fish—namely, in variations in fish length and species of prey fish that were captured across sampling locations. Therefore, whereas entering geometric mean THg concentrations in prey fish into the model might be acceptable when only a single or very few lakes are sampled, standardizing the prey fish THg concentrations for length and species when a number of lakes are sampled is desirable. This can be done following the methods we describe in section, "Statistical Methods—Mercury by Lake."

We recommend sampling at least 20 prey fish individuals from 2 species from each lake and analyzing THg concentrations on an individual, rather than a composite, basis. Prey fish should be sampled during the breeding season (approximately April–July) when wildlife are at greatest risk to potential Hg-induced impairment, and sampling date should be standardized for annual monitoring programs because seasonal variation in prey fish Hg concentrations can be substantial (Eagles-Smith and Ackerman, 2009). Furthermore, this study is specific to lakes and should not be extrapolated to other water bodies such as wetlands; in wetland habitats, THg concentrations in prey fish may not be correlated to THg concentrations in piscivorous birds (Ackerman and others, 2014).

The California State Water Resources Control Board staff may propose a target value for THg concentrations in sport fish in California lakes of 0.2 µg/g ww to be protective of sport fish and wildlife (A. Palumbo, written commun., 2015). Using the equation developed in this study and the average moisture content of sport fish, a THg concentration of 0.2 µg/g ww (0.92 µg/g dw) in sport fish corresponds to a THg concentration of 1.0 µg/g ww in grebe blood. Alternatively, if the California State Water Resources Control Board wanted to use a target value for THg concentrations in prey fish, instead of sport fish, than a THg concentration of 0.05 µg/g ww in prey fish corresponds to a THg concentration of 1.0 µg/g ww in grebe blood (using average values for prey fish moisture content and lake variables). As discussed previously, 1.0 µg/g ww in bird blood corresponds to the beginning of the "moderate risk" benchmark for potential impaired reproduction in birds. These values represent average THg concentrations in grebes within a lake, and therefore approximately one-half of the individual grebes would have THg concentrations greater than this "moderate risk" toxicity benchmark, and one-half would have less than this moderate risk toxicity benchmark. Thus, if the THg concentration of 0.2 µg/g ww in sport fish is meant to be protective for all individual grebes, and potentially other wildlife, the California State Water Resources Control Board could consider lowering this target value.

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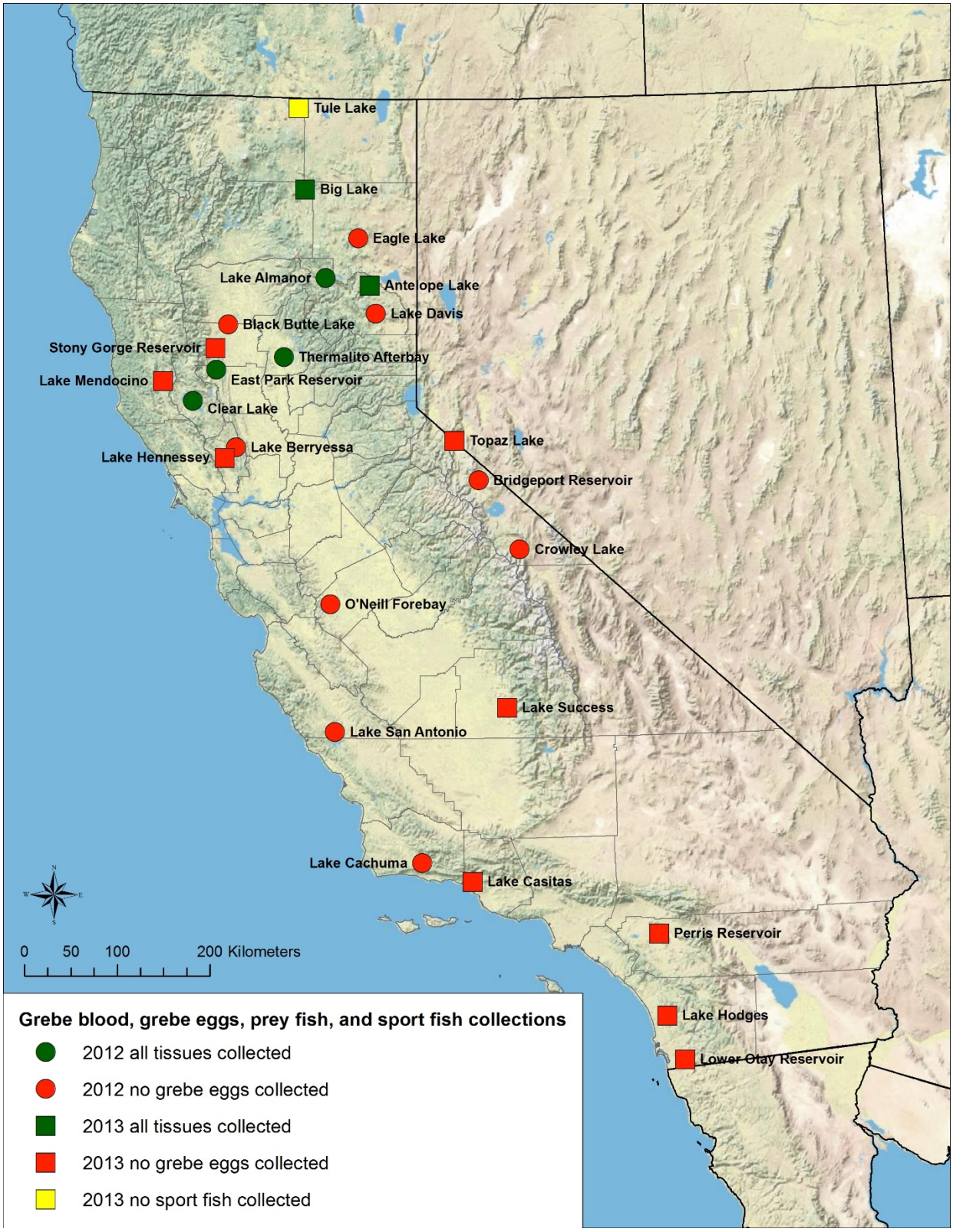

Figure 1. Map showing location of the 25 lakes and reservoirs where grebes, sport fish, and prey fish were collected for mercury analyses of blood, eggs, and tissue, California, 2012–13. Topography layer by U.S. National Park Service.

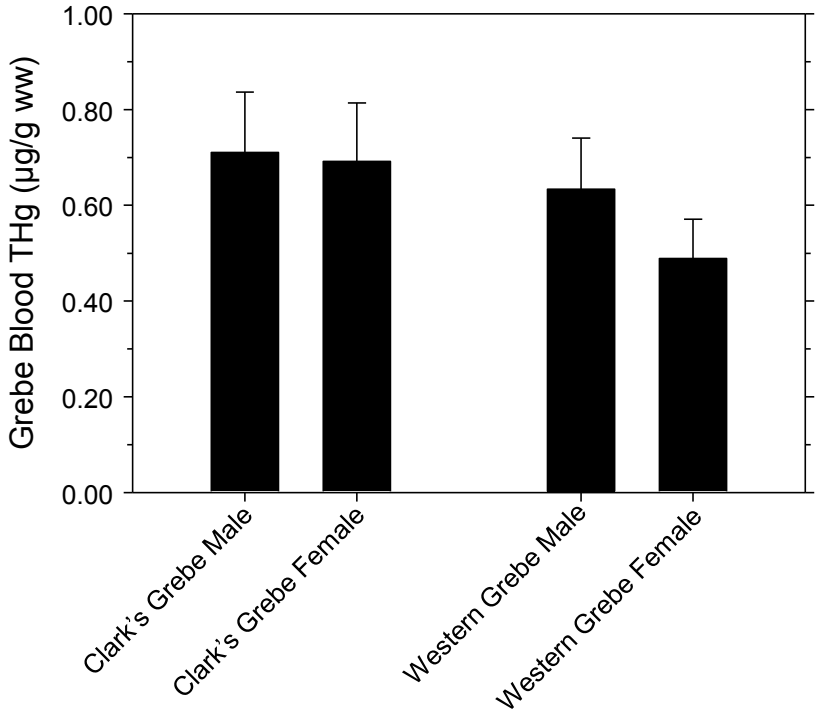

Figure 2. Graph showing total mercury (THg) concentrations (in micrograms per gram wet weight [µg/g ww]) in blood of male and female Clark's grebes and western grebes captured at 25 lakes in California, 2012–13. Values are least squares means ± standard errors from a global model accounting for species and sex, with lake as a random effect.

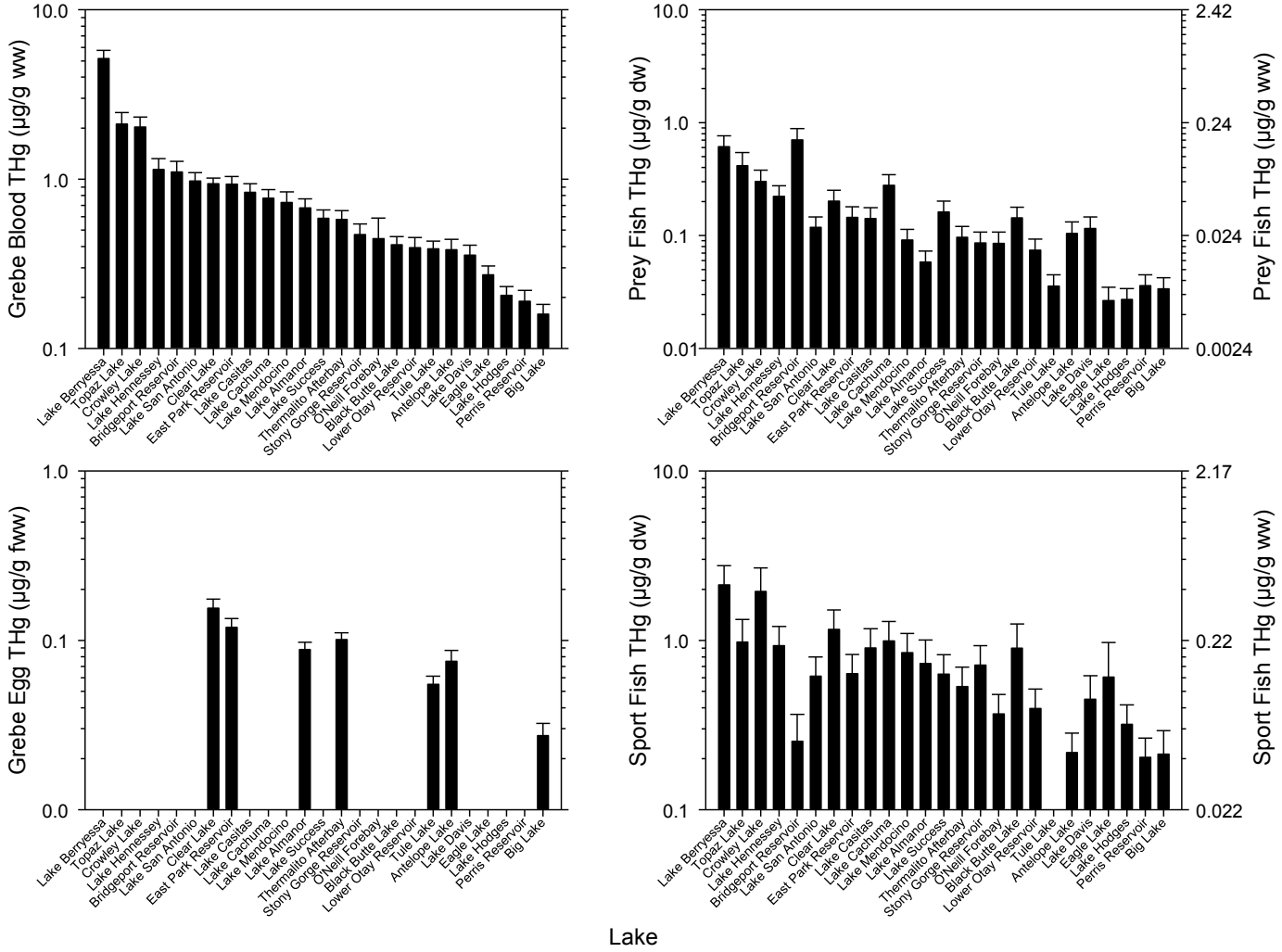

Figure 3. Graphs showing total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw] [left Y axis]; or in µg/g wet weight [ww] [right Y axis]) in grebe blood (top left panel), prey fish (top right panel), grebe eggs (bottom left panel), and sport fish (bottom right panel) sampled at as many as 25 lakes in California, 2012–13. Values are least squares means ± standard errors from separate models accounting for (1) grebe blood model: species and sex with lake as a random effect; (2) prey fish model—species, standard length, and species × length interaction with lake as a random effect; (3) grebe egg model—species and egg type with lake as a random effect; and (4) sport fish model—species, total length, and species × length interaction with lake as a random effect.

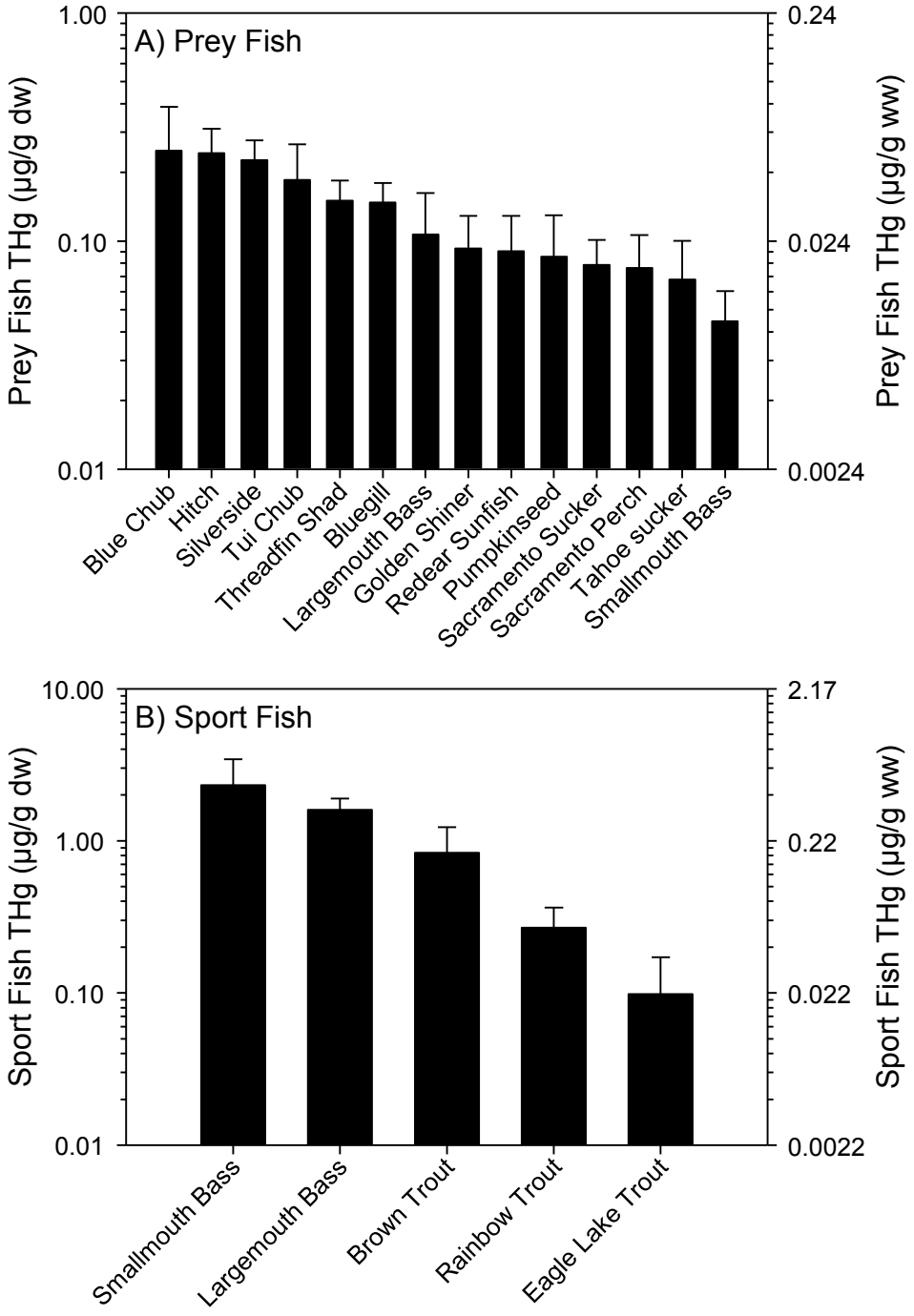

Figure 4. Graphs showing total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw] [left Y axis] or in µg/g wet weight [ww] [right Y axis]) in (A) whole prey fish by species from 25 lakes and (B) sport fish fillets by species from 24 lakes in California, 2012–13. Values are least squares means ± standard errors from separate models accounting for species, length, and species × length interaction with lake as a random effect.

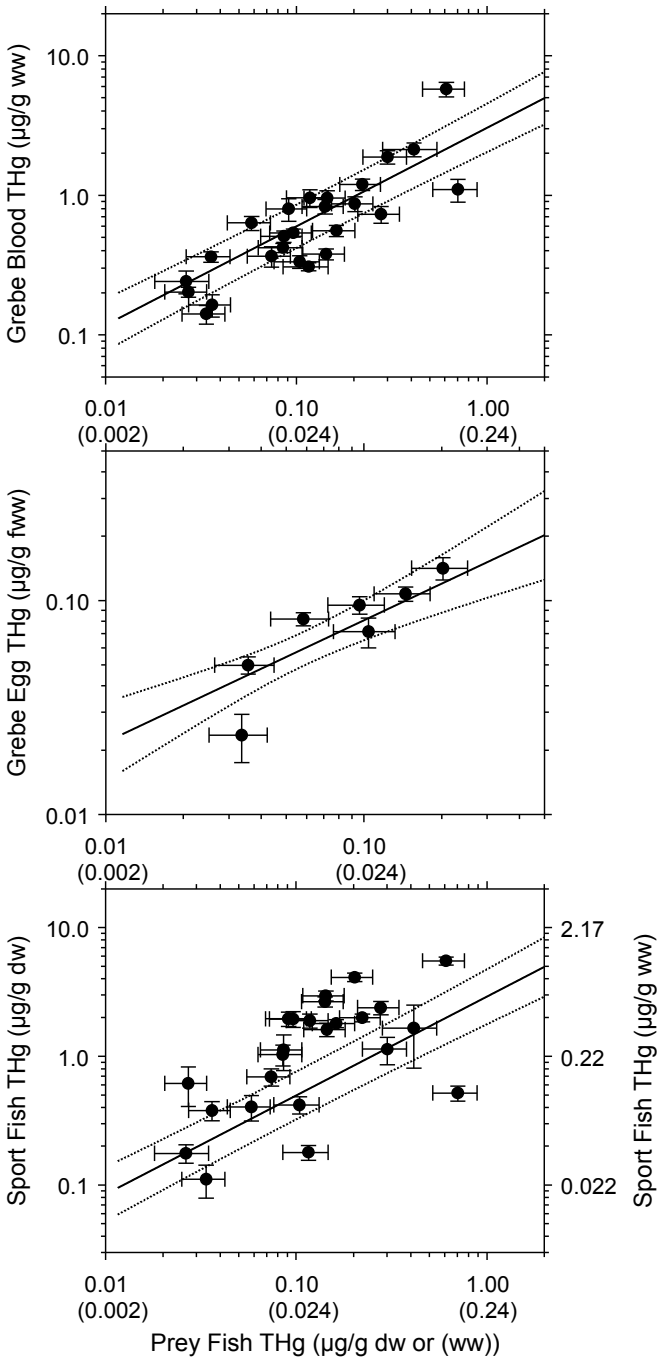

Figure 5. Graphs showing total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw] [left Y axis] or µg/g wet weight [ww] [right Y axis]) in grebe blood (top panel), grebe eggs (middle panel), and sport fish (bottom panel) versus THg concentrations in prey fish (µg/g dw [top row X axis] or µg/g ww [bottom row X axis]) sampled at up to 25 lakes in California, 2012–13. Y-axis values are geometric means ± standard errors and X-axis values are least squares means ± standard errors from a global model accounting for species, standard length, and species × length interaction with lake as a random effect. The solid line is the model-averaged predicted THg concentration and the stippled lines are the 95-percent confidence limits of the model-averaged predicted THg concentration. Model predictions were generated by setting all other variables in the predictive model to their mean values (or mode for wing molt and median for date), except for total length of sport fish, which was set to 350 millimeters.

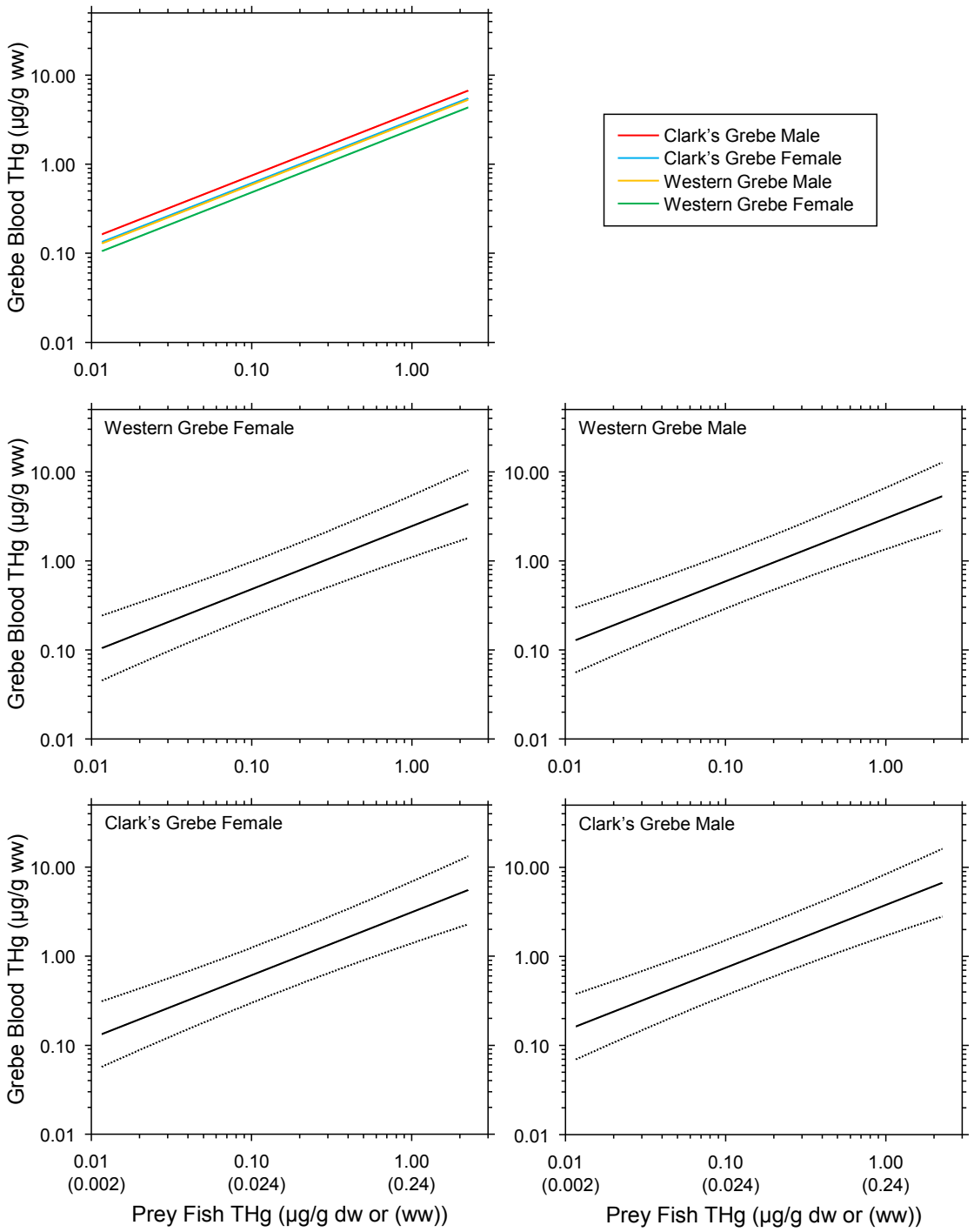

Figure 6. Graphs showing total mercury (THg) concentrations (in micrograms per gram wet weight [µg/g ww]) in grebe blood by species and sex versus THg concentrations in prey fish (µg/g dry weight [dw] [top row X axis] or in µg/g ww [bottom row X axis]) sampled at 25 lakes in California, 2012–13. The solid lines are the model-averaged predicted THg concentration and the stippled lines are the 95-percent confidence limits of the model-averaged predicted THg concentration. The top left panel shows only the model-averaged mean predicted THg concentration for each species and sex, whereas the other panels shows species and sex-specific predictions with 95-percent confidence limits. Model predictions were generated by setting all other variables in the predictive model to their mean values (or mode for wing molt and median for date).

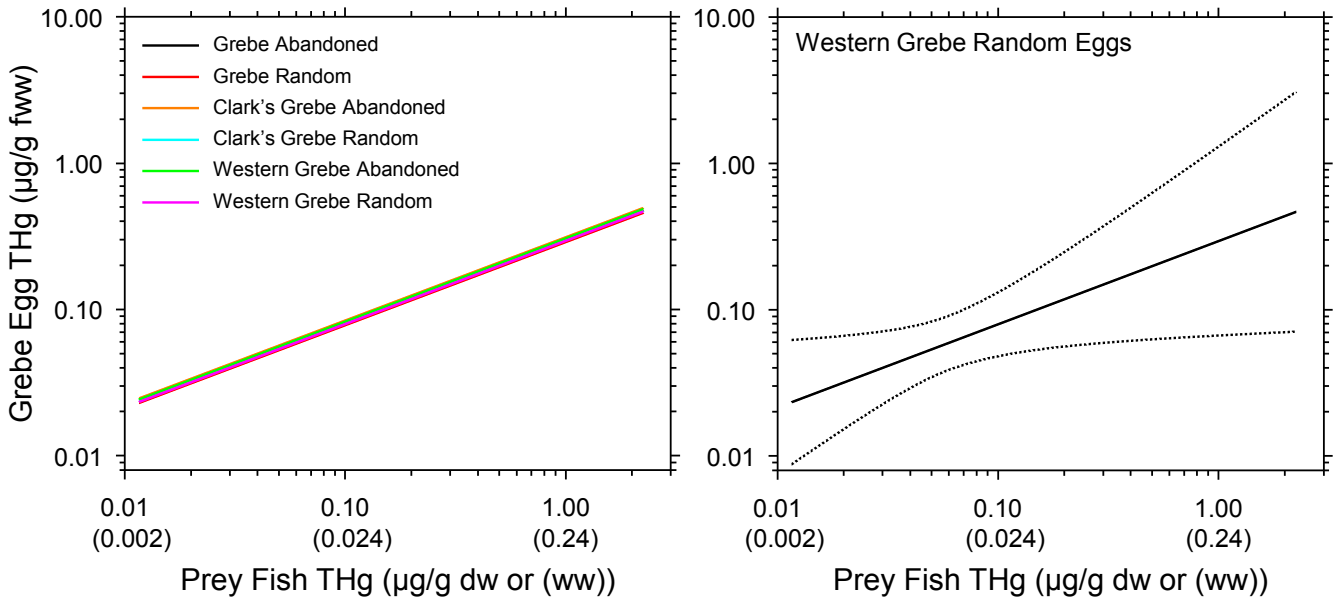

Figure 7. Graphs showing total mercury (THg) concentrations (in micrograms per gram fresh water weight [µg/g fww]) in grebe eggs by species and egg type (random or abandoned) versus THg concentrations in prey fish (in µg/g dry weight [dw] [top row X axis] or in µg/g wet weight [ww] [bottom row X axis]) sampled at seven lakes in California, 2012–13. The solid lines are the model-averaged predicted THg concentration and the stippled lines are the 95-percent confidence limits of the model-averaged predicted THg concentration. The left panel shows only the model-averaged mean predicted THg concentration for each species and egg type. The right panel shows the specific prediction with 95-percent confidence limits for randomly sampled western grebe eggs. Because there was no difference in the model-averaged predicted THg concentration among species and egg type, we show only one of the six possible combinations as an example to display the 95-percent confidence limits. Model predictions were generated by setting all other variables in the predictive model to their mean values (or median for date).

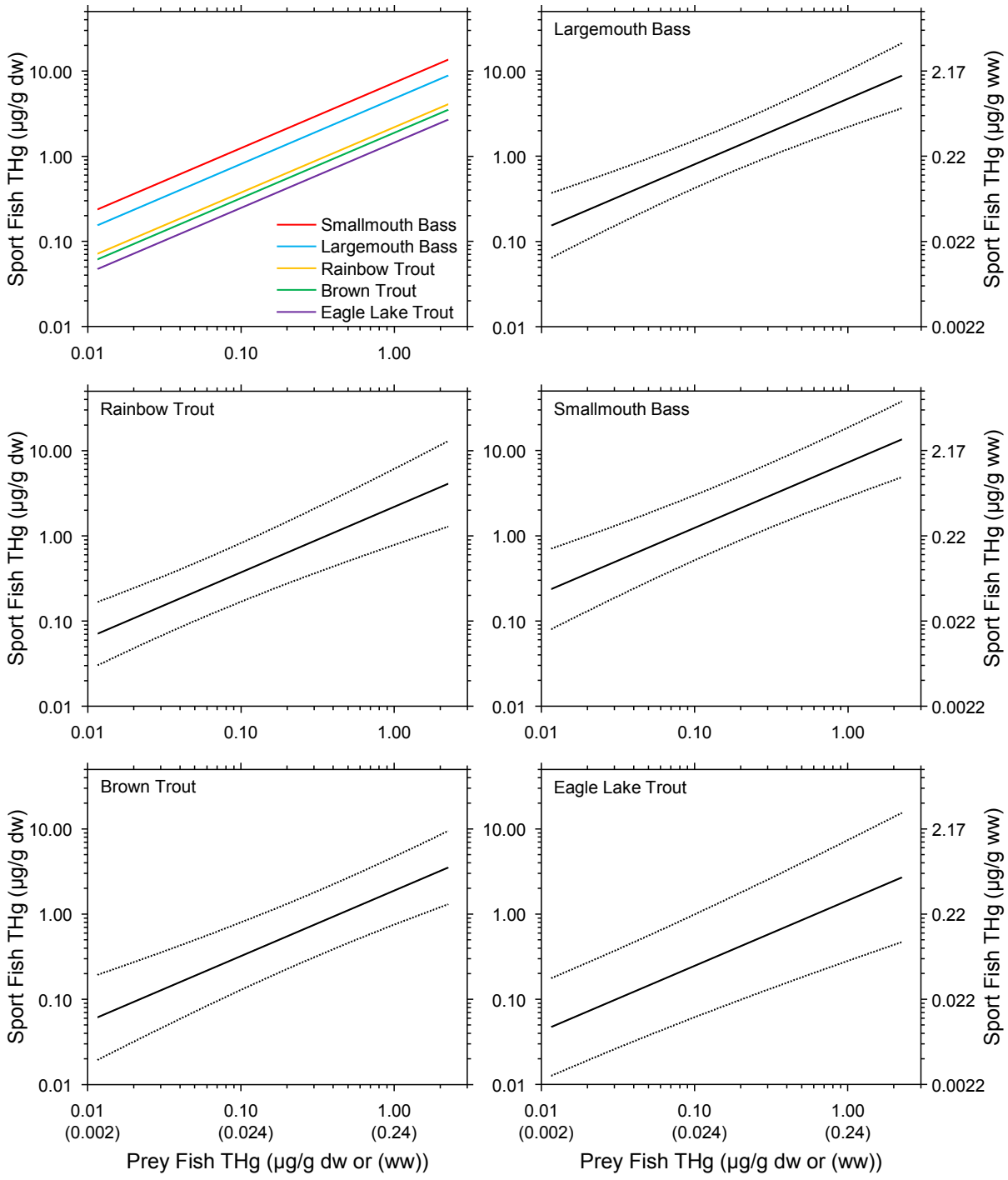

Figure 8. Graphs showing total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw] [left axis] or µg/g wet weight [ww] [right Y axis]) in sport fish by species versus THg concentrations in prey fish (µg/g dw [top row X axis] or µg/g ww [bottom row X axis]) sampled at 24 lakes in California, 2012–13. The solid lines are the model-averaged predicted THg concentration and the stippled lines are the 95-percent confidence limits of the model-averaged predicted THg concentration. The top left panel shows only the model-averaged mean predicted THg concentration for each species, whereas the other panels shows species specific predictions with 95-percent confidence limits. Model predictions were generated by setting all other variables in the predictive model to their mean values (or median for date), except for total length of sport fish, which was set to 350 millimeters.

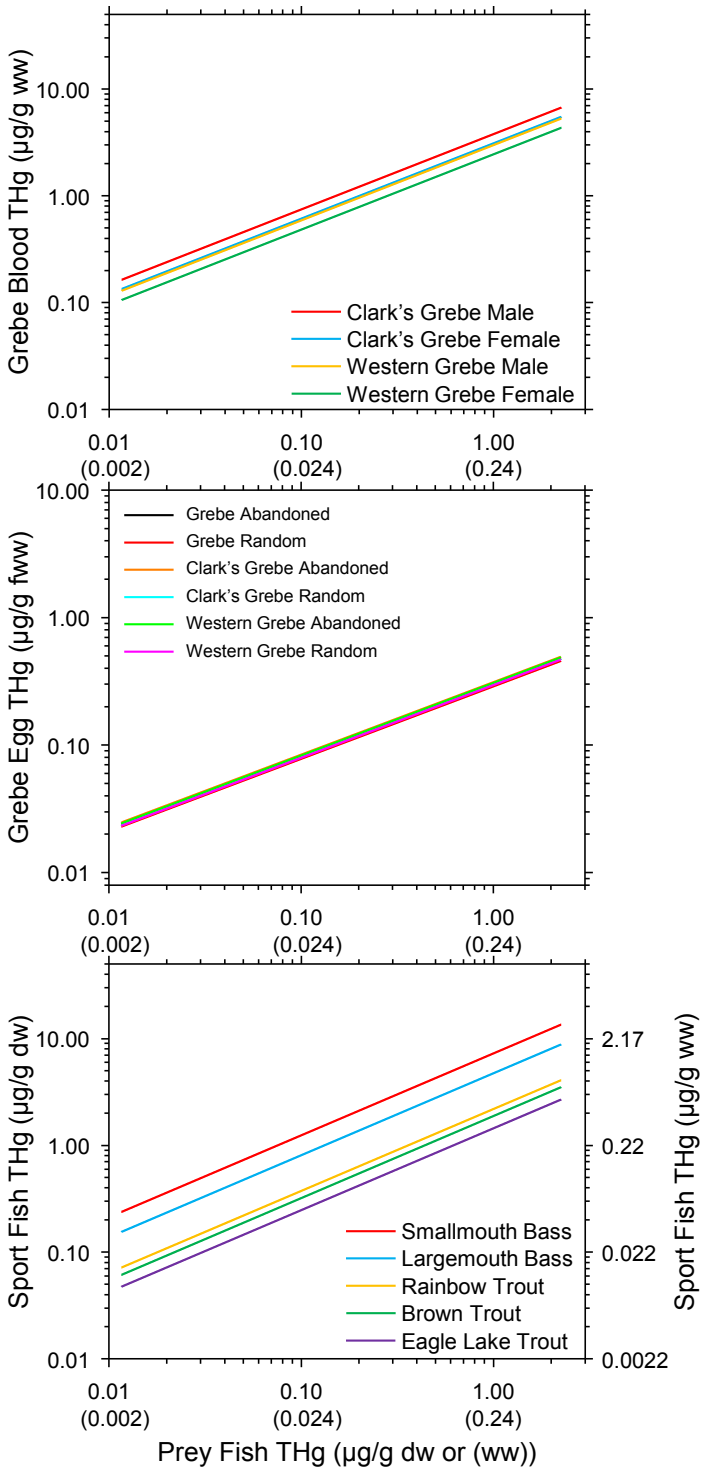

Figure 9. Graphs showing total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw] [left Y axis] or µg/g wet weight [ww] [right Y axis]) in grebe blood (top panel), grebe eggs (middle panel), and sport fish (bottom panel) versus THg concentrations in prey fish (µg/g dw [top row X axis] or µg/g ww [bottom row X axis]) sampled at as many as 25 lakes in California, 2012–13. The solid lines are the model-averaged mean predicted THg concentration by species, sex, and/or egg type. Model predictions were generated by setting all other variables in the predictive model to their mean values (or mode for wing molt and median for date), except for total length of sport fish, which was set to 350 millimeters.

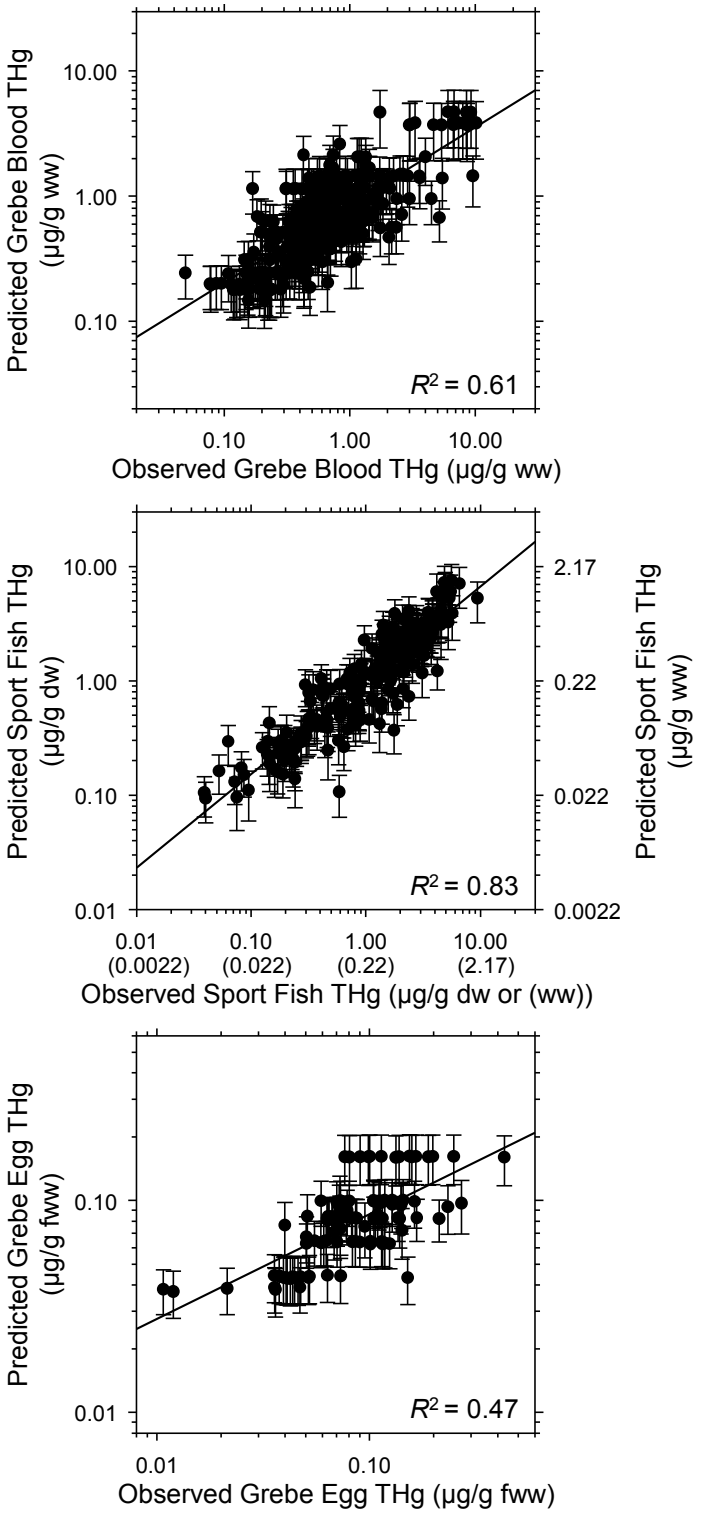

Figure 10. Graphs showing model-predicted mean ± standard errors total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw] [left Y axis] or µg/g wet weight [ww] [right Y axis]) versus observed (raw) THg concentrations (µg/g dw [top row X axis] or µg/g ww [bottom row X axis]) in grebe blood (top panel; *n*=354), sport fish (middle panel, *n*=230), and grebe eggs (bottom panel; *n*=101) in California, 2012–13. Model predictions were generated by using individual-specific data associated with the raw data point for all variables in the final model.

Model Input	
Prey Fish (enter DW or WW and %moisture)	
LS Mean [THg] µg/g dw	0.61
LS Mean [THg] µg/g ww	0.15
% moisture	75.8%
LS Mean [THg] µg/g dw	*0.61*
Date Sampled	
Days from January 1	152
Lake Variables	
Lake Size (ha)	7553
Lake Perimeter (km)	255.33
Lake Elevation (m)	133.8
Lake Shape Index	*7.34*
Sport Fish	
Sport Fish Total Length (mm)	389

Model Output: Wildlife

Species	Grebe Blood (µg/g ww)	Risk to Wildlife
All Grebes	**3.84**	**High Risk**
Clark's Grebe Male	**4.77**	**Extra High Risk**
Clark's Grebe Female	**3.90**	**High Risk**
Western Grebe Male	**3.77**	**High Risk**
Western Grebe Female	**3.08**	**High Risk**

	Grebe Eggs (µg/g fww)	Risk to Wildlife
All Grebes	**0.41**	**Medium Risk**

Model Output: Sport Fish

Species	Sport Fish (µg/g dw)	Sport Fish (µg/g ww)	Risk to Sport Fish
Largemouth Bass	**5.92**	**1.28**	**Extra High Risk**
Smallmouth Bass	**8.71**	**1.89**	**Extra High Risk**
Brown Trout	**1.97**	**0.43**	**Extra High Risk**
Rainbow Trout	**2.69**	**0.58**	**Extra High Risk**
Eagle Lake Trout	**2.16**	**0.47**	**Extra High Risk**

Figure 11. Example of our predictive tool for use by natural resource managers using Lake Berryessa specific data. Tool users will enter total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw]) in prey fish, date sampled, and the specific lake's attributes (lake area, perimeter, and elevation), and our tool will estimate the predicted THg concentrations in grebe blood, grebe eggs, and sport fish. Our tool then uses these estimated values to assess the relative risk to wildlife and sport fish by comparing the estimated THg concentrations to published toxicity benchmarks. In this example, THg concentrations in prey fish at Lake Berryessa are very high, and thus the tool estimates that wildlife and sport fish are at high risk of potential mercury impairment.

Model Input	
Prey Fish (enter DW or WW and % moisture)	
LS Mean [THg] µg/g dw	0.03
LS Mean [THg] µg/g ww	
% moisture	
LS Mean [THg] µg/g dw	*0.03*
Date Sampled	
Days from January 1	204
Lake Variables	
Lake Size (ha)	703
Lake Perimeter (km)	36.67
Lake Elevation (m)	1007.4
Lake Shape Index	*3.46*
Sport Fish	
Sport Fish Total Length (mm)	430

Model Output: Wildlife

Species	Grebe Blood (µg/g ww)	Risk to Wildlife
All Grebes	**0.23**	**Low Risk**
Clark's Grebe Male	**0.29**	**Low Risk**
Clark's Grebe Female	**0.23**	**Low Risk**
Western Grebe Male	**0.23**	**Low Risk**
Western Grebe Female	**0.18**	**Low Risk**

	Grebe Eggs (µg/g fww)	Risk to Wildlife
All Grebes	**0.04**	**Low Risk**

Model Output: Sport Fish

Species	Sport Fish (µg/g dw)	Sport Fish (µg/g ww)	Risk to Sport Fish
Largemouth Bass	**0.42**	**0.09**	**Low Risk**
Smallmouth Bass	**0.59**	**0.13**	**Low Risk**
Brown Trout	**0.12**	**0.03**	**Low Risk**
Rainbow Trout	**0.19**	**0.04**	**Low Risk**
Eagle Lake Trout	**0.19**	**0.04**	**Low Risk**

Figure 12. Example of our predictive tool for use by natural resource managers using Big Lake specific data. Tool users will enter total mercury (THg) concentrations (in micrograms per gram dry weight [µg/g dw]) in prey fish, date sampled, and the specific lake's attributes (lake area, perimeter, and elevation), and our tool will estimate the predicted THg concentrations in grebe blood, grebe eggs, and sport fish. Our tool then uses these estimated values to assess the relative risk to wildlife and sport fish by comparing the estimated THg concentrations to published toxicity benchmarks. In this example, THg concentrations in prey fish at Big Lake are very low, and thus the tool estimates that wildlife and sport fish are at low risk of potential mercury impairment.

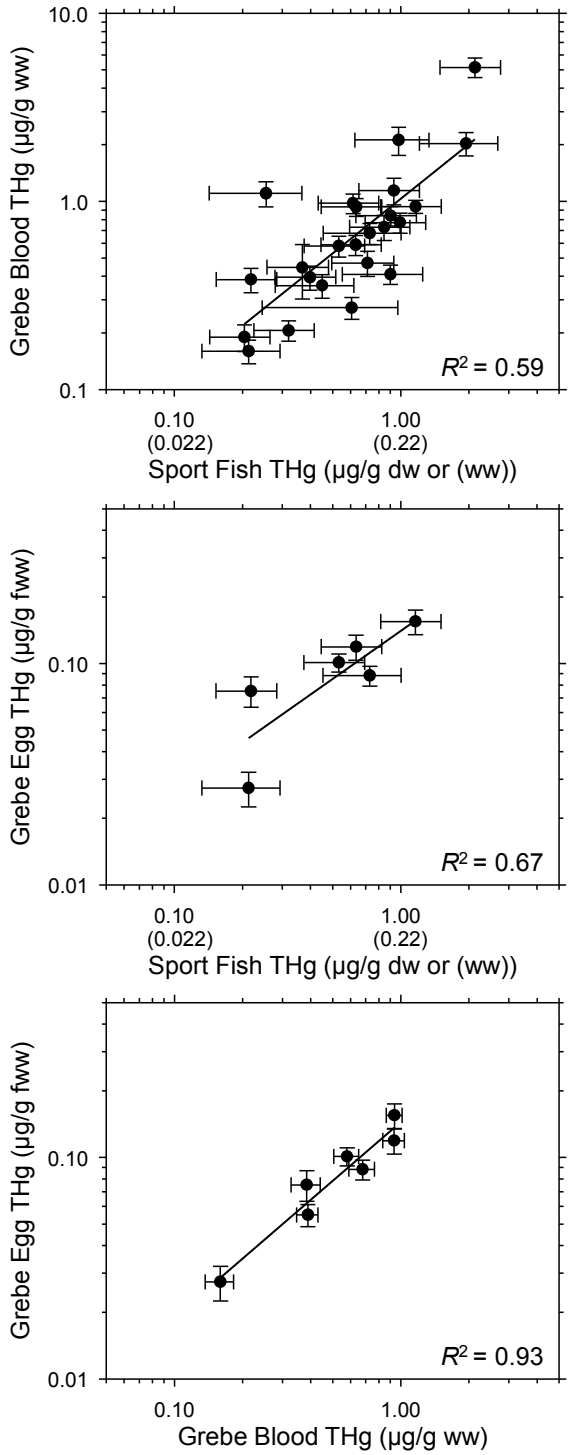

Figure 13. Graphs showing total mercury (THg) concentrations in grebe blood versus THg concentrations (in micrograms per gram dry weight [µg/g dw] [top row X axis] or µg/g wet weight [ww] [bottom row X axis]) in sport fish (top panel), grebe eggs versus sport fish (middle panel), and grebe eggs versus grebe blood (bottom panel) at up to 25 lakes in California, 2012–13. Values are least squares means ± standard errors from separate models accounting for (1) grebe blood model: species and sex with lake as a random effect; (2) grebe egg model: species and egg type with lake as a random effect; and (3) sport fish model: species, total length, and species × length interaction with lake as a random effect.

Table 1. Sample size and relative risk of blood mercury to female and male western and Clark's grebes by lake in California, 2012–13.

[µg/g ww, microgram per gram wet weight]

Lake	Year	Dates sampled	Western grebe		Clark's grebe		Total number sampled	Moderate risk (≥1.0 µg/g ww)	High risk (≥3.0 µg/g ww)
			Female	Male	Female	Male			
Antelope Lake	2013	8/23/2013–8/25/2013	6	5	0	0	11	0%	0%
Big Lake	2013	7/18/2013–7/19/2013	4	8	0	0	12	0%	0%
Black Butte Lake	2012	10/3/2012–10/6/2012	7	4	5	1	17	0%	0%
Bridgeport Reservoir	2012	6/6/2012–6/9/2012	2	5	2	1	10	60%	10%
Clear Lake	2012	5/14/2012–5/17/2012	17	10	9	2	38	32%	8%
Crowley Lake	2012	6/8/2012–6/9/2012	6	6	0	0	12	100%	8%
Eagle Lake	2012	9/4/2012–9/6/2012	7	6	0	1	14	7%	0%
East Park Reservoir	2012	6/28/2012–6/30/2012	4	5	6	5	20	50%	0%
Lake Almanor	2012	7/31/2012–8/3/2012	4	11	0	0	15	13%	0%
Lake Berryessa	2012	5/22/2012–5/25/2012	0	6	6	5	17	100%	88%
Lake Cachuma	2012	6/3/2012–6/5/2012	6	7	1	2	16	13%	0%
Lake Casitas	2013	6/3/2013–6/4/2013	3	8	4	2	17	41%	0%
Lake Davis	2012	7/16/2012–7/19/2012	7	5	0	0	12	0%	0%
Lake Hennessey	2013	8/15/2013–8/17/2013	2	3	1	3	9	78%	0%
Lake Hodges	2013	5/3/2013–5/5/2013	2	7	3	3	15	0%	0%
Lake Mendocino	2013	7/29/2013–8/2/2013	1	3	1	5	10	50%	0%
Lake San Antonio	2012	5/31/2012–6/2/2012	3	10	3	1	17	47%	6%
Lake Success	2013	6/8/2013–6/9/2013	8	2	2	4	16	0%	0%
Lower Otay Reservoir	2013	4/30/2013–5/2/2013	5	3	1	2	11	0%	0%
O'Neill Forebay	2012	9/20/2012–9/21/2012	1	0	0	1	2	0%	0%
Perris Reservoir	2013	5/8/2013–5/9/2013	4	4	1	0	9	0%	0%
Stony Gorge Reservoir	2013	8/13/2013–8/27/2013	0	3	3	4	10	0%	0%
Thermalito Afterbay	2012	7/19/2012–7/21/2012	7	5	1	2	15	0%	0%
Topaz Lake	2013	6/26/2013–6/28/2013	2	3	3	0	8	100%	13%
Tule Lake	2013	7/15/2013–7/16/2013	9	7	2	3	21	5%	0%
All Lakes	**2012–2013**	**2012–2013**	**117**	**136**	**54**	**47**	**354**	**28%**	**6%**

Table 2. Sample size of randomly sampled and abandoned eggs for western and Clark's grebes by lake in California, 2012–13.

Lake	Year	Date(s) sampled	Western grebe		Clark's grebe		Grebe species unknown		Total
			Random	Abandoned	Random	Abandoned	Random	Abandoned	
Antelope Lake	2013	8/1/2013-8/24/2013	5	1	0	0	0	1	7
Big Lake	2013	7/19/2013	1	0	0	0	1	4	6
Clear Lake	2012	7/24/2012	15	0	0	0	0	0	15
East Park Reservoir	2012	7/24/2012	6	0	5	2	2	0	15
Lake Almanor	2012	7/31/2012-8/29/2012	13	0	2	0	0	5	20
Thermalito Afterbay	2012	8/6/2012-9/13/2012	12	0	3	0	0	8	23
Tule Lake	2013	7/17/2013	10	0	3	0	0	2	15
All Lakes	**2012-2013**	**2012-2013**	**62**	**1**	**13**	**2**	**3**	**20**	**101**

Table 3. Common names, scientific names, sample sizes, and proportion of prey fish species sampled in California, 2012–13.

Common name	Scientific name	Sample size	Percentage of total prey fish sampled
Bluegill	*Lepomis macrochirus*	150	30
Mississippi silverside	*Menidia audens*	110	22
Threadfin shad	*Dorosoma petenense*	70	14
Golden shiner	*Notemigonus crysoleucas*	40	8
Sacramento perch	*Archoplites interruptus*	27	5
Sacramento sucker	*Catostomus occidentalis*	20	4
Tui chub	*Gila bicolor*	18	4
Blue chub	*Gila coerulea*	10	2
Hitch	*Lavinia exilicauda*	10	2
Largemouth bass	*Micropterus salmoides*	10	2
Pumpkinseed sunfish	*Lepomis gibbosus*	10	2
Redear sunfish	*Lepomis microlophus*	10	2
Smallmouth bass	*Micropterus dolomieu*	10	2
Tahoe sucker	*Catostomus tahoensis*	10	2

Table 4. Species and number of prey fish sampled by lake in California, 2012–13.

Lake	Year	Date(s) sampled	Silverside	Threadfin shad	Golden shiner	Tui chub	Blue chub	Hitch	Bluegill	Sacramento perch
Antelope Lake	2013	9/4/2013			10					
Big Lake	2013	7/23/2013						10	10	
Black Butte Lake	2012	10/10/2012	10	10						
Bridgeport Reservoir	2012	6/26/2012,8/28/2012			10					10
Clear Lake	2012	5/30/2012	10						10	
Crowley Lake	2012	8/27/2012			10					10
Eagle Lake	2012	9/4/2012				10				
East Park Reservoir	2012	7/2/2012	10						10	
Lake Almanor	2012	8/1/2012	10							
Lake Berryessa	2012	5/31/2012	10						10	
Lake Cachuma	2012	6/20/2012		10					10	
Lake Casitas	2013	6/10/2013		10					10	
Lake Davis	2012	7/24/2012			10					
Lake Hennessey	2013	8/29/2013	10	5					10	
Lake Hodges	2013	5/15/2013		10					10	
Lake Mendocino	2013	7/30/2013	10	5					10	
Lake San Antonio	2012	6/7/2012	10						10	
Lake Success	2013	6/11/2013		10					10	
Lower Otay Reservoir	2013	5/14/2013							10	
O'Neill Forebay	2012	9/20/2012	10							
Perris Reservoir	2013	5/13/2013	10						10	
Stony Gorge Reservoir	2013	8/18/2013		10					10	
Thermalito Afterbay	2012	7/2/2012	10						10	
Topaz Lake	2013	7/8/2013								
Tule Lake	2013	7/31/2013				8	10			7
All Lakes	**2012-2013**	**2012-2013**	**110**	**70**	**40**	**18**	**10**	**10**	**150**	**27**

—Continued on next page

Table 4. Species and number of prey fish sampled by lake in California, 2012–13.—Continued

Lake	Year	Date(s) sampled	Pumpkinseed	Redear sunfish	Largemouth bass	Smallmouth bass	Sacramento sucker	Tahoe sucker	All species
Antelope Lake	2013	9/4/2013		10					20
Big Lake	2013	7/23/2013							20
Black Butte Lake	2012	10/10/2012							20
Bridgeport Reservoir	2012	6/26/2012,8/28/2012							20
Clear Lake	2012	5/30/2012							20
Crowley Lake	2012	8/27/2012							20
Eagle Lake	2012	9/4/2012						10	20
East Park Reservoir	2012	7/2/2012							20
Lake Almanor	2012	8/1/2012					10		20
Lake Berryessa	2012	5/31/2012							20
Lake Cachuma	2012	6/20/2012							20
Lake Casitas	2013	6/10/2013							20
Lake Davis	2012	7/24/2012	10						20
Lake Hennessey	2013	8/29/2013							25
Lake Hodges	2013	5/15/2013							20
Lake Mendocino	2013	7/30/2013							25
Lake San Antonio	2012	6/7/2012							20
Lake Success	2013	6/11/2013							20
Lower Otay Reservoir	2013	5/14/2013			10				20
O'Neill Forebay	2012	9/20/2012							10
Perris Reservoir	2013	5/13/2013							20
Stony Gorge Reservoir	2013	8/18/2013							20
Thermalito Afterbay	2012	7/2/2012							20
Topaz Lake	2013	7/8/2013				10	10		20
Tule Lake	2013	7/31/2013							25
All Lakes	**2012-2013**	**2012-2013**	**10**	**10**	**10**	**10**	**20**	**10**	**505**

Table 5. Common names, scientific names, sample sizes, and proportion of sport fish species sampled in California, 2012–13.

Common name	Scientific name	Sample size	Percentage of total sport fish sampled
Largemouth bass	*Micropterus salmoides*	156	68
Rainbow trout	*Oncorhynchus mykiss*	40	17
Brown trout	*Salmo trutta*	12	5
Smallmouth bass	*Micropterus dolomieu*	12	5
Eagle Lake rainbow trout	*Oncorhynchus mykiss aquilarum*	10	4

Table 6. Species and number of sport fish sampled by lake in California, 2012–13.

Lake	Year	Date(s) sampled	Largemouth bass	Smallmouth bass	Rainbow trout	Brown trout	Eagle Lake rainbow trout	All species
Antelope Lake	2013	9/4/2013	10					10
Big Lake	2013	7/23/2013			10			10
Black Butte Lake	2012	10/10/2012		10				10
Bridgeport Reservoir	2012	8/28/2012				10		10
Clear Lake	2012	5/30/2012	10					10
Crowley Lake	2012	8/27/2012			10			10
Eagle Lake	2012	9/7/2012-9/15/2012					10	10
East Park Reservoir	2012	7/2/2012	10					10
Lake Almanor	2012	8/1/2012			10			10
Lake Berryessa	2012	5/31/2012	10					10
Lake Cachuma	2012	6/20/2012	10					10
Lake Casitas	2013	6/10/2013	10					10
Lake Davis	2012	7/24/2012			10			10
Lake Hennessey	2013	8/29/2013	10					10
Lake Hodges	2013	5/15/2013	10					10
Lake Mendocino	2013	7/30/2013	10					10
Lake San Antonio	2012	6/7/2012	10					10
Lake Success	2013	6/11/2013	10					10
Lower Otay Reservoir	2013	5/14/2013	10					10
O'Neill Forebay	2012	9/20/2012	8					8
Perris Reservoir	2013	5/13/2013	10					10
Stony Gorge Reservoir	2013	8/18/2013	8					8
Thermalito Afterbay	2012	7/2/2012	10					10
Topaz Lake	2013	7/8/2013		2		2		4
All Lakes	**2012-2013**	**2012-2013**	**156**	**12**	**40**	**12**	**10**	**230**

Table 7. Location, size, perimeter, elevation, and shape index for each of the 25 lakes sampled in California, 2012–13.

[ha, hectare, km, kilometer, m, meter]

Lake	County	Easting	Northing	Surface area (ha)	Perimeter (km)	Elevation (m)	Lake shape index
Antelope Lake	Plumas	704810	4450906	383.89	31.74	1,525.0	4.050
Big Lake	Shasta	632011	4552145	703.26	36.67	1,007.4	3.457
Black Butte Lake	Tehama&Glenn	553604	4403857	1,742.82	81.11	145.0	4.858
Bridgeport Reservoir	Mono	829457	4244854	1,036.69	30.47	1,967.5	2.366
Clear Lake	Lake	518373	4320269	16,005.75	172.93	405.0	3.417
Crowley Lake	Mono	876066	4171627	1,680.02	39.79	2,062.0	2.427
Eagle Lake	Lassen	690906	4501329	9,866.18	102.48	1,558.0	2.579
East Park Reservoir	Colusa	542605	4354871	672.77	52.08	366.0	5.020
Lake Almanor	Plumas	657158	4457388	10,273.82	100.63	1,371.6	2.482
Lake Berryessa	Napa	566309	4271951	7,553.16	255.33	133.8	7.345
Lake Cachuma	Santa Barbara	781156	3830425	1,283.80	67.29	229.8	4.695
Lake Casitas	Ventura	836215	3811714	982.47	48.94	158.0	3.904
Lake Davis	Plumas	712552	4420841	1,647.39	67.69	1,761.0	4.169
Lake Hennessey	Napa	554800	4260477	307.77	16.11	97.0	2.295
Lake Hodges	San Diego	1050421	3673333	173.34	17.09	84.0	3.246
Lake Mendocino	Mendocino	485498	4340858	686.73	26.02	226.0	2.482
Lake San Antonio	Monterey	682898	3968691	2,176.78	84.58	238.0	4.532
Lake Success	Tulare	868056	4000868	1,002.65	43.53	200.0	3.437
Lower Otay Reservoir	San Diego	1070821	3626336	445.20	21.87	151.0	2.592
O'Neill Forebay	Merced	673520	4106015	908.72	23.60	67.1	1.957
Perris Reservoir	Riverside	1039162	3761590	782.83	16.81	478.0	1.502
Stony Gorge Reservoir	Glenn	540906	4378248	559.06	33.18	257.0	3.508
Thermalito Afterbay	Butte	614993	4370806	1,632.91	66.90	42.4	4.139
Topaz Lake	Douglas	802027	4286599	890.21	20.14	1,527.0	1.687
Tule Lake	Siskiyou	621971	4639908	3,070.44	79.25	1,229.3	3.576

Table 8. Ranking of candidate model set describing western grebe and Clark's grebe blood total mercury (THg) concentrations (*n*=353 grebes) at 25 lakes, California, 2012–13.

[Akaike's Information Criterion (AIC*c*) was used to rank models. Lake was a random effect in all models. We present only the top models that were within ΔAIC*c* ≤ 2, the null model (shaded), and each model that was similar to the top model except one of the variables in the top model was removed (only shaded if ΔAIC*c* > 2). **Model:** +, an additive effect. ***k*:** Number of parameters in the model, including the intercept. ***-2logL*:** –2log-likelihood of the model. Δ***AICc*:** Difference in the value between AIC*c* of the current model and the value for the most parsimonious model. ***w*$_i$:** Akaike weight, the likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0). **Evidence ratio:** Weight of evidence that the top model is better than the selected model, given the candidate model set]

Model	*k*	-2logL	AIC*c*	ΔAIC*c*	*w*$_i$	Evidence ratio	Cumulative weight
THg Prey Fish + Species + Sex + Molt + Lake Perimeter	7	545.25	559.58	0.00	0.02	1.00	0.02
THg Prey Fish + Species + Sex + Lake Perimeter	6	547.40	559.64	0.06	0.02	1.03	0.04
THg Prey Fish + Species + Sex + Molt + Lake Perimeter + Molt²	8	543.61	560.03	0.45	0.02	1.25	0.06
THg Prey Fish + Species + Sex + Date + Lake Perimeter + Date²	8	543.77	560.19	0.62	0.02	1.36	0.08
THg Prey Fish + Species + Sex + Molt + Lake Perimeter + Lake Shape	8	544.26	560.67	1.10	0.01	1.73	0.09
THg Prey Fish + Species + Sex + Date + Molt + Lake Perimeter + Date²	9	542.17	560.69	1.12	0.01	1.75	0.11
THg Prey Fish + Species + Sex + Lake Perimeter + Lake Shape	7	546.49	560.81	1.24	0.01	1.85	0.12
THg Prey Fish + Species + Sex + Molt + Lake Perimeter + Lake Shape + Molt²	9	542.55	561.08	1.50	0.01	2.12	0.13
THg Prey Fish + Species + Sex + Date + Lake Perimeter + Lake Shape + Date²	9	542.68	561.20	1.62	0.01	2.25	0.14
THg Prey Fish + Species + Sex + Date + Lake Perimeter + Lake Area + Lake Shape + Date²	10	540.74	561.39	1.81	0.01	2.47	0.15
THg Prey Fish + Species + Sex + Lake Perimeter + Lake Area + Lake Shape	8	544.97	561.39	1.81	0.01	2.47	0.16
THg Prey Fish + Species + Sex + Molt + Lake Perimeter + Lake Area + Lake Shape	9	542.88	561.41	1.83	0.01	2.50	0.17
THg Prey Fish + Species + Sex + Date + Lake Perimeter	7	547.09	561.42	1.84	0.01	2.51	0.17
THg Prey Fish + Species + Sex + Date + Molt + Lake Perimeter + Date² + Molt²	10	540.80	561.45	1.87	0.01	2.55	0.18
THg Prey Fish + Species + Sex + Body Condition + Lake Perimeter	7	547.15	561.47	1.90	0.01	2.58	0.19
THg Prey Fish + Species + Sex + Molt + Lake Area	7	547.23	561.55	1.97	0.01	2.68	0.20
THg Prey Fish + Species + Sex + Date + Molt + Lake Perimeter + Lake Shape + Date²	10	540.95	561.59	2.01	0.01	2.74	0.21
THg Prey Fish + Species + Sex + Molt	6	550.76	563.00	3.42	0.00	5.54	0.48
THg Prey Fish + Sex + Molt + Lake Perimeter	6	558.86	571.10	11.53	0.00	318.27	0.99
THg Prey Fish + Species + Molt + Lake Perimeter	6	559.45	571.70	12.12	0.00	428.11	0.99
Species + Sex + Molt + Lake Perimeter	6	576.77	589.02	29.44	0.00	2.47×10^{6}	1.00
Null (Lake as random effect)	2	608.62	612.66	53.08	0.00	3.36×10^{11}	1.00

Table 9. Ranking of candidate model set describing western grebe and Clark's grebe egg total mercury (THg) concentrations (*n*=101 eggs) at seven lakes, California, 2012–13.

[Akaike's Information Criterion (AIC*c*) was used to rank models. Lake was a random effect in all models. We present only the top models that were within ΔAIC*c* less than or equal to 2, the null model (shaded), and each model that was similar to the top model except one of the variables in the top model was removed (only shaded if ΔAIC*c* greater than 2). **Model:** +, an additive effect. ***k*:** Number of parameters in the model, including the intercept. **-2logL:** –2log-likelihood of the model. **ΔAIC*c*:** Difference in the value between AIC*c* of the current model and the value for the most parsimonious model. w_i**:** Akaike weight, likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0). **Evidence ratio:** Weight of evidence that the top model is better than the selected model, given the candidate model set]

Model	*k*	-2logL	AIC*c*	ΔAIC*c*	w_i	Evidence ratio	Cumulative weight
THg Prey Fish + Date + Lake Perimeter	5	110.29	120.92	0.00	0.04	1.00	0.04
THg Prey Fish	3	114.71	120.95	0.03	0.04	1.02	0.08
THg Prey Fish + Lake Perimeter	4	112.95	121.37	0.45	0.03	1.25	0.11
THg Prey Fish + Date	4	113.23	121.65	0.73	0.03	1.44	0.14
THg Prey Fish + Lake Area	4	113.35	121.76	0.84	0.03	1.52	0.17
THg Prey Fish + Date + Lake Area	5	111.25	121.88	0.96	0.02	1.62	0.19
THg Prey Fish + Lake Shape	4	113.51	121.93	1.01	0.02	1.65	0.21
THg Prey Fish + Egg Type	4	113.57	121.99	1.06	0.02	1.70	0.24
THg Prey Fish + Egg Type + Lake Perimeter	5	111.75	122.38	1.46	0.02	2.07	0.26
Date + Lake Area + Lake Shape	5	111.96	122.59	1.67	0.02	2.30	0.28
THg Prey Fish + Date + Lake Perimeter + Lake Area	6	109.84	122.73	1.81	0.02	2.47	0.29
THg Prey Fish + Date + Lake Shape	5	112.17	122.80	1.88	0.02	2.56	0.31
THg Prey Fish + Date + Lake Perimeter + Date²	6	109.94	122.83	1.91	0.02	2.60	0.32
THg Prey Fish + Egg Type + Lake Area	5	112.20	122.83	1.91	0.02	2.60	0.34
THg Prey Fish + Date + Date²	5	112.22	122.86	1.93	0.02	2.63	0.35
THg Prey Fish + Date + Lake Perimeter + Lake Shape	6	109.96	122.86	1.94	0.02	2.63	0.37
THg Prey Fish + Egg Type + Date + Lake Perimeter	6	110.21	123.11	2.19	0.01	2.98	0.38
Date + Lake Perimeter	4	119.88	128.30	7.37	0.00	39.92	0.94
Null (Lake as random effect)	2	125.43	129.55	8.63	0.00	74.72	0.97

Table 10. Ranking of candidate model set describing sport fish total mercury (THg) concentrations (*n*=230 fish) at 24 lakes in California, 2012–13.

[Akaike's Information Criterion (AIC*c*) was used to rank models. Lake was a random effect in all models. We present only the top models that were within ΔAIC*c* less than or equal to 2, the null model (shaded), and each model that was similar to the top model except one of the variables in the top model was removed (only shaded if ΔAIC*c* greater than 2). **Model**: + an additive effect; ×, an interaction. ***k*:** Number of parameters in the model, including the intercept. **-2logL:** Indicates the –2log-likelihood of the model. Δ**AIC*c*:** Difference in the value between AIC*c* of the current model and the value for the most parsimonious model. w_i**:** Akaike weight**,** represents the likelihood of the model given the data, relative to other models in the candidate set (model weights sum to 1.0). **Evidence ratio:** Represents the weight of evidence that the top model is better than the selected model, given the candidate model set]

Model	*k*	-2logL	AIC*c*	ΔAIC*c*	w_i	Evidence ratio	Cumulative weight
THg Prey Fish + Species + Length + Lake Elevation + Lake Area + Species×Length	14	248.52	278.48	0.00	0.14	1.00	0.14
THg Prey Fish + Species + Length + Lake Elevation + Species×Length	13	251.15	278.84	0.36	0.12	1.20	0.26
THg Prey Fish + Species + Length + Lake Elevation + Lake Perimeter + Lake Area + Species×Length	15	247.24	279.49	1.01	0.09	1.66	0.35
THg Prey Fish + Species + Length + Lake Elevation + Lake Area + Lake Shape + Species×Length	15	247.44	279.68	1.21	0.08	1.83	0.42
THg Prey Fish + Species + Length + Lake Elevation + Lake Shape + Species×Length	14	250.37	280.33	1.85	0.06	2.52	**0.48**
THg Prey Fish + Species + Length + Date + Lake Elevation + Lake Area + Species×Length	15	248.13	280.37	1.90	0.06	2.58	0.54
THg Prey Fish + Species + Length + Lake Elevation + Lake Perimeter + Lake Shape + Species×Length	15	248.54	280.79	2.31	0.04	3.17	0.58
THg Prey Fish + Length + Lake Elevation + Lake Area	6	271.80	284.18	5.70	0.01	17.28	0.88
THg Prey Fish + Species + Length + Lake Elevation + Lake Area	10	265.08	286.09	7.61	0.00	44.93	0.94
THg Prey Fish + Species + Length + Lake Area + Species×Length	13	258.58	286.27	7.79	0.00	49.13	0.95
Species + Length + Lake Elevation + Lake Area + Species×Length	13	274.89	302.58	24.10	0.00	1.71×10^{5}	1.00
THg Prey Fish + Species + Lake Elevation + Lake Area	9	391.46	410.28	131.80	0.00	4.18×10^{28}	1.00
Null (Lake as random effect)	2	455.61	459.67	181.19	0.00	2.21×10^{39}	1.00

Table 11. Appropriate range of data for each variable used in the predictive tool for use by natural resource managers.

[Means, minima, and maxima correspond to the distribution of data used to generate the predictive model, and the tool may have limited validity outside of these general data ranges. ha, hectare, km, kilometer, m, meter, mm, millimeter]

Variables	Mean	Minimum	Maximum
Date sampled: Grebes			
Days from January 1	181	120	279
Calendar date	June 30	April 30	October 6
Date sampled: Fish			
Days from January 1	204	133	283
Calendar date	July 23	May 13	October 10
Lake variables			
Area (ha)	2,658.8	173.3	16,005.8
Perimeter (km)	61.5	16.1	255.3
Elevation (m)	691.5	42.4	2,062.0
Shape index	3.429	1.502	7.345
Sport fish			
Total length (mm)	397	178	726
Prey fish			
Standard length (mm)	58	18	123

Table 12. Toxicity benchmarks and associated citations used in the predictive tool for natural resource managers.

[Values represent total mercury concentrations in micrograms per gram wet weight [µg/g ww] for bird blood, µg/g fresh wet weight for bird eggs, and µg/g ww for sport fish]

Tissue	Low risk	Medium risk	High risk	Extra high risk	Citations
Bird blood	<1.0	1.0-2.0	2.0-3.0	>4.0	Evers and others, 2004
Bird eggs	<0.25	0.25-0.50	0.50-0.65	>0.65	Heinz and others, 2009; Ackerman and others, 2014
Sport fish-risk to fish	<0.20	0.20-0.30	0.30-0.40	>0.40	Beckvar and others, 2005; Sandheinrich and others, 2011

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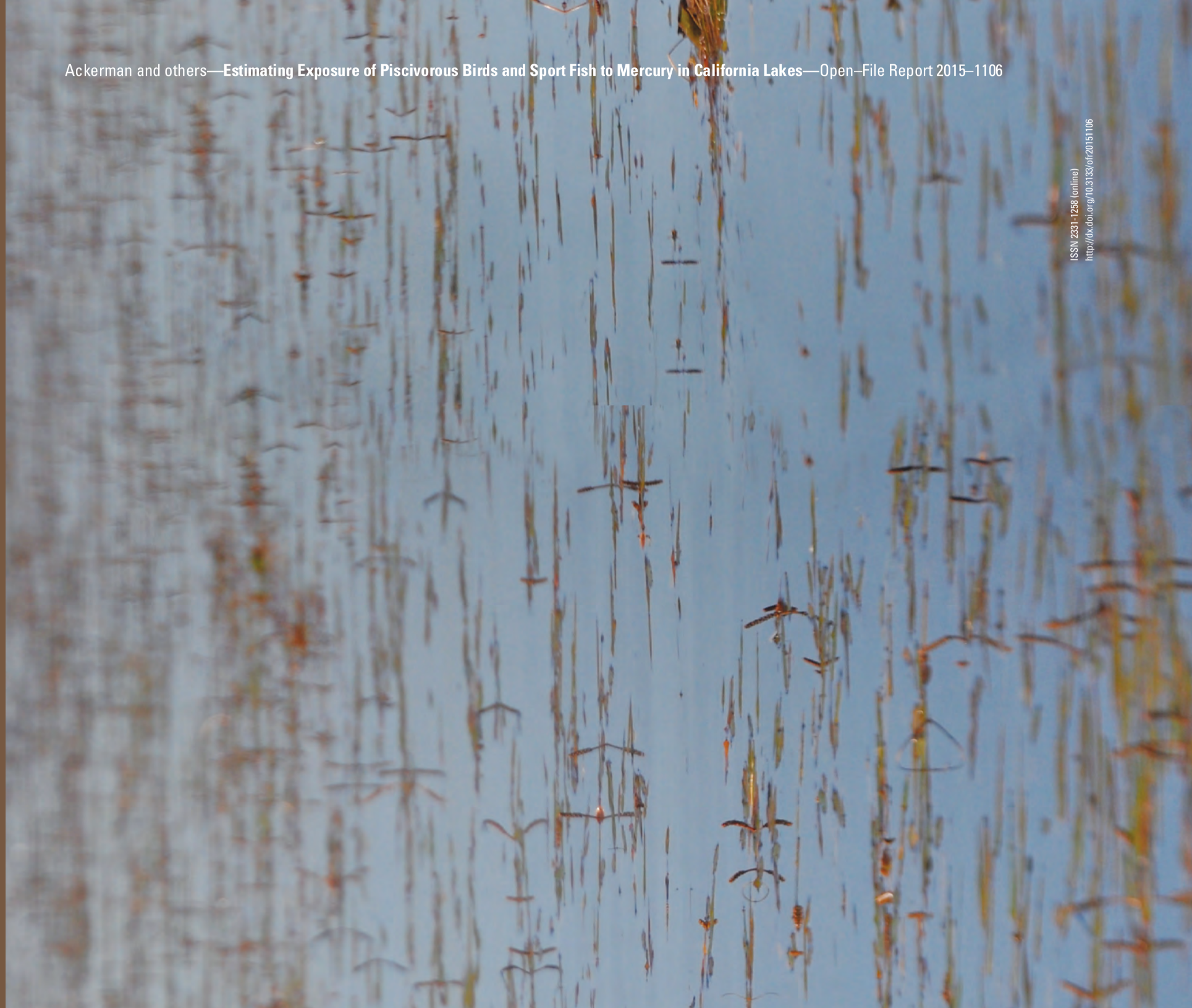

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