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USING FEATHERS TO DETERMINE MERCURY CONTAMINATION IN PEREGRINE FALCONS AND THEIR PREY

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ABSTRACT.—We document concentrations of total mercury (Hg) in feathers of Peregrine Falcons (*Falco peregrinus*) from 12 territories in Lake Mead National Recreation Area (LMNRA) and five territories in an adjacent southern Nevada (SNV) study area during 2012 and 2013. We also report total Hg concentrations in feathers of 94 species (337 individuals) collected as prey remains from peregrine nesting areas from 2008–2013. All peregrine feathers contained total Hg (range = 0.12–42.54 μg/g), and adults had a significantly higher mean total Hg concentration (12.19 μg/g) than hatch-year peregrines (3.76 μg/g). Mean total Hg concentrations in peregrines in LMNRA (adult = 17.24 μg/g, brood = 5.82 μg/g) were significantly greater than in SNV (adult = 2.7 μg/g, brood = 0.67 μg/g) for both age classes. Among peregrine territories, mean total Hg in prey was positively correlated with the proportion of aquatic birds taken as prey (biomass), and negatively correlated with distance of eyries to water. Among avian prey, the mean total Hg concentration in aquatic birds (5.07 μg/g) was significantly higher than terrestrial birds (0.76 μg/g), and aquatic invertivores were the most contaminated foraging guild (mean = 6.17 μg/g). Eared Grebes (*Podiceps nigricollis*) were the prey species with the highest mean total Hg concentration (12.27 μg/g). Peregrine Falcons, with their broad distribution, catholic diet, and use of diverse habitat types, may be an ideal indicator species of environmental Hg contamination. Contaminant studies incorporating prey analysis are useful to assess exposure pathways and evaluate potential ecological effects across a broad array of habitat types.

KEY WORDS: *Peregrine Falcon*; Falco peregrinus; *Arizona*; *breeding*; *contaminants*; *mercury*; *Nevada*; *prey*.

USO DE PLUMAS PARA DETERMINAR CONTAMINACIÓN POR MERCURIO EN *FALCO PEREGRINUS* Y SUS PRESAS

RESUMEN.—Documentamos las concentraciones totales de mercurio (Hg) en plumas de individuos de *Falco peregrinus* procedentes de 12 territorios ubicados en el Área Recreativa Nacional Lago Mead (ARNLM) y de cinco territorios de un área de estudio colindante ubicada al sur de Nevada (SNV) durante 2012 y 2013. También reportamos concentraciones totales de Hg en plumas de 94 especies (337 individuos) colectadas como restos de presas de *F. peregrinus* en sus áreas de nidificación, durante el periodo 2008–13. Todas las plumas de *F. peregrinus* contenían Hg (rango = 0.12–42.54 μg/g). La concentración total promedio de Hg en adultos fue significativamente mayor (12.19 μg/g) que la de individuos juveniles del año (3.76 μg/g). La concentración total promedio de Hg en individuos de *F. peregrinus* en ARNLM (adulto = 17.24 μg/g, pollo = 5.82 μg/g) fue significativamente mayor que en SNV (adulto = 2.7 μg/g, pollo = 0.67 μg/g) para ambas clases de edad. Entre los territorios de *F. peregrinus*, la concentración total promedio de Hg estuvo positivamente correlacionada con la proporción de aves acuáticas cazadas como presa (biomasa) y negativamente correlacionada con la distancia de los nidos al agua. Entre las presas, la concentración total promedio de Hg en aves acuáticas (5.07 μg/g) fue significativamente mayor que en aves terrestres (0.76 μg/g) y las especies que se alimentan de invertebrados acuáticos fueron el gremio de alimentación más contaminado (media = 6.17 μg/g). *Podiceps nigricollis* fue la especie presa con la concentración total promedio de Hg más elevada (12.27 μg/g). *F. peregrinus*, con su amplia distribución, amplio espectro trófico y uso de diversos tipos de hábitat, puede ser una especie indicadora ideal de la contaminación ambiental por Hg.

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Los estudios de contaminantes que incorporan el análisis de presas son útiles para determinar las vías de exposición y para evaluar los efectos ecológicos potenciales a través de una amplia variedad de tipos de hábitat.

[Traducción del equipo editorial]

Mercury (Hg) is a naturally occurring element with a global distribution (Tchounwou et al. 2003). However, in recent decades it has been documented at concentrations over three times greater than in preindustrial times, the bulk attributable to anthropogenic emissions (Driscoll et al. 2007). Mercury can be converted in nature into its more toxic organic form, methylmercury (MeHg), which bioaccumulates readily in aquatic systems along an increasing trophic level gradient (Evers et al. 2005, Driscoll et al. 2007). Predatory birds can be particularly vulnerable to MeHg toxicity through bioaccumulation because many are relatively long-lived and assume an upper trophic level position. Exposure to Hg has been correlated with increased mortality or reduced reproductive success in dosed experimental studies of raptors and wading birds (Fimreite and Karstad 1971, Spalding et al. 2000, Albers et al. 2007) and in field studies of passerine and aquatic bird species (Brasso and Cristol 2008, Evers et al. 2008, Jackson et al. 2011).

Feathers are an ideal medium to test for Hg contamination because their collection is relatively noninvasive, can be replicated on the same individual over time, and the results can be correlated with other tissues such as muscle, liver, or eggs whose sampling is often lethal to focal species. Mercury binds to the sulfide bonds of keratin during feather growth (Appelquist et al. 1984). These bonds are stable over time (Berg et al. 1966), and MeHg comprises nearly all of the total Hg content within feathers (Thompson and Furness 1989, Bond and Diamond 2009). Mercury concentrations in feathers reflect Hg levels circulating in blood at the time of feather growth (Dauwe et al. 2003), and Hg body burdens have been correlated with dietary consumption in dose-dependent experimental studies (Fimreite and Karstad 1971, Lewis and Furness 1991, Spalding et al. 2000). Mercury stored in body tissues (e.g., muscle and internal organs) since the previous molt can be remobilized and effectively removed from the bird during feather growth (Furness et al. 1986). Mercury concentrations found in feathers of nestlings reflect dietary uptake since hatching (Becker et al. 1994), while Hg concentrations in feathers of birds that have undergone at least one molt reflect relative uptake since the previous molt in addition to previously stored Hg that may have been remobilized from body tissues (Furness et al. 1986, Honda et al. 1986). Because most birds undergo feather growth during predictable molt cycles, it is possible to compare Hg concentrations found in standardized feathers in individuals over time and also among individuals, provided that the timing of feather replacement is known within the molt cycle (Furness et al. 1986, Braune 1987, Thompson et al. 1998, Dauwe et al. 2003).

Peregrine Falcons (*Falco peregrinus*) are upper trophic level predators with a global distribution (White et al. 2013). Historically, in western North America, their breeding distribution was thought to be limited primarily to cliffs or other vertical structures near aquatic systems (Cade 1982), although recent research has documented them breeding across a wide range of habitat types, including in the deserts of the southwestern U.S. far from water (J. Enderson, C. Klinger pers. comm., this study). Peregrines are opportunist predators that target a wide variety of avian species often based on availability (White et al. 2013), and at least 102 avian species or species groups have been documented as prey in our study area (Barnes 2011). This broad dietary breadth renders peregrines susceptible to bioaccumulation of MeHg, which allows their potential consideration as an indicator species to assess environmental contamination. In light of their vulnerability to contamination, the U.S. Fish and Wildlife Service (USFWS) has recommended testing them for Hg through 2015, the end of the postdelisting monitoring period following their removal from the federal list of threatened and endangered species (USFWS 2003).

Toxic effects of Hg exposure vary widely among avian species (Wolfe et al. 1998, Scheuhammer et al. 2007), and the threshold concentrations for adverse effects on peregrine behavior, survival, or reproductive success are unclear. In a historical assessment of birds in Sweden, Berg et al. (1966) documented a dramatic increase of Hg in peregrines associated with widespread use of alkyl Hg as a seed dressing. Lindberg and Odsjö (1983) found a positive correlation between Hg concentrations in feathers of adult peregrines and their reliance on aquatic birds as prey in a rapidly declining population in Fenno-

scandia, although they could not separate the effects of Hg from those of organochlorine pesticides. Although focused on organochlorines, Peakall et al. (1990) found Hg concentrations in eggs were below theorized threshold levels (i.e., 1 μg/g) associated with mortality or reproductive failure during a period when peregrine populations were increasing across Canada. Researchers assessing recovering populations of peregrines in the eastern U.S. did not find a correlation between reproductive success and Hg concentration in eggs for addled eggs collected from 1990–1993 (Augspurger and Boynton 1998) and 1993–1999 (Clark et al. 2009). However, Mora et al. (2002) speculated that Hg levels, up to 2.5 μg/g in carcasses of potential prey, may affect reproduction in a small breeding population of peregrines exhibiting low reproductive output in Texas.

Elevated Hg levels have been detected in avian communities in several aquatic systems in Nevada (Hill et al. 2008) and surrounding states (Cahill et al. 1998, Naftz et al. 2008). Lakes Mead and Mohave, southern Nevada, supply water for approximately 25 million people (Holdren and Turner 2010), and high Hg levels in these lakes may have negative human health implications. Additionally, these lakes have been identified as important stopovers for tens of thousands of migrating and wintering aquatic birds in the arid southwestern U.S. (Barnes and Jaeger 2012), and elevated levels of Hg have been documented in several species of migratory waterfowl in nearby wildlife refuges (Gerstenberger 2004). We assess total Hg concentrations in peregrines breeding in Lake Mead National Recreation Area (LMNRA) surrounding the two lakes, and in the open desert of southern Nevada (SNV). Our primary objective was to determine baseline total Hg concentrations in feathers of year-round resident peregrines and their young during the 2012 and 2013 breeding seasons. In an effort to assess variation in total Hg contaminant levels among feathers and feather types, we also collected abundant feather samples from deceased peregrine offspring encountered fortuitously in the vicinity of eyries. We also assessed total Hg concentrations in feathers collected as prey remains at peregrine territories from 2008–2013. This was an effort to identify pathways of Hg exposure to peregrines through their prey, and to determine broad-scale Hg contaminant levels in the avian community within our study area. Our intent, in part, was to evaluate the suitability of using feather analysis of peregrines and their prey as an ecological monitoring tool to evaluate ecosystem health.

METHODS

Study Area. Our study areas were within LMNRA (36°0.6′N, 114°47.8′W) and an area of SNV encompassing nearly 8000 km² of arid lands bordering LMNRA and surrounding the metropolitan area of Las Vegas, Nevada. Both study areas are in the eastern Mojave Desert and receive an average of <14 cm/yr of precipitation (Hereford et al. 2004). Lake Mead National Recreation Area comprises 4025 km² of land surrounding Lakes Mead and Mohave overlapping the state border between southern Nevada and northwest Arizona. Our SNV study area has very little surface water except isolated low discharge springs. Elevations range from 192 to 1719 m in LMNRA and approximately 500 to 3632 m in SNV. Vegetation along slopes and canyons in LMNRA consists of Mojave Desert scrub dominated by creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*), with narrow strips of riparian vegetation lining the shores of both lakes. Vegetation within SNV is primarily Mojave Desert scrub at lower elevations, transitioning to pinyon-juniper woodlands (*Pinus* spp., and *Juniperus* spp.) along mountain slopes, and culminating in a treeless alpine zone on the higher peaks.

Peregrine Feather Collection. We estimated age of peregrine nestlings using 10 × 42 binoculars, or a 20–60× spotting scope, by comparing feather growth with a photographic guide (Clum et al. 1996). Flight and body feathers are not completely grown by fledging, so we classified free-flying hatch-year (HY) peregrines as fledglings when a sheath was still present around the base of feathers. We classified peregrines as after-hatch-year (AHY) when we confirmed they had at least entered their second year or had attained full adult plumage (i.e., definitive basic plumage; Pyle 2008).

We collected feather samples from AHY and nestling peregrines during the 2012 and 2013 breeding seasons (19 March to 19 June 2012; 24 January to 13 June 2013). We captured AHY peregrines using noose-harnessed Rock Pigeons (*Columba livia*; Bloom et al. 2007) at the base of eyrie cliffs during the courtship and nestling breeding stages. Nestlings were sampled from the eyrie when they were between 21–30 d old to allow for adequate feather growth. We banded each peregrine with a standard U.S. Geological Survey aluminum band, and with a uniquely coded, alphanumeric black anodized color band (Acraft Sign and Nameplate Co. Ltd., Edmonton, Alberta, Canada) to aid future identification of individuals. We generally sexed individuals by tarsus

width (male <6 mm; female ≥6 mm) and used published wing chord lengths for verification of adult sex when necessary (Pyle 2008).

We removed 1.5–2.0 cm of the distal end of the fourth primary flight feather (p4) from both wings using clean stainless steel scissors. We took care to not cut the follicle when sampling nestlings, which is vascularized and prone to bleeding in growing feathers (USFWS 2003). We also collected axillary feathers from four AHY peregrines in order to investigate differences in total Hg concentrations between feather types. Axillaries were cut near the base of the feather vane excluding the calamus. Additionally, we collected samples from as many feather types as possible from dead peregrine nestlings and fledglings discovered in the vicinity of eyries, and we collected molted feathers from adults at eyries from 2008–2013. All feather samples were stored in polyethylene collection bags at room temperature prior to analysis.

Collection of Prey Remains. During the 2012 and 2013 breeding seasons, we collected feathers of prey remains from eyries, the base of eyrie cliffs, and from associated plucking perches when banding nestlings and again after young fledged. We also collected prey remains during a related project following the 2008–2011 breeding seasons. In collaboration with a regional expert (N.J. Schmitt), we identified feathers to the lowest taxonomical unit (i.e., family, genus, or species), which in some cases consisted of >1 similar species (i.e., ''species group''). Our selection of feather types for Hg analysis and species identification was limited by the types of feathers available at the eyries and perches, but we preferentially tested remiges (i.e., primaries and secondaries) and retrices. We classified avian prey as ''aquatic'' or ''terrestrial'' based on their nesting and foraging habitat requirements (i.e., ''bird type''). We also assigned them to a foraging guild (i.e., aquatic herbivore, aquatic invertivore, carnivore, frugivore, granivore, insectivore, omnivore, piscivore) based on the primary breeding season diet of each species, as determined by personal observations and from Ehrlich et al. (1988).

We estimated proportions by biomass of bird type consumed per territory using prey remains and direct observation during previous research within LMNRA from 2005–2010 (Barnes 2011), and from prey remains collected in both study areas from 2011–2013. We determined the number of individuals in prey remains by counting the minimum number of bills, legs, and diagnostic flight feathers per species, and estimated mass using published values of adults (Dunning 2007). We measured the straight line distance from the active eyrie in each territory to the nearest lake shoreline (i.e., Lake Mead or Lake Mohave) using a geographic information system (ArcGIS v. 9.3, Environmental Systems Research Institute, Redlands, California, U.S.A.), in order to assess the importance of distance to permanent water when considering prey composition and contaminant levels within territories.

Feather Analysis. We tested total Hg in feathers using an AMA 254 atomic absorption spectrometer (method detection limit = 2.5 ng/g [ppb]; Leco Corporation, St. Joseph, Michigan, U.S.A.) at the environmental and occupational health laboratory at the University of Nevada, Las Vegas. Results are presented as total Hg on a fresh weight (fw) basis in μg/g (equivalent to ppm). Total Hg levels are a surrogate for MeHg because virtually all total Hg in feathers has been found to be the organic methylated form (Thompson and Furness 1989, Bond and Diamond 2009). We limited analysis to the distal end of feather samples (1.5–4.0 cm) when dealing with large flight feathers (i.e., primaries, secondaries, rectrices) from relatively large-bodied species of prey (e.g., raptors, large aquatic birds, doves, etc.), but analyzed the entire feather, excluding the calamus, when presented with smaller body feathers or most feathers from small-bodied birds (e.g., passerines). Using stainless steel scissors, we cut each sample into small pieces to allow it to fit in a small nickel weigh boat. Analyzed portions of feathers weighed from 2.1–41.8 mg fw. We then placed the weigh boat with sample in a catalyst tube in the AMA 254 atomic absorption spectrometer for thermal decomposition (750°C for 320 sec). Ultra pure O_2 was used as a carrier gas to transport the gaseous sample to a gold-plated amalgamator where total Hg was determined using a wavelength of 253.65 nm. We ran quality control tests every 10–12 samples, consisting of a method blank and one or two samples of standard certified reference material (CRM; CRM 1633b, CRM 2709, CRM 2711; National Institute of Standards and Technology, Gaithersburg, Maryland, U.S.A.), to verify calibration. Accepted CRM recoveries ranged from 86–111% of the certified values of total Hg (mean = 94.7 ± 5.2%, n = 118). We report all samples with a total Hg level below our method detection limit as zero.

Statistical Analysis. We report the individual with the highest level of total Hg when >1 AHY peregrine was tested in a territory in order to gauge maximum exposure in each territory. For peregrine

Table 1. Pearson's coefficient correlation table of variables relating to total mercury contamination at Peregrine Falcon breeding territories in the Southern Nevada and Lake Mead National Recreation Area, Nevada and Arizona study areas, 2008–2013. Sample size is the number of territories assessed for each variable. Distance to water is the straight-line distance (km) of the eyrie to the nearest lake (i.e., Lakes Mead or Mohave), and aquatic prey biomass is the proportion of aquatic birds taken relative to all prey taken per territory.

VARIABLES	*n*	ADULT HG (μg/g)	BROOD HG (μg/g)	MEAN PREY HG (μg/g)	DISTANCE TO WATER (km)	AQUATIC PREY BIOMASS
Adult Hg (μg/g)	17	—				
Brood Hg (μg/g)	9	0.66	—			
Mean prey Hg (μg/g)	12	0.65*	0.69	—		
Distance to water (km)	19	−0.28	−0.45	−0.45	—	
Aquatic prey biomass	12	0.51	0.60	0.84**	−0.72**	—

** $P < 0.01$.
* $P < 0.05$.

nestlings, we report all brood means for total Hg, but use the nestling with the highest total Hg concentration within broods (six broods) when comparing among territories. In prey, when we verified >1 feather from the same individual, we relied on the feather sample with the highest total Hg level to account for maximum total Hg exposure. Our ability to confidently attribute multiple feathers to the same prey item was limited because of the haphazard nature of collecting plucked feathers from eyries; however, we analyzed >1 feather from 54 prey individuals representing 30 species.

Based on highly significant Shapiro-Wilk tests ($P < 0.001$), total Hg concentrations in peregrines and their prey were not normally distributed, so we used nonparametric tests to assess differences among groups. We used Mann-Whitney *U*-tests to compare overall difference of total Hg concentrations between peregrine age class (HY vs. AHY), and by age class between study areas. To assess differences between total Hg concentrations in peregrines in which we sampled both p4s (i.e., right and left fourth primary), we pooled by age class and compared means using a paired samples *t*-test because the difference between means of the two feathers was normally distributed.

We used Mann-Whitney *U*-tests to compare differences between mean total Hg concentration detected in prey remains collected per peregrine territory by study area, and mean total Hg concentration by bird type (i.e., aquatic vs. terrestrial). We used Kruskal-Wallis tests to assess differences among bird types by study area and differences of mean total Hg concentrations of prey foraging guilds, using stepwise step-down comparisons to look for significant differences. We performed Pearson's coefficient correlations to analyze relationships by territory between adult total Hg, brood total Hg, mean prey total Hg, distance of eyries to Lakes Mead or Mohave, and the proportion of aquatic birds taken as prey by biomass. We used independent samples *t*-tests to compare mean distance of eyries to permanent water by study area and the proportion of bird types taken as prey in the two study areas.

We report arithmetic means ± SE unless otherwise indicated, and consider results significant at $P \leq 0.05$. All statistical tests were conducted in SPSS 21 (IBM SPSS, Armonk, New York, U.S.A.).

RESULTS

Peregrine Falcons. We captured 14 AHY peregrines during the 2012 and 2013 breeding seasons, and collected an additional 11 molted AHY feathers, representing 12 territories within LMNRA and five territories from SNV. From only one territory did we capture both a resident male and female, and this was done in subsequent years. We sampled a total of 24 HY peregrines, representing six broods from LMNRA and 3 broods from SNV. All peregrine feather samples contained detectable levels of total Hg (range = 0.12–42.54 μg/g, $n = 49$). Overall, total Hg concentrations in AHY peregrines (mean = 12.19 ± 2.5 μg/g, $n = 25$) were significantly higher than in HY peregrines (mean = 3.76 ± 0.8 μg/g, $n = 24$; $t_{29} = -3.213$, $P = 0.003$). There was not a significant correlation between total Hg detected in adult peregrines compared to their broods ($r = .65$, $P = 0.075$; Table 1), although this comparison was limited by small sample size (i.e., only eight broods sampled with ≥1 attendant adult also sampled).

Table 2. Total mercury concentrations (μg/g fresh weight) detected in Peregrine Falcon nestlings within the same brood in territories in the Southern Nevada (S1 and S2) and Lake Mead National Recreation Area (L1–L4), Nevada and Arizona study areas, 2012. All nestlings within broods were analyzed.

	PEREGRINE TERRITORY					
BROOD SUMMARY STATISTICS	S1	S2	L1	L2	L3	L4
Brood size	3	3	4	2	2	4
Brood mean Hg (μg/g)	0.61	0.23	6.49	12.29	4.42	1.84
SD	0.01	0.13	3.12	1.08	0.45	0.22
Range (μg/g)	0.60–0.63	0.12–0.31	4.75–11.16	11.53–13.05	4.1–4.74	1.54–2.03

Total Hg concentrations in p4s of AHY peregrines at territories in LMNRA (mean = 17.24 ± 4.13 μg/g, range = 1.46–42.54 μg/g, n = 12) were significantly greater than in AHY peregrines in SNV (mean = 2.7 ± 1.06 μg/g, range = 0.93–6.8 μg/g, n = 5; Mann-Whitney U = 7.0, z = −2.424, P = 0.014). We were precluded from conducting statistical analyses between sexes because we generally did not sample both sexes from the same territory; however, we detected total Hg means of 19.4 ± 5.28 μg/g in AHY females (range = 1.39–42.54 μg/g, n = 8) and 4.35 ± 1.53 μg/g in AHY males (range = 1.46–10.77 μg/g, n = 6). In LMNRA, AHY females had a mean of 21.97 ± 5.32 μg/g total Hg (range = 7.15–42.54 μg/g, n = 7) compared to 4.34 ± 2.2 μg/g in AHY males (range = 1.46–10.77 μg/g, n = 4), while in SNV a single AHY female had 1.39 μg/g and two AHY males had 1.94 μg/g and 6.8 μg/g respectively. The only territory in which we sampled both AHY sexes, albeit in subsequent years, was in LMNRA and the female had 16.82 μg/g of total Hg compared to the male with 10.77 μg/g.

Total Hg concentrations in p4s of peregrine broods in LMNRA (mean = 5.82 ± 2.07 μg/g, range = 0.75–13.05 μg/g, n = 6) were significantly greater than in SNV (mean = 0.67 ± 0.18 μg/g, range = 0.37–1.0 μg/g, n = 3; Mann-Whitney U = 1.0, z = −2.066, P = 0.048). We sampled broods from two LMNRA territories in consecutive years, with an increase of mean brood total Hg concentration of 0.86 μg/g between years at one territory (2012 = 1.84 μg/g, 2013 = 2.7 μg/g) and a decrease of 0.62 μg/g between years at a second territory (2012 = 4.42 μg/g, 2013 = 3.8 μg/g). Overall, we detected total Hg means of 3.05 ± 0.75 μg/g in female nestlings (range = 0.6–11.53 μg/g, n = 15) and 4.52 ± 2.06 μg/g in male nestlings (range = 0.12–13.05 μg/g, n = 7). In LMNRA, female nestlings had a mean of 3.9 ± 0.89 μg/g total Hg (range = 0.75–11.53 μg/g, n = 11) compared to 7.73 ± 2.62 μg/g for male nestlings (range = 1.96–13.05 μg/g, n = 4), while in SNV female nestlings had a mean of 0.71 ± 0.1 μg/g (range = 0.6–1.0 μg/g, n = 4) compared to a mean of 0.23 ± 0.07 μg/g in male nestlings (range = 0.12–0.37 μg/g, n = 3).

Eyries in LMNRA were significantly closer to water (mean = 1.3 km, n = 12) than those in SNV (mean = 40.4 km, n = 7; t_6 = −2.54, P = 0.044) and aquatic birds comprised a significantly greater percent of prey remains by biomass in peregrine territories in LMNRA (mean = 64.3%, eight territories) than in SNV (14.7%, four territories; t_{10} = 5.78, $P < 0.001$). Adult peregrine total Hg concentrations were positively correlated with mean prey total Hg (r = .65, P = 0.042); however, brood total Hg concentrations were not significantly correlated with mean prey total Hg (r = .69, P = 0.089; Table 1). The proportion by biomass of aquatic birds taken as prey was positively correlated with mean prey total Hg (r = .84, P = 0.001) and negatively correlated with distance of eyries to water (r = −.72, P = 0.008; Table 1).

Variation Within Individuals and Broods. We did not detect a significant difference in total Hg between paired p4s within individuals (t_{21} = −1.113, n = 22, P = 0.278). We were hindered by small sample size from conducting statistical analysis on individuals from which we collected p4 and axillary feather samples (i.e., for HY n = 3; for AHY n = 4). However the difference in total Hg concentration between these two feather types within HY peregrines was relatively small (mean difference = 1.22 μg/g, range = 0.41–2.74 μg/g), whereas it was much greater in AHY peregrines (mean difference = 14.69 μg/g, range = 3.46–37.27 μg/g).

Variation of total Hg among nestlings within broods was generally low (Table 2), although small sample size precluded rigorous testing. Excluding one anomalous territory (L1), the mean difference in total Hg among individuals within broods was

Table 3. Total mercury concentrations (μg/g fresh weight) detected in feathers of carcasses of hatch-year Peregrine Falcons in the Southern Nevada and Lake Mead National Recreation Area, Nevada and Arizona study areas, 2012.

INDIVIDUAL	FEATHER TYPE	*n*	MEAN (μg/g)	SD	RANGE (μg/g)
Nestling 1	primary	8	0.67	0.08	0.56–0.81
	secondary	10	0.72	0.07	0.62–0.83
	rectrix	1	0.62		
	axillary	4	0.23	0.05	0.17–0.27
	covert	2	0.73	0.05	0.69, 0.76
	overall	25	0.62	0.19	0.17–0.83
Nestling 2	primary	9	2.94	0.17	2.68–3.14
	secondary	1	2.69		
	rectrix	2	2.75	0.09	2.68, 2.82
	axillary	2	2.29	0.58	1.87, 2.7
	overall	14	2.8	0.32	1.87–3.14
Nestling 3	primary	5	1.3	0.06	1.25–1.39
	secondary	3	1.35	0.04	1.31–1.38
	rectrix	2	1.23	0.01	1.22, 1.24
	covert	2	1.24	0.13	1.15, 1.33
	breast	1	1.08		
	vent	1	1.09		
	overall	14	1.26	0.1	1.08–1.39
Fledgling 1	primary	10	6.92	1.23	5.11–8.38
	secondary	1	9.64		
	rectrix	2	6.27	1.44	5.25, 7.29
	axillary	1	4.91		
	overall	14	6.88	1.47	4.91–9.64
Fledgling 2	primary	2	0.26	0.01	0.25, 0.27
	secondary	1	0.25		
	covert	1	0.12		
	overall	4	0.22	0.07	0.12–0.27

only 0.58 μg/g ($n = 5$). Only a single nestling varied greatly from its brood-mates (nestling with highest total Hg in L1 was 126% greater than its siblings' mean) and development of this individual was stunted relative to its siblings; its tail length was only 61% as long as the mean for its siblings (41 mm vs. a mean of 67 mm) and the emerged portion of its p4 was just 50% of its siblings' mean (23 mm vs. a mean of 46 mm).

We analyzed various feathers and feather types from the remains of five HY peregrines (three nestlings, two fledglings) found in eyries or at the base of eyrie cliffs (4–25 feathers/individual; Table 3). Overall variation of total Hg detected between feathers was low, with 1.42 μg/g being the mean difference between highest and lowest concentration within individuals (range = 0.15–4.73 μg/g, mean SD = 0.43). The individual with the most variation (fledgling 1) also had the highest total Hg levels and survived longer than the others (i.e., survived ≥2 wk after fledging). We could not confirm cause of death in any instance; however, nestling 1 likely was predated as a nearly fledged nestling based on feather growth, and fledgling 1 had very low pectoral muscle mass as if from starvation.

Analysis of Prey. We tested feathers from 337 individuals representing 94 species, or species types, from avian prey (1–26 individuals/prey type; Appendix 1), measuring detectable levels of total Hg in all but 39 individuals. Mean total Hg concentrations detected in prey remains collected per peregrine territory in LMNRA (mean = 2.26 ± 0.46 μg/g, range = 0.27–3.9 μg/g, $n = 7$ territories) were significantly greater than in SNV (mean = 0.23 ± 0.06 μg/g, range = 0.09–0.4 μg/g, $n = 5$ territories; Mann-Whitney $U = 33.0$, $z = 2.517$, $P = 0.01$). Eared Grebes (*Podiceps nigricollis*) contained some of the highest total Hg concentrations (mean = 12.27 ± 2.2 μg/g, range = 0.2–30.93 μg/g, $n = 22$), followed by Red-winged Blackbirds (*Agelaius phoeniceus*; mean = 6.96 ± 6.83 μg/g, range = <0.01–34.29 μg/g, $n = 5$) and Black-necked Stilts (*Himantopus mexicanus*;

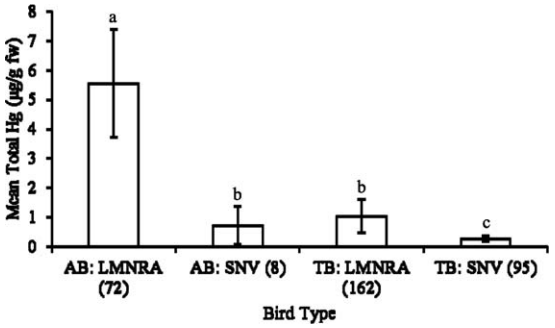

Figure 1. Concentrations of mean total mercury (µg/g fresh weight) detected in avian prey by bird type collected from Peregrine Falcon territories in the Southern Nevada (SNV) and Lake Mead National Recreation Area (LMNRA), Nevada and Arizona study areas, 2008–2013. Avian prey is categorized by bird type (AB = aquatic bird, TB = terrestrial bird) based on general habitat type preferred by each species for foraging and breeding. Mean total Hg levels are shown with 95% confidence intervals. Sample size is indicated in parentheses for each group. Letters above each bar indicate significant difference among means, determined with a Kruskal-Wallis test using stepwise step-down comparisons.

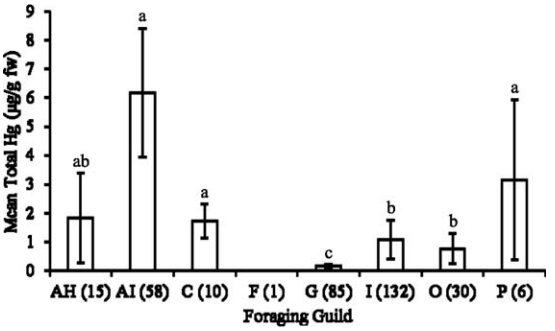

Figure 2. Concentrations of mean total mercury (µg/g fresh weight) detected in avian prey by foraging guild collected from Peregrine Falcon territories in the Southern Nevada and Lake Mead National Recreation Area, Nevada and Arizona study areas, 2008–2013. Avian prey is categorized by foraging guild based on each species' primary diet during the breeding season (AH = aquatic herbivore, AI = aquatic invertivore, C = carnivore, F = frugivore, I = insectivore, G = granivore, O = omnivore, P = piscivore), and study areas are pooled. Mean total Hg levels are shown with 95% confidence intervals. Sample size is indicated in parentheses for each guild. Letters above each bar indicate significant difference among means, determined with a Kruskal-Wallis test using stepwise step-down comparisons.

mean = 6.57 ± 2.21 µg/g, range = 0.13–13.8 µg/g, $n = 6$). Some commonly taken species with relatively low concentrations of total Hg were American Coots (*Fulica americana*; mean = 0.8 ± 0.42 µg/g, range = 0.08–3.23 µg/g, $n = 7$), Great-tailed Grackles (*Quiscalus mexicanus*; mean = 0.43 ± 0.11 µg/g, range = <0.01–2.29 µg/g, $n = 25$) and the four commonly taken Columbidae species as a whole (mean = 0.11 ± 0.03 µg/g, range = <0.01–1.4 µg/g, $n = 51$).

Overall, aquatic birds (mean = 5.07 ± 0.84 µg/g, range = <0.01–30.93 µg/g, $n = 80$) contained a significantly higher concentration of total Hg than terrestrial birds (mean = 0.76 ± 0.18 µg/g, range = <0.01–34.29 µg/g, $n = 257$; Mann-Whitney $U = 16886$, $z = 8.69$, $P < 0.001$). There were significant differences in mean total Hg found in bird type by study area (Fig. 1; $H_3 = 96.4$, $n = 337$, $P < 0.001$). Stepwise step-down comparisons indicated aquatic birds from LMNRA (mean = 5.55 ± 0.92 µg/g, range = <0.01–30.93 µg/g, $n = 72$) contained significantly more total Hg than all other groups, whereas terrestrial birds from SNV were significantly lower than all other groups (mean = 0.27 ± 0.05 µg/g, range = <0.01–2.19 µg/g, $n = 95$). There were also significant differences in mean total Hg among foraging guilds pooled by study area (Fig. 2; $H_6 = 134.6$, $n = 337$, $P < 0.001$). Although stepwise step-down comparisons indicated overlap among several of the guilds, aquatic invertivores yielded the highest mean total Hg level (mean = 6.17 ± 1.11 µg/g, range = 0.06–30.93 µg/g, $n = 58$), followed by piscivores (mean = 3.16 ± 1.08 µg/g, range = 1.13–7.89 µg/g, $n = 6$) and aquatic herbivores (mean = 1.83 ± 0.73 µg/g, range = <0.01–9.92 µg/g, $n = 15$). The total Hg concentration for the single individual we analyzed from the frugivore guild (Cedar Waxwing; *Bombycilla cedrorum*) was below our detection limit.

DISCUSSION

This baseline assessment indicates peregrines in LMNRA and SNV are widely contaminated by total Hg (AHY = 0.57–42.54 µg/g, HY = 0.12–13.05 µg/g), several at concentrations high enough to cause concern. All peregrine feathers contained detectable amounts of total Hg. However, the large differences in mean total Hg detected between peregrines breeding in LMNRA (AHY = 17.24 ± 4.13 µg/g, HY = 5.82 ± 2.07 µg/g), compared with peregrines in our SNV study area (AHY = 2.7 ± 1.06 µg/g, HY = 0.67 ± 0.18 µg/g), suggests that distance to the major water bodies of Lakes Mead and Mohave, and the corre-

sponding difference in diet both largely influence risk of Hg contamination. There was a correlation between adult peregrine total Hg concentration in p4s and the mean total Hg concentration found in prey remains, with the mean total Hg concentration in adult peregrines approaching an order of magnitude greater than in their prey mean in each study area. Our results indicate aquatic bird consumption poses the greatest source of contaminant exposure to peregrines breeding in our study area. However, we are unaware of a local point source of Hg contamination, nor what effect local sources may have on peregrine health and reproduction.

The total Hg concentration in feathers of several adult peregrines breeding in LMNRA were high enough to indicate a body burden that may negatively influence health (i.e., five AHYs >15 μg/g, four nestlings >10 μg/g). Toxicity studies specific to peregrines are lacking, and research indicates there are substantial species-specific differences in Hg toxicity thresholds in birds (Scheuhammer et al. 2007, Heinz et al. 2009), as well as deposition rates of Hg into feathers (Thompson et al. 1990, Becker et al. 1994). However, Eisler (1987) considered that Hg concentrations in feathers as low as 5 μg/g were correlated with neuropathologies resulting in behavioral changes and decreased reproduction in birds, whereas others found that feather Hg concentrations of 15 μg/g were associated with adverse reproduction in some predatory birds (Spry and Wiener 1991). Lindberg and Odsjö (1983) detected a mean Hg concentration in feathers of 17.6 μg/g in a declining population of peregrines in Sweden; however, they were not able to distinguish between effects of Hg and chlorinated hydrocarbon pesticides. Bednarek et al. (1975) found a mean concentration of 9.25 μg/g Hg in feathers was correlated with reduced reproduction by breeding female Eurasian Sparrowhawks (*Accipiter nisus*) in Germany, but they also were unable to separate effects of Hg from pesticide contamination. In contrast, studies evaluating Hg in piscivorous raptors in North America have not linked adult mean feather Hg concentrations as high as 58.09 μg/g in Osprey (*Pandion haliaetus*; DesGranges et al. 1998), or 21 μg/g and 18.74 μg/g in Bald Eagles (*Haliaeetus leucocephalus*; Bowerman et al. 1994, Bechard et al. 2009) to declines in reproduction or population size. A reproductive assessment of peregrines in LMNRA from 2006–2010 indicated 72% breeding success and 1.8 young/breeding attempt in an expanding local population (Barnes et al. 2015). Although that study did not assess Hg contamination, it appears on a population level that no adverse reproductive effects were manifested at that time.

Concentration of Hg in feathers of juvenile birds reflect short-term, site-specific exposure, based on contamination of local prey sources at the time of feather growth; however, Hg in feathers of adults reflect Hg uptake since the previous molt (Evers et al. 2005). Because of this, for non-sedentary adults the feather Hg level is an indication of Hg accumulation from various locations (e.g., along migration routes, staging areas, wintering grounds) during the breeding and nonbreeding seasons. Therefore, Hg concentrations found in the two age classes are often informative on differing temporal and spatial scales. Monthly surveys of unmarked peregrines during a single nonbreeding season in LMNRA (September–January; Barnes et al. 2015) showed that adults were present on territory throughout the year at most territories; it was assumed these were the breeding adults. However, the extent of local movements was unknown. Because of these uncertainties, it is not prudent to assume all Hg measured in feathers of territory-holding peregrines in LMNRA was acquired locally. Much less is known about daily or seasonal movement patterns of peregrines breeding in our SNV study area. Even so, total Hg concentrations in feathers of AHY peregrines pooled from both study areas were positively correlated with those found in their prey during the breeding season.

Mercury levels in feathers of nestling birds has been shown to be positively correlated with post-hatching diet (Becker et al. 1993), and therefore the total Hg concentrations we measured in broods are reflective of contaminant levels in locally selected prey. We measured a positive but nonsignificant trend of increasing brood total Hg with mean prey total Hg; however, small sample size limited statistical inference and we were unable to sample all prey consumed. Also, our analysis of Hg contamination in prey was derived from prey collected over six breeding seasons, whereas brood total Hg concentration only reflect Hg uptake during the 21–30 d nestling period prior to our sampling visit.

We used p4 as our standardized feather sample because replacement of flight feathers begins with the fourth primary in all North American falconidae species (Pyle 2008). As such, it should contain the highest concentration of Hg relative to other flight feathers (Honda et al. 1986, Dauwe et al. 2003), and

be most representative of Hg exposure since the previous molt. In addition, analysis of p4 should provide a relatively accurate record of Hg exposure experienced by peregrines on the breeding grounds because it is replaced on territory prior to molt suspension for breeding or migration (Pyle 2008). Standardized sampling of the first flight feather to be replaced enables spatial and temporal analysis of Hg exposure for species with high site fidelity, and particularly in sedentary, nonmigratory species or individuals (Lodenius and Solonen 2013), although sampling migratory birds can be informative over broad geographical scales (Bildstein 2001). This approach will also allow trend analysis within individuals over time, and facilitate comparisons among age classes and species. Adherence to standardized feather sampling is less critical when assessing Hg contamination in nestlings because growth of juvenal flight feathers is generally concurrent, which likely explains the low variation of total Hg we detected between feathers from HY peregrines (Table 3). A detailed analysis of Hg concentration among feather types may provide differences of exposure relative to nestling growth and allow tighter temporal precision of contaminant analysis, depending on the exact pattern and timing of feather growth among individual feathers and feather types. When considering fledged HY birds, it is important to consider inserted molts (e.g., preformative molts), which occur in many species within their first full molt cycle, but generally do not include remiges in North American raptors (Pyle 2008).

It came to our attention during our research that several ongoing peregrine studies routinely collect axillary feathers, and many of these samples are retained in long-term storage (G. Doney pers. comm., B. Robinson pers. comm.). Berg et al. (1966) demonstrated that Hg disulphide bonds are retained in feathers for periods greater than 100 yr, thereby facilitating temporal trend analysis by testing archived samples. Because of this, we collected axillary feathers for a comparison of total Hg concentration between p4 and axillaries within individuals. Our preliminary findings suggest the difference in total Hg concentration between these two feather types may be minimal in HY peregrines. In AHY peregrines, the difference between the two feather types was much greater, which may limit the value of direct comparisons in older individuals. Also, concentrations of Hg in p4 are easier to interpret, particularly with nonmigratory individuals, because p4 is the first flight feather to be replaced (see above; Pyle 2008). We observed variation in the timing of axillary feather replacement relative to replacement of p4, thereby hindering our ability to draw conclusions concerning fine-scale Hg uptake relative to the timing of feather growth between the two feather types. It is likely that axillaries at least provide a minimum relative index of exposure that can be informative for long-term, regional, or population-wide contaminant studies.

Prey Analysis. In a synthesis of research on Hg concentrations of 38 species of birds between 1969–2003 in northeastern North America, Evers et al. (2005) indicated that trophic level largely influenced differences in Hg burdens, and availability of MeHg was based on general habitat type (e.g., aquatic > terrestrial). Although exposure was greater in aquatic systems, there was a gradient of increasing Hg based on the trophic level of foraging guilds such that herbivore < omnivore < insectivore < piscivore. Concentrations of total Hg in the eight foraging guilds we examined largely followed this progression, with the notable exception that aquatic invertivores exceeded piscivores as the guild with the highest mean total Hg concentration, followed by aquatic herbivores above all others (Fig. 2). Our ability to evaluate the Hg risk posed by piscivorous prey to raptors was limited by the small number of individuals we collected ($n = 6$), but the large body size of many of the piscivores (e.g., cormorants, mergansers, *Aechmophorus* grebes, herons, and egrets, etc.) likely reduces the predation risk they face from peregrines. The high concentration of total Hg in aquatic herbivores was somewhat surprising, but many of these species also feed on aquatic insects and invertebrates (Ehrlich et al. 1988). The levels of total Hg we detected in terrestrial insectivores (mean = 1.07 ± 0.34 μg/g) and omnivores (mean = 0.77 ± 0.26 μg/g) were both higher than those Keller et al. (2014) documented for the same guilds in the southern Appalachian Mountains, an area with very high Hg deposition.

In LMNRA, Eared Grebes appear to be the single largest contributor of total Hg to peregrines, based on availability (i.e., they constituted 25.3% of all aquatic birds on Lake Mead during aquatic bird surveys from 2004–2009; Barnes and Jaeger 2012), contribution to diet (i.e., 14.9% of the peregrine diet by biomass; Barnes 2011), and high Hg concentrations (mean = 12.27 μg/g, $n = 22$). Seasonal patterns recorded in LMRNA from 2004–2009 indicated that Eared Grebes were generally present in large numbers during April and May (Barnes and

Jaeger 2012), roughly corresponding with the incubation and early nestling stages of local peregrines (Barnes et al. 2015). Nearly half of the North American Eared Grebe population annually stage from August–January on the Great Salt Lake, where they forage on brine shrimp during their molt migration (Aldrich and Paul 2002). Water samples from the Great Salt Lake contained the highest MeHg concentrations recorded for surface water in the U.S. (Naftz et al. 2008), and Hg concentrations in the livers of several species of wintering waterfowl on the Great Salt Lake were among the highest in published literature for those species (Vest et al. 2009).

Although the total Hg concentrations we detected in terrestrial birds were fairly low for both study areas (mean LMNRA = 1.04 μg/g, mean SNV = 0.27 μg/g) relative to aquatic birds, it is interesting that terrestrial birds in LMNRA had significantly higher total Hg levels than those in SNV. Terrestrial birds foraging near shorelines in LMNRA were likely exposed to Hg levels more closely associated with aquatic systems (i.e., consuming insects with larval development in aquatic systems; see Keller et al. 2014). Based on recent modeling of reduced nest success associated with Hg concentration in tail feathers of Carolina Wrens (*Thryothorus ludovicianus*; nest success reductions of 10, 20, and 30% with levels of 3.0, 4.7, and 6.4 μg/g Hg; Jackson et al. 2011), we considered total Hg concentrations in six species of terrestrial passerines in LMNRA were potentially high enough to affect reproduction. Most alarming, were the high concentrations of total Hg we detected in Red-winged Blackbirds (mean = 6.96 μg/g, range = 0–34.29 μg/g), Brewer's Blackbirds (*Euphagus cyanocephalus*; mean = 5.54 μg/g, range = 0.02–23.51 μg/g), and Common Ravens (*Corvus corax*; mean = 3.75 μg/g, range = 1.41–7.54 μg/g; Appendix 1). Many of the terrestrial bird species we tested from both study areas breed locally (Floyd et al. 2007), whereas many aquatic birds in LMNRA were highly migratory, with very little local breeding (Barnes and Jaeger 2012). As such, it is possible that Hg found in terrestrial birds may be more indicative of local contamination than aquatic birds. Although we did not quantify it, a sizable proportion of our terrestrial bird prey remains consisted of feathers with retained sheaths. These feathers represent recently fledged birds not yet able to make long flights, thereby reflecting Hg contamination in the immediate vicinity of breeding territories.

Summary. Our study represents the first assessment of Hg contaminant levels in peregrines and their avian prey in southern Nevada and northwest Arizona. We documented baseline total Hg concentrations within peregrines breeding in our two study areas and determined general dietary pathways of exposure through which they are vulnerable to bioaccumulation. We could not infer where sources of Hg contamination originated without knowing the details of species-specific and individual movements of prey prior to capture by peregrines. The large difference in Hg contamination between our study areas indicated a trend of increasing contamination with decreasing distance to water, likely driven by availability of aquatic birds. We did not assess breeding performance and therefore, in the absence of toxicological studies, we were unable to determine effects total Hg may have on breeding peregrines. However, we note that the breeding population of peregrines in LMNRA was expanding from 2006–2010 and reproductive output appeared to be healthy overall (Barnes et al. 2015).

Within North America, upper trophic level piscivorous birds such as the Common Loon (*Gavia immer*; Fevold et al. 2003, Evers et al. 2005), Osprey (DesGranges et al. 1998), and Bald Eagle (Bowerman et al. 2002, Bechard et al. 2009) have been used as biomonitors of Hg in the environment. The applicability of using a single species as a bioindicator of ecosystem health can be limited when the species is restricted to a specific habitat type (e.g., aquatic systems) or has a limited geographic breeding distribution. This is particularly apparent, in light of recent research on biomagnification of Hg in terrestrial systems (Rimmer et al. 2005, Cristol et al. 2008, Keller et al. 2014). We suggest that Peregrine Falcons, with their cosmopolitan breeding distribution, catholic diet, and use of diverse habitat types (e.g., marine and freshwater shorelines, Arctic tundra, alpine cliffs, temperate forest, open desert, urban areas, etc.; White et al. 2013), may be an ideal indicator species of Hg contamination globally. Additional research is needed to establish adverse effect thresholds of Hg on peregrines, and studies that incorporate prey contamination will be especially valuable for assessing ecosystem health by determining system-wide effects of Hg across a broad range of avian species.

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LITERATURE CITED

ALBERS, P.H., M.T. KOTERBA, R. ROSSMANN, W.A. LINK, J.B. FRENCH, R.S. BENNETT, AND W.C. BAUER. 2007. Effects of methylmercury on reproduction in American Kestrels. *Environmental Toxicology and Chemistry* 26:1856–1866.

ALDRICH, T.W. AND D.S. PAUL. 2002. Avian ecology of Great Salt Lake. Pages 343–374 *in* J.W. Gwynn [ED.], Great Salt Lake: an overview of change. Special Publication. Utah Department of Natural Resources, Salt Lake City, UT U.S.A.

APPELQUIST, H., S. ASBIRK, AND I. DRABAEK. 1984. Mercury monitoring: mercury stability in bird feathers. *Marine Pollution Bulletin* 15:22–24.

AUGSPURGER, T. AND A. BOYNTON. 1998. Organochlorines and mercury in Peregrine Falcon eggs from western North Carolina. *Journal of Raptor Research* 32:251–254.

BARNES, J.G. 2011. An ecological study of Peregrine Falcons (*Falco peregrinus*) at Lake Mead National Recreation Area, 2006–10. M.S. thesis, University of Nevada, Las Vegas, NV U.S.A.

———, R. HALEY, D.B. THOMPSON, AND J.R. JAEGER. 2015. Attributes of a breeding population of Peregrine Falcons associated with reservoirs on the Colorado River. Manuscript submitted for publication in *Journal of Raptor Research* 49 in press.

——— AND J.R. JAEGER. 2012. Aquatic birds. Pages 95–99 *in* M.R. Rosen, K. Turner, S.L. Goodbred, and J.M. Miller [EDS.], A synthesis of aquatic science for management of lakes Mead and Mohave. Circular 1381. U.S. Geological Survey, Reston, VA U.S.A.

BECHARD, M.J., D.N. PERKINS, G.S. KALTENECKER, AND S. ALSUP. 2009. Mercury contamination in Idaho Bald Eagles. *Bulletin of Environmental Contamination and Toxicology* 83:698–702.

BECKER, P.H., R.W. FURNESS, AND D. HENNING. 1993. Mercury dynamics in young Common Tern chicks from a polluted environment. *Ecotoxicology* 2:33–40.

———, D. HENNING, AND R.W. FURNESS. 1994. Differences in mercury contamination and elimination during feather development in gull and tern broods. *Archives of Environmental Contamination and Toxicology* 27:162–167.

BEDNAREK, W., W. HAUSDORF, U. JORISSEN, E. SHULTE, AND H. WEGENER. 1975. Uber die Ausiwirkungen der chemischen Umwelthelastung auf Greifvogel in zwei Probeflachen Westfalens. *Journal fur Ornithologie* 116:181–194.

BERG, W., A. JOHNELS, B. SJOSTRAND, AND T. WESTERMARK. 1966. Mercury content in feathers of Swedish birds from the past 100 yr. *Oikos* 17:71–83.

BILDSTEIN, K.L. 2001. Why migratory birds of prey make great biological indicators. Pages 169–179 *in* K.L. Bildstein and D. Klem [EDS.], Hawkwatching in the Americas. Hawk Migration Association of North America, North Wales, PA U.S.A.

BLOOM, P.H., W.S. CLARK, AND J.W. KIDD. 2007. Capture techniques. Pages 193–219 *in* D.M. Bird and K.L. Bildstein [EDS.], Raptor research and management techniques. Hancock House Publishers, Blaine, WA U.S.A.

BOND, A.L. AND A.W. DIAMOND. 2009. Total and methyl mercury concentrations in seabird feathers and eggs. *Archives of Environmental Contamination and Toxicology* 56:286–291.

BOWERMAN, W.W., E.D. EVANS, J.P. GIESY, AND S. POSTUPALSKY. 1994. Using feathers to assess risk of mercury and selenium to Bald Eagle reproduction in the Great Lakes region. *Archives of Environmental Contamination and Toxicology* 27:294–298.

———, A.S. ROE, M.J. GILBERTSON, D.A. BEST, J.G. SIKARSKIE, R.S. MITCHELL, AND C.L. SUMMER. 2002. Using Bald Eagles to indicate the health of the Great Lakes environment. *Lakes and Reservoirs: Research and Management* 7:183–187.

BRASSO, R.L. AND D.A. CRISTOL. 2008. Effects of mercury exposure on the reproductive success of Tree Swallows. *Ecotoxicology* 17:133–141.

BRAUNE, B.M. 1987. Comparison of total mercury levels in relation to diet and molt for nine species of marine birds. *Archives of Environmental Contamination and Toxicology* 16:217–224.

CADE, T.J. 1982. The falcons of the world. Cornell University Press, Ithaca, NY U.S.A.

CAHILL, T.M., D.W. ANDERSON, R.A. ELBERT, B.P. PERLEY, AND D.R. JOHNSON. 1998. Elemental profiles in feather samples from a mercury-contaminated lake in central California. *Archives of Environmental Contamination and Toxicology* 35:75–81.

CLARK, K.E., Y. ZHAO, AND C.M. KANE. 2009. Organochlorine pesticides, PCBs, dioxins, and metals in postterm Peregrine Falcon eggs from the Mid-Atlantic states, 1993–99. *Archives of Environmental Contamination and Toxicology* 57:174–184.

CLUM, N., P. HARITY, AND W. HECK. 1996. Aging young peregrines. Pages 37–63 *in* T.J. Cade, J.H. Enderson, and J. Linthicum [EDS.], Guide to management of Peregrine Falcons at the eyrie. The Peregrine Fund, Boise, ID U.S.A.

CRISTOL, D.A., R.L. BRASSO, A.M. CONDON, R.E. FOVARGUE, S.L. FRIEDMAN, K.K. HALLINGER, A.P. MONROE, AND A.E. WHITE. 2008. The movement of aquatic mercury through terrestrial food webs. *Science* 320:335.

Dauwe, T., L. Bervoets, R. Pinxten, R. Blust, and M. Eens. 2003. Variation of heavy metals within and among feathers of birds of prey: effects of molt and external contamination. *Environmental Pollution* 124: 429–436.

DesGranges, J.L., J. Rodrigue, B. Tardif, and M. Laperle. 1998. Mercury accumulation and biomagnification in Ospreys in the James Bay and Hudson Bay regions of Quebec. *Archives of Environmental Contamination and Toxicology* 35:330–341.

Driscoll, C.T., J. Han, C.Y. Chen, D.C. Evers, K.F. Lambert, T.M. Holsen, N.C. Kamman, and R.K. Munson. 2007. Mercury contamination in forest and freshwater ecosystems in the northeastern United States. *BioScience* 57:17–28.

Dunning, J.B., Jr. 2007. CRC handbook of avian body masses, Second Ed. CRC Press, Boca Raton, FL U.S.A.

Ehrlich, P.R., D.S. Dobkin, and D. Wheye. 1988. The birder's handbook: a field guide to the natural history of North American birds. Simon and Schuster, Inc., Fireside, New York, NY U.S.A.

Eisler, R. 1987. Mercury hazards to fish, wildlife, and invertebrates: a synoptic review. U.S. Fish and Wildlife Service Biological Report 85(1.10), Laurel, MD U.S.A.

Evers, D.C., N.M. Burgess, L. Champoux, B. Hoskins, A. Major, W.M. Goodale, R.J. Taylor, R. Poppenga, and T. Daigle. 2005. Patterns and interpretation of mercury exposure in freshwater avian communities in northeastern North America. *Ecotoxicology* 14:193–221.

———, L.J. Savoy, C.R. DeSorbo, D.E. Yates, W. Hanson, K.M. Taylor, L.S. Siegel, J.H. Cooley, Jr., M.S. Bank, A. Major, K. Munney, B.F. Mower, H.S. Vogel, N. Schoch, M. Pokras, M.W. Goodale, and J. Fair. 2008. Adverse effects from environmental mercury loads on breeding Common Loons. *Ecotoxicology* 17:69–81.

Fevold, B.M., M.W. Meyer, P.W. Rasmussen, and S.A. Temple. 2003. Bioaccumulation patterns and temporal trends of mercury exposure in Wisconsin Common Loons. *Ecotoxicology* 12:83–93.

Fimreite, N. and L. Karstad. 1971. Effects of dietary methyl mercury on Red-tailed Hawks. *Journal of Wildlife Management* 35:293–300.

Floyd, T., C.S. Elphick, G. Chisholm, K. Mack, R.G. Elston, E.M. Ammon, and J.D. Boone. 2007. Atlas of the breeding birds of Nevada. University of Nevada Press, Reno, NV U.S.A.

Furness, R.W., S.J. Muirhead, and M. Woodburn. 1986. Using bird feathers to measure mercury in the environment: relationships between mercury content and moult. *Marine Pollution Bulletin* 17:27–30.

Gerstenberger, S.L. 2004. Mercury concentrations in migratory waterfowl harvested from southern Nevada wildlife management areas, U.S.A. *Environmental Toxicology* 19:35–44.

Heinz, G.H., D.J. Hoffman, J.D. Klimstra, K.R. Stebbins, S.L. Kondrad, and C.A. Erwin. 2009. Species differences in the sensitivity of avian embryos to methylmercury. *Archives of Environmental Contamination and Toxicology* 56:129–138.

Hereford, R., R.H. Webb, and C.I. Longpre. 2004. Precipitation history of the Mojave Desert region, 1893–2001. U.S. Geological Survey. http://pubs.usgs.gov/fs/fs117-03/ (last accessed 17 February 2014).

Hill, E.F., C.J. Henny, and R.A. Grove. 2008. Mercury and drought along the lower Carson River, Nevada: II. Snowy Egret and Black-crowned Night-Heron reproduction on Lahontan Reservoir, 1997–2006. *Ecotoxicology* 17:117–131.

Holdren, C.G. and K. Turner. 2010. Characteristics of Lake Mead, Arizona-Nevada. *Lake and Reservoir Management* 26:230–239.

Honda, K., T. Nasu, and R. Tatsukawa. 1986. Seasonal changes in mercury accumulation in the Black-eared Kite. *Environmental Pollution* 42:325–334.

IBM Corp. 2012. IBM SPSS statistics for Windows, Version 21.0. Armonk, NY U.S.A.

Jackson, A.K., D.C. Evers, M.A. Etterson, A.M. Condon, S.B. Folsom, J. Detweiler, J. Schmerfeld, and D.A. Cristol. 2011. Mercury exposure affects the reproductive success of a free-living terrestrial songbird, the Carolina Wren (*Thryothorus ludovicianus*). *Auk* 128:759–769.

Keller, R.H., L. Xie, D.B. Buchwalter, K.E. Franzreb, and T.R. Simons. 2014. Mercury bioaccumulation in southern Appalachian birds, assessed through feather concentrations. *Ecotoxicology* 23:304–316.

Lewis, S.A. and R.W. Furness. 1991. Mercury accumulation and excretion in laboratory reared Black-headed Gull chicks. *Archives of Environmental Contamination and Toxicology* 21:316–320.

Lindberg, P. and T. Odsjö. 1983. Mercury in feathers of Peregrine Falcon compared with total mercury content in some of its prey species in Sweden. *Environmental Pollution* 5:297–318.

Lodenius, M. and T. Solonen. 2013. The use of feathers of birds of prey as indicators of metal pollution. *Ecotoxicology* 22:1319–1334.

Mora, M., R. Skiles, B. McKinney, M. Paredes, D. Buckler, D. Papoulias, and D. Klein. 2002. Environmental contaminants in prey and tissues of the Peregrine Falcon in the Big Bend region, Texas, U.S.A. *Environmental Pollution* 116:169–176.

Naftz, D., C. Aneroth, T. Kenney, B. Waddell, N. Darnall, S. Silva, C. Perschon, and J. Whitehead. 2008. Anthropogenic influences on the input and biogeochemical cycling of nutrients and mercury in Great Salt Lake, Utah, U.S.A. *Applied Geochemistry* 23:1731–1744.

Peakall, D.B., D.G. Noble, J.E. Elliott, J.D. Somers, and G. Erickson. 1990. Environmental contaminants in Canadian Peregrine Falcons: a toxicological assessment. *Canadian Field-Naturalist* 104:244–254.

Pyle, P. 2008. Identification guide to North American birds, Part II anatidae to alcidae. Slate Creek Press, Point Reyes Station, CA U.S.A.

RIMMER, C.C., K.P. MCFARLAND, D.C. EVERS, E.K. MILLER, Y. AUBRY, D. BUSBY, AND R.J. TAYLOR. 2005. Mercury concentrations in Bicknell's Thrush and other insectivorous passerines in montane forests of northeastern North America. *Ecotoxicology* 14:223–240.

SCHEUHAMMER, A.M., M.W. MEYER, M.B. SANDHEINRICH, AND M.W. MURRAY. 2007. Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio* 36:12–18.

SPALDING, M.G., P.C. FREDERICK, H.C. MCGILL, S.N. BOUTON, L.J. RICHEY, I.M. SCHUMACHER, C.G.M. BLACKMORE, AND J. HARRISON. 2000. Histologic, neurologic, and immunologic effects of methylmercury in captive Great Egrets. *Journal of Wildlife Diseases* 36:423–435.

SPRY, D.J. AND J.G. WIENER. 1991. Metal bioavailability and toxicity to fish in low-alkalinity lakes: a critical review. *Environmental Pollution* 71:243–304.

TCHOUNWOU, P.B., W.K. AYENSUS, N. NINASHVILI, AND D. SUTTON. 2003. Environmental exposure to mercury and its toxicopathologic implications for public health. *Environmental Toxicology* 18:149–175.

THOMPSON, D.R., S. BEARHOP, J.R. SPEAKMAN, AND R.W. FURNESS. 1998. Feathers as a means of monitoring mercury in seabirds: insights from stable isotope analysis. *Environmental Pollution* 101:193–200.

——— AND R.W. FURNESS. 1989. Comparison of the levels of total and organic mercury in seabird feathers. *Marine Pollution Bulletin* 20:577–579.

———, F.M. STEWART, AND R.W. FURNESS. 1990. Using seabirds to monitor mercury in marine environments. *Marine Pollution Bulletin* 21:339–342.

UNITED STATES FISH AND WILDLIFE SERVICE (USFWS). 2003. Monitoring plan for the American Peregrine Falcon, a species recovered under the endangered species act. U.S. Fish and Wildlife Service, Divisions of Endangered Species and Migratory Birds and State Programs, Pacific region, Portland, OR U.S.A.

VEST, J.L., M.R. CONOVER, C. PERSCHON, J. LUFT, AND J.O. HALL. 2009. Trace element concentrations in wintering waterfowl from the Great Salt Lake, Utah. *Archives of Environmental Contamination and Toxicology* 56:302–316.

WHITE, C.M., T.J. CADE, AND J.H. ENDERSON. 2013. Peregrine Falcons of the world. Lynx Edicions, Barcelona, Spain.

WOLFE, M.F., S. SCHWARZBACH, AND R.A. SULAIMAN. 1998. Effects of mercury on wildlife: a comprehensive review. *Environmental Toxicology and Chemistry* 17:146–160.

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Appendix 1. Mean total mercury (Hg) concentrations (μg/g fresh weight) detected in feathers of prey taken by Peregrine Falcons in the Southern Nevada and Lake Mead National Recreation Area, Nevada and Arizona study areas, 2008–2013. Feathers are identified to the lowest possible taxa. Sample size (*n*) refers to the number of individuals analyzed, while the number in parentheses indicates number of individuals with a total Hg concentration below the method detection limit. We report the highest total Hg level when more than one feather was analyzed per individual (54 individuals representing 30 species). Prey is categorized by aquatic bird (AB) and terrestrial bird (TB) types based on general habitat type preferred for foraging and breeding. Prey is sorted into foraging guilds based on each species' primary diet during the breeding season (AH = aquatic herbivore, AI = aquatic invertivore, C = carnivore, F = frugivore, I = insectivore, G = granivore, O = omnivore, P = piscivore).

PREY TYPE	*n*	MEAN (μg/g)	RANGE (μg/g)	BIRD TYPE	FORAGING GUILD
Mallard (*Anas platyrhynchos*)	1	0.36		AB	AH
Blue-winged/Cinnamon Teal (*Anas discors/cyanoptera*)	5	3.55	<0.01–9.92	AB	AH
Green-winged Teal (*Anas crecca*)	1	1.5		AB	AH
Common Goldeneye (*Bucephala clangula*)	1	5.92		AB	AI
Ruddy Duck (*Oxyura jamaicensis*)	5	0.51	0.06–1.12	AB	AI
Gambel's Quail (*Callipepla gambelii*)	2 (1)	0.02	0, 0.02	TB	G
Eared Grebe (*Podiceps nigricollis*)	22	12.27	0.2–30.93	AB	AI
Double-crested Cormorant (*Phalacrocorax auritus*)	2	1.45	1.13, 1.77	AB	P
Green Heron (*Butorides virescens*)	1	2.13		AB	P
White-faced Ibis (*Plegadis chihi*)	4	1.01	0.41–1.56	AB	AI
Virginia Rail (*Rallus limicola*)	1	0.78		AB	AI
Sora (*Porzana carolina*)	1	2.26		AB	AH
American Coot (*Fulica americana*)	7	0.8	0.08–3.23	AB	AH
Killdeer (*Charadrius vociferus*)	1	0.12		AB	AI
Black-necked Stilt (*Himantopus mexicanus*)	6	6.57	0.13–13.8	AB	AI
American Avocet (*Recurvirostra americana*)	3	0.29	0.07–0.55	AB	AI
Yellowlegs spp. (*Tringa melanoleuca/flavipes*)	1	0.01		AB	AI
Whimbrel (*Numenius phaeopus*)	1	1.96		AB	AI
Long-billed Curlew (*Numenius americanus*)	1	0.59		AB	AI
Marbled Godwit (*Limosa fedoa*)	1	0.51		AB	AI
Least Sandpiper (*Calidris minutilla*)	1	0.85		AB	AI
Dowitcher spp. (*Limnodromus scolopaceus/griseus*)	2	0.85	0.25, 1.46	AB	AI
Wilson's Phalarope (*Phalaropus tricolor*)	1	0.89		AB	AI
Red-necked Phalarope (*Phalaropus lobatus*)	2	0.92	0.21, 1.62	AB	AI
Phalarope spp. (*Phalaropus tricolor/lobatus/fulicarius*)	2	9.0	1.52, 16.49	AB	AI
Bonaparte's Gull (*Chroicocephalus philadelphia*)	1	1.26		AB	AI
Franklin's Gull (*Leucophaeus pipixcan*)	2	2.61	1.85, 3.38	AB	AI
Ring-billed Gull (*Larus delawarensis*)	1	0.91		AB	O
Caspian Tern (*Hydroprogne caspia*)	1	7.89		AB	P
Forster's Tern (*Sterna forsteri*)	1	4.68		AB	P
Common/Forster's Tern (*Sterna hirundo/forsteri*)	1	1.38		AB	P
Rock Pigeon (*Columba livia*)	14 (2)	0.16	0–0.96	TB	G
Eurasian Collared-Dove (*Streptopelia decaocto*)	6	0.29	0.02–1.4	TB	G
White-winged Dove (*Zenaida asiatica*)	5	0.07	0.01–0.14	TB	G
Mourning Dove (*Zenaida macroura*)	26 (10)	0.05	0–0.3	TB	G
Lesser Nighthawk (*Chordeiles acutipennis*)	5	0.7	0.36–1.18	TB	I
Common Poorwill (*Phalaenoptilus nuttallii*)	4	0.12	0.02–0.3	TB	I
White-throated Swift (*Aeronautes saxatalis*)	18 (1)	0.43	0–1.19	TB	I
Ladder-backed Woodpecker (*Picoides scalaris*)	1	0.08		TB	I
Northern Flicker (*Colaptes auratus*)	2	0.44	0.41, 0.47	TB	I
American Kestrel (*Falco sparverius*)	10	1.72	0.53–3.37	TB	C
Empidonax flycatcher unid.	1	0.08		TB	I
Say's Phoebe (*Sayornis saya*)	2	0.26	0.1, 0.43	TB	I
Western Kingbird (*Tyrannus verticalis*)	7	0.38	0.05–0.93	TB	I

Appendix 1. continued.

PREY TYPE	*n*	MEAN (μg/g)	RANGE (μg/g)	BIRD TYPE	FORAGING GUILD
Cassin's/Western Kingbird (*Tyrannus vociferans/verticalis*)	2	0.14	0.08, 0.19	TB	I
Loggerhead Shrike (*Lanius ludovicianus*)	8	0.83	0.18–1.54	TB	I
Pinyon Jay (*Gymnorhinus cyanocephalus*)	1	0.17		TB	O
Western Scrub-Jay (*Aphelocoma californica*)	2	0.13	0.12, 0.13	TB	I
Clark's Nutcracker (*Nucifraga columbiana*)	1	0.4		TB	G
Common Raven (*Corvus corax*)	3	3.75	1.41–7.54	TB	O
Horned Lark (*Eremophila alpestris*)	3	0.34	0.07–0.73	TB	G
Tree Swallow (*Tachycineta bicolor*)	3 (1)	1.47	0–3.7	TB	I
Cliff Swallow (*Petrochelidon pyrrhonota*)	6	0.35	0.11–0.6	TB	I
Barn Swallow (*Hirundo rustica*)	1	0.54		TB	I
Bushtit (*Psaltriparus minimus*)	1 (1)	0		TB	I
Cactus Wren (*Campylorhynchus brunneicapillus*)	3	0.68	0.26–0.9	TB	I
Rock Wren (*Salpinctes obsoletus*)	4 (1)	0.64	0–2.19	TB	I
Bewick's Wren (*Thryomanes bewickii*)	1	2.31		TB	I
Canyon Wren (*Catherpes mexicanus*)	1	3.95		TB	I
Western/Mountain Bluebird (*Sialia mexicana/currucoides*)	1	0.55		TB	I
Swainson's Thrush (*Catharus ustulatus*)	1 (1)	0		TB	I
American Robin (*Turdus migratorius*)	1	0.42		TB	I
Northern Mockingbird (*Mimus polyglottos*)	6	0.37	0.14–0.64	TB	I
Crissal/Le Conte's Thrasher (*Toxostoma crissale/lecontei*)	1	0.07		TB	I
European Starling (*Sturnus vulgaris*)	3	0.38	0.05–0.61	TB	G
Cedar Waxwing (*Bombycilla cedrorum*)	1 (1)	0		TB	F
Yellow Warbler (*Setophaga petechia*)	2	2.07	0.35, 3.79	TB	I
Oporornis spp. unid.	1	0.01		TB	I
Wilson's Warbler (*Cardellina pusilla*)	1	0.72		TB	I
MacGillivray's/Wilson's Warbler (*Geothlypis/Cardellina*)	1	0.2		TB	I
Warbler (Parulidae) unid.	1	0.61		TB	I
Green-tailed Towhee (*Pipilo chlorurus*)	1	0.47		TB	I
Abert's Towhee (*Melozone aberti*)	1	1.69		TB	I
Brewer's Sparrow (*Spizella breweri*)	1	0.53		TB	I
Black-throated Sparrow (*Amphispiza bilineata*)	3 (2)	0.09	0–0.28	TB	I
Song Sparrow (*Melospiza melodia*)	1	0.5		TB	I
White-crowned Sparrow (*Zonotrichia leucophrys*)	1	1.33		TB	I
Sparrow (Emberizidae) unid.	1	0.01		TB	G
Western Tanager (*Piranga ludoviciana*)	7 (2)	0.28	0–1.61	TB	I
Black-headed Grosbeak (*Pheucticus melanocephalus*)	1 (1)	0		TB	I
Red-winged Blackbird (*Agelaius phoeniceus*)	5 (1)	6.96	0–34.29	TB	I
Western Meadowlark (*Sturnella neglecta*)	5	0.67	0.02–1.48	TB	I
Yellow-headed Blackbird (*Xanthocephalus xanthocephalus*)	3	0.26	0.24–0.29	TB	I
Brewer's Blackbird (*Euphagus cyanocephalus*)	8	5.54	0.02–23.51	TB	I
Blackbird (Icteridae) unid.	2	0.1	0.1, 0.11	TB	I
Great-tailed Grackle (*Quiscalus mexicanus*)	25 (1)	0.43	0–2.29	TB	O
Brown-headed Cowbird (*Molothrus ater*)	4 (1)	0.59	0–1.01	TB	G
Hooded/Bullock's Oriole (*Icterus cucullatus/bullockii*)	1	0.05		TB	I
Oriole unid. (*Icterus cucullatus/bullockii/parisorum*)	4	0.43	0.28–0.51	TB	I
House Finch (*Carpodacus mexicanus*)	14 (10)	0.17	0–1.34	TB	G
Pine Siskin (*Spinus pinus*)	1	0.23		TB	G
Lesser Goldfinch (*Spinus psaltria*)	1 (1)	0		TB	G
Evening Grosbeak (*Coccothraustes vespertinus*)	1	0.01		TB	G
House Sparrow (*Passer domesticus*)	3 (1)	0.04	0–0.1	TB	G