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RESEARCH ARTICLE

Feasibility of California Condor recovery in northern California, USA: Contaminants in surrogate Turkey Vultures and Common Ravens

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ABSTRACT

Areas of northern California, USA, have been identified as quality habitat for an expanded California Condor (*Gymnogyps californianus*) Recovery Program. Nonetheless, lead poisoning continues to complicate California Condor recovery efforts within their current range and threatens the viability of future propagules. Therefore, background levels of lead and other contaminants should be assessed as part of a feasibility analysis to determine the efficacy of expanding the Recovery Program into northern California. A California-wide ban on the use of lead ammunition for hunting, scheduled to go into effect in 2019, coupled with hunter outreach programs aimed at reducing the use of lead ammunition, may present new opportunities for California Condor recovery in this region. As such, we captured and studied 2 surrogate species, Common Ravens (*Corvus corax*) and Turkey Vultures (*Cathartes aura*), in coastal and near-coastal habitats of northern California to examine relationships between contaminant (lead, mercury, zinc, and copper) exposure relative to distance from the coast (vultures and ravens), age (vultures and ravens), and hunting season (ravens only). Although blood lead concentrations were relatively low throughout our study area for vultures (median $= 5.99\ \mu g\ dL^{-1}$, $n = 137$), median blood lead concentrations of ravens captured during the hunting season ($6.4\ \mu g\ dL^{-1}$, $n = 10$) were almost 6-fold higher than those of birds captured during the nonhunting season ($1.1\ \mu g\ dL^{-1}$, $n = 17$). In addition, for both species, blood concentrations of mercury decreased with increasing distance from the coast, while blood concentrations of lead increased. Given the significant increase in blood lead concentration in ravens during the hunting season, we believe that pervasive exposure to lead demonstrates a risk facing potential propagules of California Condors throughout the species' historical range.

Keywords: ammunition, California Condor, contaminants, *Gymnogyps californianus*, lead, recovery, Turkey Vulture, Common Raven

Factibilidad de Recuperación de *Gymnogyps californianus* en el Norte de California: Contaminantes en *Cathartes aura* y *Corvus corax* como Sustitutos

RESUMEN

Se han identificado áreas en el norte de California como hábitat de calidad para la expansión del Programa de Recuperación del Condor de California. Sin embargo, el envenenamiento con plomo continua complicando los esfuerzos de recuperación de *Gymnogyps californianus* al interior de su rango actual y amenaza la viabilidad de los futuros propágulos. Por ende, se deben evaluar los niveles de base de plomo y otros contaminantes como parte de un análisis de factibilidad para determinar la eficacia de expandir el Programa de Recuperación hacia el norte de California. Una prohibición en toda California del uso de munición con plomo para cazar, programada para entrar en efecto en 2019, junto con programas de extensión para cazadores dirigidos a reducir el uso de munición con plomo, podrían significar nuevas oportunidades para la recuperación de *G. californianus* en esta región. Con este fin, capturamos y estudiamos dos especies sustitutas, *Corvus corax* y *Cathartes aura*, en hábitats costeros y cercanos a la costa del norte de California, para examinar las relaciones entre la exposición a contaminantes (plomo, mercurio, zinc y cobre) con la distancia desde la costa (*C. aura* y *C. corax*), la edad (*C. aura* y *C. corax*) y la estación de caza (solo para *C. corax*). Aunque las concentraciones de plomo en sangre fueron relativamente bajas a través de nuestra área de estudio para *C. aura* (mediana $5.99\ \mu g\ dL^{-1}$, $n = 137$), las concentraciones medianas de plomo en sangre de individuos de *C. corax* capturados durante la estación de caza ($6.4\ \mu g\ dL^{-1}$, $n = 10$) fueron casi seis veces mayores que para las aves capturadas fuera de la estación de caza ($0.9\ \mu g\ dL^{-1}$, $n = 17$). Adicionalmente, las concentraciones de mercurio en sangre para ambas especies disminuyeron con un aumento de la distancia desde la costa mientras que las concentraciones de plomo en sangre aumentaron. Dado el aumento significativo de plomo entre los individuos de *C. corax* durante la estación de caza, creemos que la exposición omnipresente al plomo demuestra los riesgos que enfrentan los potenciales propágulos de *G. californianus* a través del rango histórico de la especie.

Palabas clave: Cathartes aura, Condor de California, contaminantes, *Corvus corax*, *Gymnogyps californianus*, munición, plomo, recuperación

INTRODUCTION

Deleterious effects of lead on wildlife prompted a federal ban on hunting waterfowl with lead pellets in 1991, which aided the subsequent recovery of many waterfowl species in North America (Anderson et al. 2000, Samuel and Bowers 2000). Given the well-documented susceptibility of scavengers and birds of prey to lead contamination (Tranel and Kimmel 2009), it is not surprising that researchers have identified lead exposure, specifically from ammunition sources, as the primary limiting factor preventing the recovery of the federally endangered California Condor (*Gymnogyps californianus*), the largest avian scavenger in North America (Church et al. 2006, Cade 2007, Hunt et al. 2007, Finkelstein et al. 2012, Rideout et al. 2012, Kelly et al. 2014, 2015).

Lead appears to have played a major role in California Condor population declines in the 1980s and has continued to impede contemporary conservation efforts (Snyder and Snyder 2000, Finkelstein et al. 2012). For example, between the years of 1997 and 2010, ~48% of captured free-flying condors in California, USA, exhibited blood lead levels in need of chelation treatment for lead poisoning (lead $\geq$45 μg dL^{-1}; Finkelstein et al. 2012). Furthermore, lead toxicosis was responsible for 26% of juvenile condor deaths and 67% of adult condor deaths between the years of 1992 and 2009 (Rideout et al. 2012). Even at sublethal levels, lead exposure can affect avian health and reproduction (Scheuhammer 1987, Burger and Gochfeld 2000, Dey et al. 2000, Fisher et al. 2006). These statistics were the impetus for a ban on the use of lead ammunition for hunting within the current range of the condor in California in 2008. The ban appears to have been somewhat effective, resulting in a significant decrease in the amount of lead detected in 2 surrogate species, Turkey Vultures (*Cathartes aura*) and Golden Eagles (*Aquila chrysaetos*; Kelly et al. 2011). Despite the reduction of lead used for hunting in the proximity of the contemporary condor range in California, lead poisoning continues to affect wild condors (Kelly et al. 2014). The pervasive threat that lead poses to wildlife ultimately prompted the California Legislature to pass Assembly Bill 711, which prohibits the use of lead ammunition for hunting throughout the state and is scheduled to be fully implemented in 2019 (but see Grima 2015). Recent research has shown that the survivorship of reintroduced condors is positively associated with the proportion of time that birds spend in coastal environments, likely due to birds being less exposed to lead from hunting ammunition in these areas (Bakker et al. 2017). This has spurred interest from condor field managers into manipulating condor foraging behavior to favor coastal areas. While this may reduce lead exposure risk, condors may be exposed to methyl mercury—a highly bioavailable, neurotoxic metal known to affect birds that forage on marine resources (Boening 2000). Mercury is found in some food resources preferred by California Condors, namely marine mammal carcasses (Koford 1953, Wagemann and Muir 1984, Chamberlain et al. 2005, Burnett et al. 2013). Direct condor mortality due to ingestion of copper and/or zinc has not been identified; however, elevated levels of copper and/or zinc have been detected in condors, especially in nestlings that have succumbed to microtrash ingestion (Mee et al. 2007, Rideout et al. 2012). Clarification regarding levels of avian scavenger exposure to these metals remains a priority for condor biologists, especially with regard to geographically specific environmental sources of exposure (Mee et al. 2007, Rideout et al. 2012). While the dangers posed by all of these contaminants are of concern, lead remains the primary factor limiting contemporary condor populations and species recovery (Finkelstein et al. 2012).

To date, there has been no effort to restore California Condors to their former central or northern ranges in northern California and throughout the Pacific Northwest, USA. Geographic, biological, and social factors in coastal and near-coastal northern California suggest that this area may represent an ideal location into which to expand condor recovery. This region is believed to contain potentially high value California Condor habitat because California Condors are known to have occurred in the area well into the last century (Wilbur 1978, Toone and Wallace 1994) and ecological niche models for California Condors applied to the region have identified high quality habitat containing nesting, roosting, and feeding areas (D'Elia et al. 2015). The U.S. Fish and Wildlife Service (USFWS) oversees the recovery of California Condors, a trust species of cultural significance to the Yurok Tribe, and has acknowledged that establishment of a northern California population may ultimately enhance condor viability by serving as a buffer from ongoing and unforeseen threats to southerly populations (Hall 2013, Condor MOU 2014, 2016, USFWS 2014). Due to the cultural significance of the species, the Yurok Tribe initiated efforts to reintroduce condors to the Yurok Ancestral Territory (YAT) in 2003. YAT lies in the center of what was the condor's range at the time of Euro-American contact (Snyder and Snyder 2005, D'Elia and Haig 2013) and may buffer propagules from unsuitable habitat found on the periphery of their historical range. Based on the recognition of YAT as potentially suitable habitat for California Condor reintroduction, a broad group of 16 federal, state, and nongovernmental organizations entered into a formal agreement to assess the possibility of recovering California Condors in the northern portion of their historical range through releases in YAT (Condor MOU 2016).

Regardless of the availability of quality condor habitat in YAT, the threat of lead poisoning could confound future reintroduction efforts, and reduction in condor lead exposure is needed to realize condor recovery goals and range expansion (Finkelstein et al. 2012, Kelly et al. 2015). However, efficacy of the 2019 state-wide ban on lead ammunition for hunting will depend on compliance from California's hunting communities (Epps 2014). Therefore, outreach and education projects such as the Yurok Tribe's Hunters as Stewards Program (and similar efforts by groups such as the Institute for Wildlife Studies, Pinnacles National Park, Ventana Wildlife Society, the Oregon Zoo, and the Peregrine Fund) are critical to help local hunting communities transition to a lead-free future (West 2010).

To identify threats as part of a feasibility analysis targeting California Condor reintroduction into YAT, we collected blood from 2 surrogate species, Turkey Vultures (*Cathartes aura*) and Common Ravens (*Corvus corax*), both of which have been used effectively to demonstrate the availability of lead in the avian scavenger system (Craighead and Bedrosian 2008, Kelly and Johnson 2011, Kelly et al. 2011). Both ravens and vultures represent appropriate surrogates because they are the most common avian scavengers in the study area and readily feed on carrion of concern frequented by condors: gut piles and beached marine mammals (Koford 1953, Burnett et al. 2013). Although it has been suggested that surrogate species may not be useful for toxicological investigations due to differential tolerance to lead ingestion and subsequent poisoning among species (Carpenter et al. 2003), the primary purpose of this study was to measure the presence of contaminants, not their direct effects on scavenger health and fitness. Specifically, our objective was to evaluate baseline levels and spatial patterns of lead, mercury, copper, and zinc in vultures and ravens.

Because California Condors routinely feed on washed-up marine mammal carcasses (Koford 1953, Burnett et al. 2013), and because current research shows a correlation between proximity to the coast and declines in lead-based condor mortality (Bakker et al. 2017), we also examined patterns of contaminant exposure in vultures and ravens as a function of distance from the coast. The deer-hunting season overlaps Turkey Vulture migration in YAT, confounding our ability to identify the location of contaminant exposure in vultures sampled for blood lead levels during this time; therefore, we examined patterns of lead exposure in nonmigratory Common Ravens during 2 time periods: during and outside the deer-hunting season. Our research represents the first feasibility analysis for California Condor reintroduction based on measuring contaminants in surrogate species within the northern portion of the species' historical range in California.

METHODS

Our study area encompassed the greater YAT region of northern coastal California, from approximately Humboldt Bay to the Oregon border (Figure 1). This region is within the historical range of the California Condor and contains high quality nesting, roosting, and foraging habitat when assessed in relation to condor recovery needs (D'Elia et al. 2015, C. J. West personal observation). We captured Turkey Vultures and Common Ravens at 9 sites at varying distances from the coast (Table 1).

Because Turkey Vultures are facultative migrants, sampling them during migratory periods potentially violates the assumption that blood contaminants collected from individuals are representative of exposure in the study area. Thus, we limited the influence of migration by focusing vulture capture efforts during the nonmigratory season (mid-May through mid-August). Unfortunately, by limiting our sampling to the nonmigratory season we were unable to evaluate differences in lead exposure during and outside the hunting season. Conversely, the nonmigratory nature of Common Ravens facilitated an expanded trapping effort from mid-May through mid-October, inclusive of deer-hunting season (mid-September through mid-October), thereby allowing us to measure differences in lead exposure among individual ravens relative to hunting activity. In this study, ravens captured during the hunting season and up to 2 weeks afterward were grouped together due to residual carcasses in the field and lead depuration rates in blood per Kelly et al. (2011). Blood levels indicating exposure to lead point sources beyond background have been inconsistently applied (Fry and Maurer 2003, Craighead and Bedrosian 2008, Kelly and Johnson 2011). Following Kelly and Johnson (2011), we considered blood lead levels ≤ 10 μg dL^{-1} to be baseline or background exposure levels, and levels >10 μg dL^{-1} to be indicative of exposure to a lead point source within the past 2 weeks.

Trapping sites were chosen based on their geographic breadth throughout the study area (Figure 1) and their accessibility and habitat suitability for Turkey Vultures and Common Ravens. Trapping was carried out using a carrion-baited, net-sided, walk-in or drop-in trap (Bub 1991), or via a carrion-baited cannon net (Craighead and Bedrosian 2008). The carrion that we used was locally

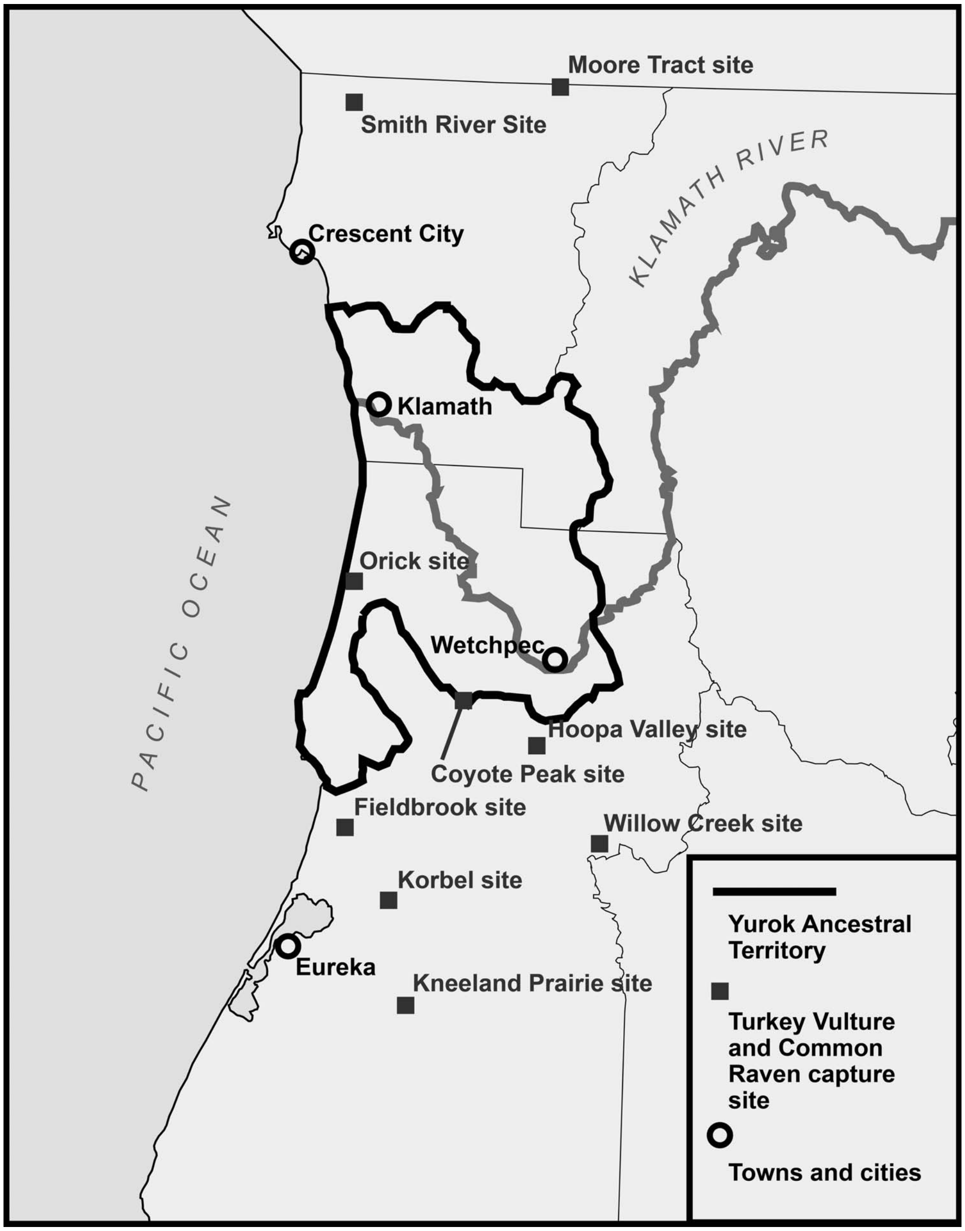

FIGURE 1. Map of the study area in northern California, USA, where Turkey Vultures and Common Ravens, surrogate species for the California Condor, were captured between 2009 and 2013.

sourced roadkill or domestic animals from nearby ranches, which would have been available to the local avian scavenger community under normal circumstances. Upon capture, we determined the age (hatching-year or after-hatching-year) of the bird and collected a blood sample (for detailed descriptions of traps, methodologies, and processing information see Supplemental Material Appendix A). All blood samples were assayed for contaminants at the Diagnostic Center for Population and Animal Health at Michigan State University (Lansing, Michigan, USA) following protocols detailed by Lehner et al. (2013). Negative controls were used to assess potential contamination during sampling and processing via inclusion of one sample of deionized water drawn from an individual autoclaved container per trapping day and processed with that day's blood samples. Minimum detection limits varied per analyte over the course of the study due to changing methodologies within the analyzing laboratory and due to the use of both fresh blood and dried blood spot techniques. For detailed descriptions of laboratory methods see Supplemental Material Appendix A.

TABLE 1. Avian scavenger trap site locations in northern California, USA, month and year of use, and number of each species trapped to determine blood lead level concentrations.

Trap site	UTM zone 10T coordinates	Distance from coast (km)	Month	Year	Turkey Vulture	Common Raven
Coyote Peak	427908E, 4554126N	23	July	2009	2	0
Orick	411697E, 4572843N	3	August	2009	22	8
Kneeland Prairie	419460E, 4507796N	16	July–August	2010	31	4
Hoopa Valley	442332E, 4547550N	31	November	2010	0	8
Fieldbrook	412149E, 4535413N	7	May–June	2011	12	0
Korbel	416962E, 4523521N	14	June–July	2011	15	0
Willow Creek	448402E, 4532632N	43	October	2011	0	1
Hoopa Valley	442332E, 4547550N	31	November	2011	0	1
Smith River	407646E, 4644656N	8	July	2012	24	0
Moore Tract	438735E, 4648415N	39	August	2013	31	5

We formulated a series of linear models to examine spatial patterns of contaminant load among Turkey Vultures and Common Ravens. In total, there were 8 groups of a priori models in which blood contaminants measured in μg dL^{-1} (lead [Pb], copper [Cu], Mercury [Hg], and Zinc [Zn]) in ravens and vultures served as response variables. For values of analytes that fell below minimum detection limits (MDLs), we used the MDL as an estimate in each model. Explanatory variables included bird age (Age) to examine differences in exposure rates due to potential dominance hierarchies at food sources (Wallace and Temple 1983), and distance (km) from the coast (Coast) as a linear covariate (range = 3–43 km). For the Common Raven model in which Pb served as the response variable, we also included the categorical variable Hunt, which indicated whether samples were collected during or outside the hunting season. Candidate models with additive combinations of Age, Coast, and Hunt were evaluated and compared with the null model. We hypothesized that blood lead levels in ravens would be higher during the deer-hunting season than outside this season. We further hypothesized that hunting pressure and lead availability would escalate for both species farther inland (away from the coast) with increased availability of upland habitat. Conversely, known sources of mercury (marine mammal carrion) are more available to our surrogate species along the coast, and we hypothesized that there would be a correlative increase in blood mercury levels with increased proximity to the coast. We examined residual plots for heteroscedasticity to determine whether data transformations were warranted (Zuur et al. 2009) and log-transformed Pb and Hg values for both species before analysis. To test the sensitivity of our results to the inclusion of MDL values, we created a pruned dataset that excluded MDL values and reran the analysis, finding no change in the ranking of top models. Further, we removed a single Pb outlier from the Turkey Vulture dataset (603 μg dL^{-1}). We formulated candidate models, derived associated beta estimates, and evaluated relative support for the models based on Akaike's information criterion corrected for small sample size (AIC_c) in program R (R Core Team 2013).

RESULTS

We sampled a total of 137 Turkey Vultures and 27 Common Ravens between 2009 and 2013. Median Pb concentration for Turkey Vultures outside the deer-hunting season was 6.0 μg dL^{-1} (Figure 2, Table 2), with 33 (24%) of the birds sampled showing elevated blood levels consistent with exposure to lead point sources (>10 μg dL^{-1}; Table 2). Outside the hunting season, no Common Ravens sampled showed elevated lead levels, and median Pb concentrations were lower (1.1 μg dL^{-1}, $n = 17$) than during the hunting season (6.4 μg dL^{-1}, $n = 10$; Figure 3, Table 2), when 1 individual (10%) showed evidence of exposure to lead point sources (Table 2). In general, Turkey Vultures were found to have higher levels of Pb and Hg and similar levels of Cu and Zn relative to Common Ravens (Figures 2 and 3, Table 3).

In our analysis of contaminants relative to bird age and distance from the coast for Turkey Vulture samples, the top model in the candidate set for Pb (Table 4) included Coast, where the amount of Pb in vultures increased with distance from the coast ($\beta = 0.010$, 95% CL = 0.001, 0.019; Supplemental Material Appendix C Figure S1). The second most competitive model for Pb included Age, and older vultures tended to have higher levels of Pb ($\beta = -0.014$, 95% CL = –0.324, 0.296; Supplemental Material Appendix C Figure S5). In the top model for Hg (Table 4), levels of Hg decreased with distance from the coast ($\beta = -0.035$, 95% CL = –0.046, –0.024; Supplemental Material Appendix C Figure S2). The second most competitive model for Hg also included bird age, and young vultures tended to have higher levels of Hg relative to adults ($\beta =$

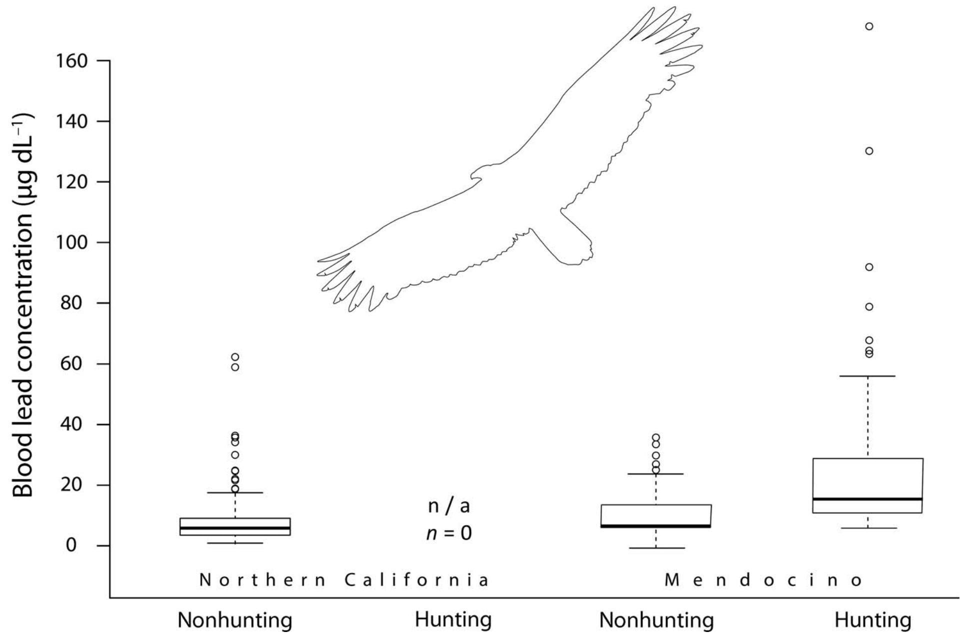

FIGURE 2. Box-and-whisker plot showing outliers (circles), minimum and maximum values (whiskers), inner and outer quartile ranges (boxes), and the median value (heavy bar) of blood lead concentrations of Turkey Vultures captured during the nonhunting season. Data from northern California, USA, were collected during this study; results from Mendocino County, California (Kelly and Johnson 2011, T. R. Kelly personal communication), are shown for comparative purposes.

TABLE 2. Blood lead levels in Turkey Vultures and Common Ravens measured in this study (Humboldt and Del Norte counties, California, USA, 2009–2013) in comparison with values from other studies in the western United States from 2008 to 2015. We report the sample size (*n*), median level (μg dL^{-1}), minimum–maximum values (μg dL^{-1}), standard error (SE), and percentage of individuals with elevated levels (>10 μg dL^{-1}, indicating exposure to lead point sources) relative to the following treatments: OD = outside deer-hunting season; DD = during deer-hunting season; LP = low pig hunting intensity; MP = medium pig hunting intensity; HP = high pig hunting intensity; NP = no pig hunting; PreB = before lead ammunition ban; and PostB = after lead ammunition ban. Values less than the minimum reflect unspecified values below minimum detection limits (MDLs).

Region or county, state [a]	Treatment	*n*	Median	Minimum–maximum	SE	Percentage elevated
Turkey Vulture						
Humboldt & Del Norte, CA	OD, LP [b]	136	6.0	<0.5–62.3	0.8	24
Orange, CA	OD, LP [c]	52	4.0	<6.0–38.0	0.8	13
Mendocino, CA	DD, MP [c]	34	15.0	<6.0–170.0	6.5	76
Mendocino, CA	OD, MP [c]	39	7.0	<6.0–36.0	1.9	36
Monterey, CA	OD, HP, PreB [c]	38	14.0	<6.0–21.0	1.6	61
Monterey, CA	OD, HP, PostB [c]	33	6.0	<6.0–44.0	0.6	9
Common Raven						
Humboldt & Del Norte, CA	DD, LP [b]	10	6.4	1.1–10.8	0.9	10
Humboldt & Del Norte, CA	OD, LP [b]	17	1.1	<0.5–5.1	0.3	0
Greater Yellowstone, WY	DD, NP [d]	145	10.7	4.5–55.5	1.7	55
Greater Yellowstone, WY	OD, NP [d]	159	1.8	0.2–12.1	0.3	2

[a] CA = California; WY = Wyoming.
[b] Data from this study. MDL in whole blood = 0.5 μg dL^{-1} and MDL in dried blood = 1.0 μg dL^{-1}. Six vultures were below MDLs; 3 ravens were below MDLs.
[c] Data from Kelly and Johnson (2011) and T. R. Kelly (personal communication). Twenty-six samples were below MDLs.
[d] Data from Craighead and Bedrosian (2008) and Craighead Beringia South (Kelly, Wyoming, USA). Three samples were below MDLs (differences in sample size and percent of birds elevated from Craighead and Bedrosian (2008) reflect corrections to the original manuscript).

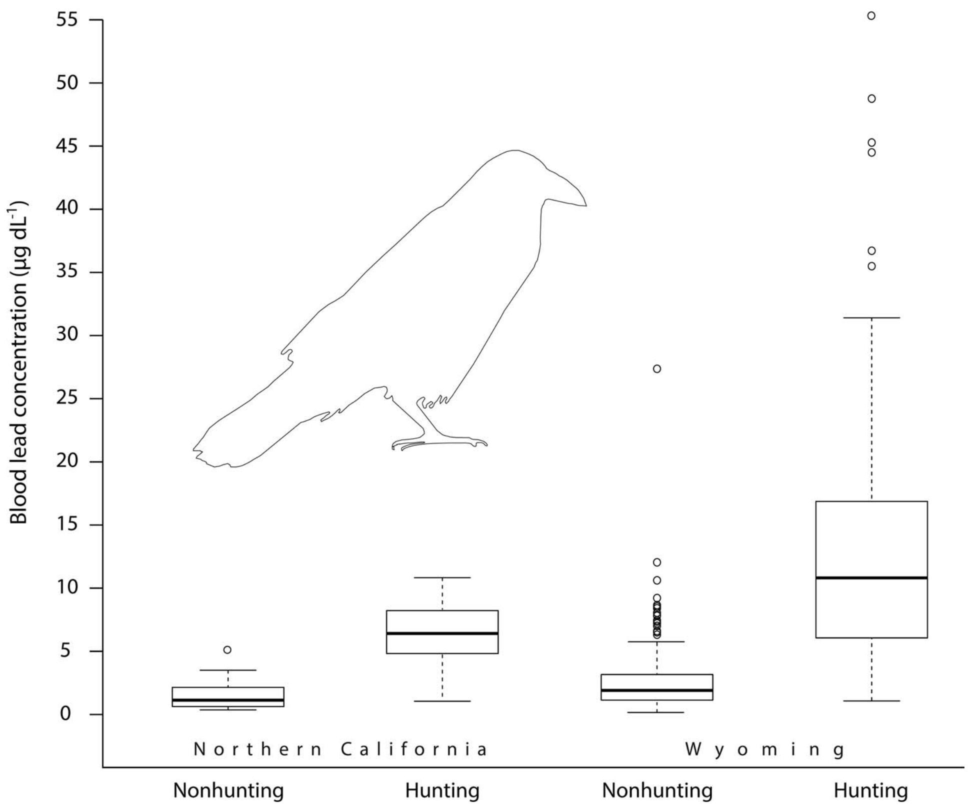

FIGURE 3. Box-and-whisker plot showing outliers (circles), minimum and maximum values (whiskers), inner and outer quartile ranges (boxes), and the median value (heavy bar) of blood lead concentrations of Common Ravens captured during the nonhunting and hunting seasons. Data from northern California, USA, were collected during this study; results from Wyoming, USA (Craighead and Bedrosian 2008, R. Crandall personal communication), are shown for comparative purposes.

0.24, 95% CL = –0.16, 0.63; Supplemental Material Appendix C Figure S6). Distance from the coast was the most competitive model for explaining levels of Zn and Cu in vultures (Supplemental Material Appendix B Table S1); levels decreased away from the coast for Zn (β = –0.44, 95% CL = –0.95, 0.07; Supplemental Material Appendix C Figure S3) and Cu (β = –0.14, 95% CL = –0.21, –0.07; Supplemental Material Appendix C Figure S4). Similarly to Hg, our second most competitive model for Cu suggested that young vultures had higher levels of Cu than adults (β = 1.31, 95% CI = –1.11, 3.73; Supplemental Material Appendix B Table S1)

For Common Ravens, the top model in the candidate set for Pb included the variables Hunt and Coast (Table 5); lead levels increased during the hunting season (β = –0.84, 95% CI = –1.22, –0.46) as well as with distance from the

TABLE 3. Median blood contaminant level (μg dL^{-1}), minimum–maximum values, standard error (SE), sample size (*n*), and number of samples below minimum detection limits (*n* below MDLs) for Turkey Vultures and Common Ravens captured between 2009 and 2013 in northern California, USA. Values less than the minimum reflect unspecified values below minimum detection limits (MDLs).

Contaminant	Median	Minimum–maximum	SE	*n*	*n* below MDLs [a]
Turkey Vulture					
Mercury (Hg)	11.3	<2.0–170.5	2.3	137	13
Copper (Cu)	19.0	10.9–41.0	0.5	126	0
Zinc (Zn)	168.0	92.0–307.0	3.4	126	0
Common Raven					
Mercury (Hg)	4.9	<2.0–50.4	2.3	27	10
Copper (Cu)	17.0	14.0–24.6	0.8	17	0
Zinc (Zn)	145.5	76.7–220.0	10.1	17	0

[a] MDLs for analytes in this study: mercury in whole blood = 2.5 μg dL^{-1}, mercury in dried blood = 2.0 μg dL^{-1}, copper in serum = 2.0 μg dL^{-1}, and zinc in serum = 5.0 μg dL^{-1}.

TABLE 4. Candidate linear models examined to explain levels of lead (Pb) and mercury (Hg) detected in the blood of Turkey Vultures ($n = 137$) and Common Ravens ($n = 27$) in northern California, USA, 2009–2013, including the number of parameters (K), differences in Akaike's information criterion corrected for small sample size (ΔAIC_c), model weights (w_i), and model deviances (Dev). Covariates in models include the age of the bird (Age; adult vs. young) and the distance (km) of the trapping site from the coast (Coast).

		Turkey Vulture						Common Raven		
		Pb			Hg			Hg		
Model	K	ΔAIC_c	w_i	Dev	ΔAIC_c	w_i	Dev	ΔAIC_c	w_i	Dev
Coast	2	0.00 [a]	0.57	62.79	0.00 [b]	0.59	103.19	0.00 [c]	0.84	7.64
Age + Coast	3	2.12	0.20	62.79	0.71	0.41	102.14	3.34	0.16	7.61
Null	1	2.45	0.17	64.94	30.74	0.00	129.65	11.96	0.00	18.94
Age	2	4.50	0.06	64.92	30.99	0.00	129.65	13.19	0.00	18.45

[a] Minimum $AIC_c = 285.96$.
[b] Minimum $AIC_c = 354.65$.
[c] Minimum $AIC_c = 31.77$.

coast (β = 0.015, 95% CI = 0.003, 0.028; Supplemental Material Appendix C Figure S7). To determine whether the relationship between Pb and distance from the coast was sensitive to samples collected during the hunting season, we conducted a post hoc analysis wherein we removed all samples collected during the hunting season and reran the Coast model. Our post hoc analysis found a similar relationship, in which Pb increased with distance from the coast (β = 0.017, 95% CL = 0.006, 0.027; Supplemental Material Appendix C Figure S7). In the top model for Hg (Table 4), similarly to vultures, levels decreased with distance from the coast (β = –0.038, 95% CL = –0.054, –0.022; Supplemental Material Appendix C Figure S8). Model selection procedures for Zn ranked Age as the top model (Supplemental Material Appendix B Table S2); older ravens exhibited higher levels of Zn than young birds (β = –43.02, 95% CL = –82.22, –3.82; Supplemental Material Appendix C Figure S10). The top model for Cu was the null model (Supplemental Material Appendix B Table S2), while the second most competitive model for Cu suggested that levels of Cu decreased with distance from the coast (β = –0.15, 95% CL = –0.34, 0.04; Supplemental Material Appendix C Figure S9).

DISCUSSION

Our study provided several important findings. First, lead was found in higher levels during the hunting season than during the nonhunting season in Common Ravens (Figure 3, Table 2). Specifically, we found that median blood lead concentrations were almost 6-fold higher during the hunting season than outside the hunting season; however, only a single individual raven was captured with levels that indicated significant exposure to point sources of lead. These findings are somewhat concordant with those of a similar study conducted in Wyoming, USA, where blood lead concentrations also were higher during than outside the hunting season, but where a much higher percentage (55%) of ravens captured during the hunting season exhibited elevated blood lead levels (Figure 3; R. Crandall personal communication). Such dramatic increases in lead exposure during the hunting season in a facultative scavenger underscore the specter of lead toxicity for a potential propagule of California Condors released into YAT. Although our research did not attempt to determine the source of lead detected in our target species, ingestion of lead ammunition is the most parsimonious explanation for the observed differences in blood lead levels, and other research has directly linked such seasonal differences in avian scavengers to ingestion of ammunition (Church et al. 2006, Cade 2007, Finkelstein et al. 2010). Increased levels of lead during the hunting season is also consistent with findings of previous studies conducted in Mendocino County, California (~300 km south of our study area), where Turkey Vulture blood lead concentrations increased

TABLE 5. Candidate linear models examined to explain levels of lead (Pb) detected in the blood of Common Ravens ($n = 27$) in northern California, USA, 2009–2013, including number of parameters (K), differences in Akaike's information criterion corrected for small sample size (ΔAIC_c), model weights (w_i), and model deviances (Dev). Covariates in models include the age of the bird (Age; adult vs. young), distance (km) of the trapping site from the coast (Coast), and whether samples were collected during or outside the deer-hunting season (Hunt).

Model	K	ΔAIC_c	w_i	Dev
Hunt + Coast	3	0.00 [a]	0.53	4.08
Age + Hunt + Coast	4	1.21	0.29	3.82
Hunt	2	2.84	0.13	5.03
Age + Hunt	3	4.75	0.05	4.87
Coast	2	12.95	0.00	7.31
Age + Coast	3	15.69	0.00	7.30
Null	1	24.73	0.00	12.43
Age	2	26.69	0.00	12.16

[a] Minimum $AIC_c = 35.44$.

114% during the hunting season compared with the nonhunting season (Figure 2; Kelly and Johnson 2011). Similarly, lead exposure decreased in sampled Turkey Vultures and Golden Eagles only after lead ammunition was banned for hunting in 2008 within the current range of the condor in California (Kelly et al. 2011). These results constitute a scientific consensus that blood lead levels and lead point-source exposure in avian scavengers may be lowered by hunters switching to lead-free ammunition (Craighead and Bedrosian 2008, Kelly and Johnson 2011, Kelly et al. 2011).

The second important finding of our study was that of an inverse relationship between lead and mercury in Turkey Vultures and Common Ravens relative to the distance at which samples were collected from the coast. Mercury levels decreased and lead levels increased with distance from the coast, supporting our hypotheses with regard to avian scavenger contaminant exposure potential and proximity to the coast. Mercury concentrations are known to be much higher in marine systems than in terrestrial systems (Scheuhammer et al. 2007), and scavengers accessing marine resources should consequently experience greater exposure to mercury than scavengers not using these resources. The likelihood of avian scavengers using marine resources should decline farther from the coast, whereas hunting with lead ammunition, the primary source of lead in avian scavengers, increases with distance from the coast, which may explain this inverse relationship. Bakker et al. (2017) found that not only did blood lead levels in California Condors decrease with proximity to the coast, but also that a corresponding increase in condor survival was observed.

The third important finding from our study was that after-hatching-year (older) vultures tended to have higher blood concentrations of lead, but not mercury. For lead, this weak pattern could be explained by dominance hierarchies in which older and presumably more dominant birds may exclude younger, subordinate individuals from scavenging carrion (Marzluff and Heinrich 1991, Kirk and Houston 1995, Donázar et al. 1999). This has been specifically suggested for California Condors, in which dominant individuals may access carcasses earlier than subordinates via openings from wound channels (Hall et al. 2007). Variation in blood mercury levels by age are likely attributable to variations in diet, as blood mercury levels in birds are often variable over time due to depuration of mercury into growing feathers (Thompson et al. 1991, Boening 2000, Ackerman et al. 2011).

Our findings, in association with the results of previous research, stress the importance of understanding the relationship between the use of lead ammunition for hunting activities and heightened exposure of scavengers—including California Condors—to toxicosis. Linking actual deer harvest rates to blood lead levels in scavengers would be a worthwhile future research effort in our study area, although such work would be confounded by unknown levels of depredation, sport shooting of nongame wildlife, and illegal poaching, as well as a lack of spatially explicit harvest data from state agencies. The California-wide ban on using lead ammunition for hunting, scheduled to take effect in 2019, may reduce lead available to avian scavengers, and may contribute to a successful expansion of condor recovery efforts in northern California, where lead levels are already relatively low. Effects of the 2019 lead ban may best be measured in condors directly, via the standard blood-lead-level monitoring procedures that are currently undertaken at all condor release sites and that are planned for implementation as part of a northern California release. However, given the striking increase in lead exposure that we detected during the hunting season in ravens and similar increases detected by other research in Turkey Vultures, we believe that the success of an expanded California Condor Recovery Program cannot rely solely on regulatory processes. Outreach programs, such as the Yurok Tribe's Hunters as Stewards Program, must support the hunting community in the Pacific Northwest in a transition away from lead and toward alternative types of ammunition. Recovery efforts will be confounded if hunters and recreational shooters are not part of the effort to remove toxic lead ammunition from the condor's environment. The 1991 ban on lead ammunition for use in hunting waterfowl is widely hailed as a conservation success (Anderson et al. 2000, Samuel and Bowers 2000), and was brought forth largely by the hunting community in an effort to conserve the wildlife that they care about. Hunters are a part of our modern ecosystem and are critical, as apex predators, to scavengers such as vultures, ravens, and condors in natural settings. Transitioning from lead to nonlead ammunition should help to reduce the deleterious effects of lead on wildlife; ultimately, reducing exposure to lead will not be possible without a sound scientific understanding of routes of exposure, effective and accessible alternative ammunition, and full engagement with the hunting and shooting community (Sieg et al. 2009, Sullivan et al. 2007, Cromie et al. 2015).

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