J. Raptor Res. 46(2):000–000

EXPOSURE OF BALD EAGLES TO LEAD ON THE NORTHERN CHANNEL ISLANDS, CALIFORNIA

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ABSTRACT.—Bald Eagles (*Haliaeetus leucocephalus*) were one of the upper-trophic-level avian predators on the Channel Islands, California, prior to their extirpation by 1960 caused in part by large amounts of DDT discharged into the Southern California Bight. From 2002 to 2006, 61 Bald Eagles were reintroduced onto the northern Channel Islands, as part of a 5-yr feasibility study conducted under the auspices of the Montrose Settlement Restoration Program. In December 2005, a yearling Bald Eagle female was found on Santa Rosa Island with a broken wing and elevated lead levels in her blood of 52.2 ug/dl (0.522 ppm). This incident raised concerns that lead poisoning could be a potential threat to the restoration effort and prompted further investigation. Femurs from five female and two male Bald Eagles reintroduced to the northern Channel Islands were collected postmortem for analyses of lead and other metals. Lead levels detected in femurs of these birds ranged from 0.2 to 55.0 ppm (dry weight). Lead levels in liver were also determined for two of the seven Bald Eagles. Analysis of Bald Eagle movement data from satellite telemetry transmitters suggested that eagles that spent the most time on Santa Rosa Island had the highest lead levels. The results of this study suggested that spent ammunition containing lead found in carrion (offal and entire carcasses) from deer and elk hunting on Santa Rosa Island may have been a primary source of contamination. The on-island hunt program converted to nontoxic bullets in 2007 and ended in late 2011.

KEY WORDS: *Bald Eagle*; Haliaeetus leucocephalus; *California Channel Islands*; *contaminants*; *lead exposure*; *lead ammunition*; *metal*.

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EXPOSICIÓN DE *HALIAEETUS LEUCOCEPHALUS* AL PLOMO EN LAS ISLAS DEL CANAL DEL NORTE, CALIFORNIA

RESUMEN.—*Haliaeetus leucocephalus* fue una de las especies de aves predadoras de más alto nivel trófico en las Islas del Canal, California, previa a su extirpación en 1960 causada en parte por las grandes cantidades de DDT vertidas en la Ensenada Sur de California. Durante el período de 2002 al 2006, 61 individuos de *H. leucocephalus* fueron reintroducidos en las Islas del Canal del Norte como parte de un estudio de factibilidad de cinco años realizado con el auspicio del Programa de Restauración del Acuerdo de Montrose. En Diciembre del 2005, una hembra de *H. leucocephalus* de un año de edad fue encontrada en la Isla de Santa Rosa con un ala rota y con niveles elevados de plomo en sangre de 52.2 ug/dl (0.522 ppm). Este incidente generó la preocupación de que el envenenamiento por plomo podría ser una amenaza potencial para los esfuerzos de restauración y dio lugar a mayores investigaciones. Se colectaron post mortem fémures de cinco hembras y dos machos de *H. leucocephalus* reintroducidos a las Islas del Canal del Norte para análisis de plomo y otros metales. Los niveles de plomo detectados en los fémures de estas aves oscilaron entre 0.2 y 55.0 ppm (peso seco). También se determinaron los niveles de plomo en hígado para dos de los siete individuos colectados. El análisis de los datos de movimiento obtenidos por telemetría satelital sugirió que las águilas que pasaron la mayor cantidad de tiempo en la Isla de Santa Rosa tuvieron los niveles más altos de plomo. Los resultados de este estudio sugieren que las municiones de plomo encontradas en carroña (despojos y cadáveres enteros) de ciervos y alces cazados en la Isla de Santa Rosa pueden haber sido una fuente primaria de contaminación. El programa de caza de la isla se transformó a balas no tóxicas en 2007 y terminó a finales del 2011.

[Traducción del equipo editorial]

Prior to the advent and widespread use of DDT (dichloro-diphenyl-trichloroethane), Bald Eagles (*Haliaeetus leucocephalus*) were an upper-trophic-level avian predator on the Channel Islands (Kiff 1980), an archipelago located between 20–100 km off the southern California coast. High levels of DDE (dichloro-diphenyl-dichlorethylene), a metabolite of DDT, in the southern California marine ecosystem (Burnett 1971, Hom et al.1974) contributed to the extirpation of the Bald Eagle from the Channel Islands by 1960 (Kiff 1980). Prior to their extirpation from the Channel Islands, the last known successful Bald Eagle nests were in 1949 on Anacapa Island (ANI), and 1950 on Santa Rosa Island (SRI; Kiff 1980, M. Daily pers. comm.).

Efforts to restore the Bald Eagle to the Channel Islands began in 1980. A total of 33 Bald Eagles were initially released on Santa Catalina Island from 1980–87 (Garcelon 1988). In 1987, the first breeding attempt failed on Santa Catalina Island due to continued high levels of DDE (Garcelon et al. 1989). Starting in 1989, the population of Bald Eagles on Santa Catalina Island was sustained through an intensive program of artificial incubation of eggs and fostering of nestlings back into the nests (Garcelon 1997). A second restoration effort occurred between 2002–06 during which 61 Bald Eagles were released on Santa Cruz Island (SCI) within Channel Islands National Park (Dooley et al. 2005, Sharpe and Garcelon 2005).

In December 2005, a female Bald Eagle was found on Santa Rosa Island with a broken wing and lead levels in her blood of 52.2 ug/dl (0.522 ppm). This discovery raised concerns that lead poisoning could be a potential threat to the reintroduction effort. Among the most likely sources of lead was spent ammunition found in carrion (offal and entire carcasses) from mule deer (*Odocoileus hemionus*) and elk (*Cervus canadensis*) hunting on SRI. Kaibab mule deer and elk were introduced to SRI in the early 1900s as part of Vail and Vickers Company efforts to provide wild game and hides to their workers (Livingston 2004). Commercial hunting first occurred in the late 1970s as a private game ranch operation. After SRI was sold to the National Park Service (NPS) in 1986, the NPS chose to allow the nonnative deer and elk to remain on the island and managed the hunt operation with a series of Special Use Permits. Most hunting has been guided and occurs from August to December. GPS telemetry revealed that most Bald Eagles spent time on SRI during the fall hunting season and were observed feeding upon deer and elk carcasses and offal piles from hunts (Dooley et al. 2005).

Lead poisoning is known to inhibit activities of enzymes, causing neurological effects (Pattee and Pain 2003). Lead can interfere with heme synthesis and subsequently the formation of hemoglobin and mitochondrial cytochromes. Delta-aminolevulinic acid dehydratase (ALAD) is one of the enzymes involved in heme synthesis that is sensitive to lead and exhibits reduced activity upon exposure in multiple tissues including blood, liver, and brain. Reduced erythrocyte ALAD activity is the most sensitive biochemical response to lead, and if sustained over time, may result in anemia (Eisler 1988, USEPA 2005). Lead inhibition of heme synthesis may also impair the function of liver enzymes involved in metabolism of endogenous compounds and detoxification of xenobiotics. In addition to effects on heme synthesis, lead is known to mimic or inhibit the action of calcium as a regulator of cell function, interfere with calcium deposition and homeostasis in bones, and form lead-protein complexes some of which may impair organ function (most notably in the kidney; ATSDR 2007). The nervous system is the most sensitive to lead's effects on calcium as a cell function regulator, resulting in common clinical signs associated with nerve cell impairments, including gastrointestinal colic and anorexia (ATSDR 2007).

In raptors, lead severely weakens the birds by causing emaciation and muscular paralysis, whereby they are susceptible to other forms of mortality. Clinical signs of lead poisoning most often observed in raptors include lime green feces, paralysis, vomiting, diarrhea, drooping wings, loss of balance, blindness, and epilepiform seizures (Lumeij 1985, Kramer and Redig 1997, Pattee and Pain 2003, Stauber et al. 2010). Other less conspicuous effects of lead toxicity in avian species include poor growth, reduced egg production, and reduced number of offspring (USEPA 2005).

Reintroduction has proven effective to increase and maintain the Channel Islands Bald Eagle population. In 2006, a Bald Eagle nestling successfully hatched in the wild on SCI. This was the first Bald Eagle pair to successfully hatch a nestling without human intervention on the Channel Islands in 50 yr. In 2010, four nests were found on SCI, two on SRI, and seven on Santa Catalina Island. A total of 15 young fledged from 11 nests. Despite the apparent success of reintroductions, Channel Island Bald Eagles continue to be affected by DDE contamination (Sharpe and Garcelon 2005). The exposure of Bald Eagles to lead (and potentially other metals) is also a concern for this reintroduction effort.

Study Area

SCI, SRI, San Miguel (SMI), and ANI Islands are within southern California's Channel Island archipelago and are considered the northern Channel Islands (NCI; Fig. 1). The Channel Islands are at the confluence of the California and north equatorial ocean currents, which create considerable niches for marine and terrestrial biological diversity. The native vegetation communities of the NCI are shrublands and woodlands characteristic of a coastal Mediterranean ecosystem (Wallace 1985, Moody 2000). Introduction of nonnative herbivores in the mid-1800s resulted in loss of vegetative cover and conversion to nonnative grasslands. The climate is Mediterranean, with temperatures ranging from 11.7–20.9°C and mean annual rainfall of 50 cm (Junak et al. 1995). Bald Eagle foraging habitat is both coastal and inland. The habitat used by Bald Eagles on the NCI is protected by the NPS and The Nature Conservancy within the Channel Islands National Park (Fig. 1).

Methods

From 2002–06, 61 juvenile Bald Eagles (40 male, 21 female) were released on SCI from hacking towers. Of those 61 eagles, 34 were hatched at the San Francisco Zoo, California, 23 were hatched in the wild in Tongass National Forest, Alaska, and 4 were from California wildlife rehabilitation centers. These birds were relocated to hacking towers on SCI and released around 12 wk of age (Garcelon 1988, Dooley et al. 2005). Each Bald Eagle was banded and fitted with a 70-g backpack-mounted Argos/GPS solar-powered PTT (Microwave Telemetry, Inc., Columbia, Maryland, U.S.A.) with an attached 23-g VHF transmitter (Advanced Telemetry Systems, Isanti, Minnesota, U.S.A.). The PTTs were capable of obtaining and storing hourly locations, which were uploaded to a satellite every third day. Global Positioning System (GPS) data were entered into Arcview (Environmental Systems Research Institute, Redlands, California, U.S.A.), and we estimated the proportion of time each eagle spent on each island by dividing the number of points on an island by the total number of points received for each bird.

The carcasses of the five female and two male Bald Eagles used in this study were recovered on SCI, SRI, and the southern California mainland. The carcasses were at various stages of decomposition at collection. Although the GPS data indicated when an eagle does not move more than 50 m/d, biologists are not always able to recover the bird immediately for several reasons. First, the GPS data is uploaded to satellites every 3 d, creating a lag time for recovery of the carcass. Second, logistical challenges on the remote Channel Islands often prevented timely collection of carcasses due to weather, transportation, etc. For the seven eagles that were used in this study, three were recovered dead after floating for multiple days in the ocean; one was

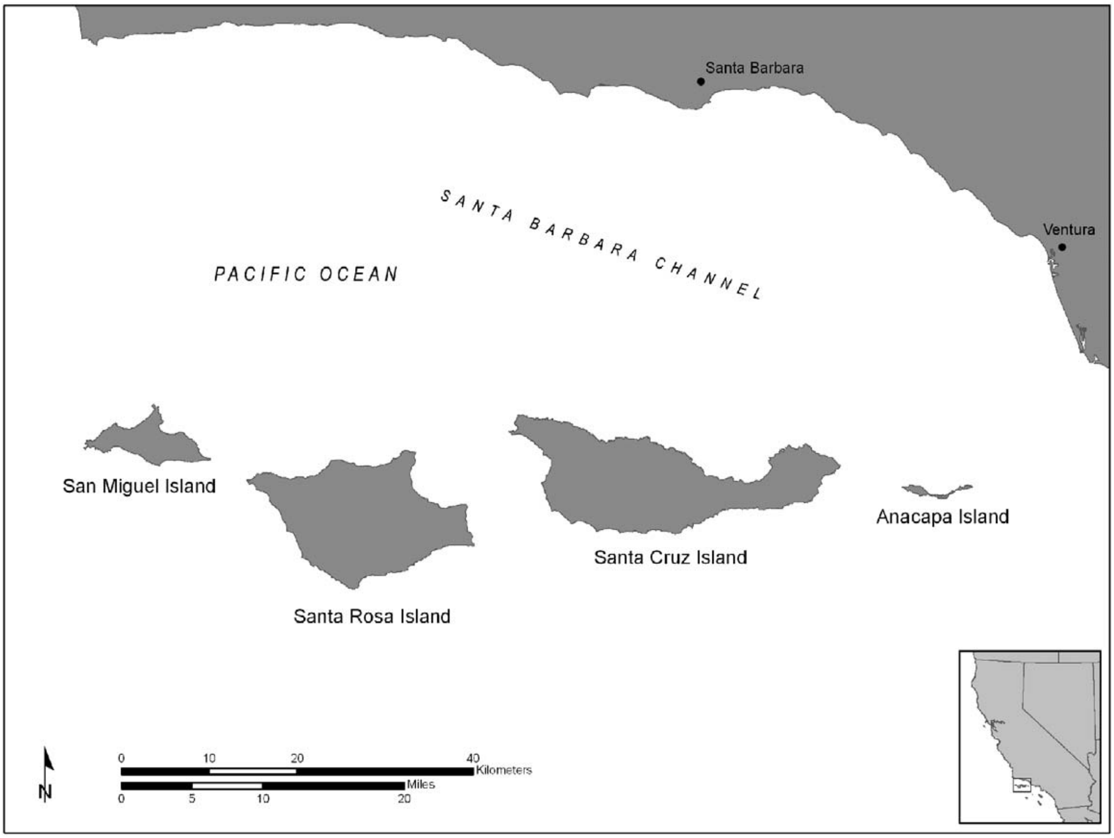

Figure 1. Map of the Northern Channel Islands with inset of California, U.S.A.

found dead in a tree on SRI several months after the transmitter indicated the bird was not moving and was likely dead; two were found on different beaches on SCI at least 3 d after the GPS data indicated the bird was not moving; and one was recovered in a creek on SRI several weeks after the GPS data indicated the bird was not moving. Each eagle carcass was frozen after collection. Only two eagles (A-42 and A-50) were in sufficient condition to conduct necropsies and collect soft tissue for analysis. Toxicological analyses for lead were conducted on liver samples from A-42 and A-50. Approximately 13 to 28 g of femur bone was collected from each of the seven eagles and placed in whirl-packs for contaminant analysis.

Bone samples were homogenized, freeze-dried, and analyzed by Laboratory and Environmental Testing, Inc. (Columbia, Missouri, U.S.A.). Percent moisture was determined during the freeze-dry step. Lead levels were quantified using microwave digestion/graphite furnace atomic absorption. Arsenic and selenium levels were quantified using magnesium dry ash/hydride generation atomic absorption. Mercury levels were quantified using microwave digestion (extraction) and cold vapor atomic absorption. Aluminum, boron, barium, beryllium, cadmium, chromium, copper, iron, magnesium, manganese, molybdenum, nickel, strontium, vanadium, and zinc levels were quantified using microwave digestion, followed by inductively coupled plasma spectrometry. Results were reported in parts per million (ppm) wet weight and ppm dry weight (d.w.).

RESULTS

The Bald Eagles in this study (five female, two male) ranged in age from 4 to 28 mo (Table 1). All eagles reported here were released to the wild via hacking (Dooley et al. 2005) and subsequently died between 15 September 2002 and 29 July 2006. Lead was found in the long bones of all seven of the eagles examined; however, the highest concentrations (31 and 55 ppm d.w.) were found in the oldest Bald Eagles that spent the most time on SRI (A-14,

Table 1. Use of the northern Channel Islands by Bald Eagles based upon the percentage of GPS data points received. A-35 was found alive with a broken wing and subclinical lead exposure. All other birds were found dead.

Bird	Sex and Source[c]	# GPS Locations	Dates (Release-Death/Injury)	Locations on Individual Islands: Anacapa % Locations	SantaCruz % Locations	Santa Rosa % Locations	San Miguel % Locations
A-09	F, AK	36	9 April 2002–22 September 2002	19.44	80.56	.	.
A-14	F, AK	4001	23 August 2003–4 October 2004	.	75.43	24.57	.
A-15	M, Zoo	480	25 July 2003–6 September 2003	53.96	46.04	.	.
A-18	F, AK	4955	24 August 2003–30 August 2005	.	32.17	67.83	
A-41[a]	M, AK	1489	12 July 2005–4 October 2005	.	100	.	.
A-42	F, Zoo	3115	12 July 2005–18 February 2006	15.05	23.02	61.45	0.48
A-50	F, Zoo	527	25 June 2006–31 July 2006	.	100	.	.
A-35[b]	F, Zoo	2465	2 July 2005–19 December 2005	.	26.69	73.31	.

[a] Bird was held in captivity for a year to recover from avian pox.
[b] Bird was recovered alive with a broken wing and lead exposure.
[c] Birds collected from nests near Juneau, Alaska (AK) or from captive breeding birds at the San Francisco Zoo (Zoo).

A-18, A-42; Table 1, 2, Fig. 2). Other metal contaminants were also assayed in the event that data may be useful for other studies (Table 1).

Of the seven Bald Eagles used in this study, only A-42 and A-50 were determined to be suitable for necropsy and soft tissue analysis. Necropsy results of A-42 indicated drowning as the suspected cause of death. For A-50, the cause of death could not be determined due to advanced decomposition. The lead liver value for A-42 was 0.67 ppm wet weight, which indicated that the bird had been exposed to lead. According to Franson and Pain (2011), lead concentrations in liver <2 ppm wet weight are considered background, while concentrations between 2–<6 ppm wet weight are thresholds for subclinical effects. For A-50, a bird that did not spend any time on SRI, the lead liver value was below 0.50 ppm wet weight. Each bird reported here had between 36 and 4955 GPS positions (Table 1), which described movements of the birds over the 2–28 mo following release, until their post-mortem recovery.

DISCUSSION

In maritime ecosystems, such as the Channel Islands, Bald Eagles are avian predators of fish, seabirds, and other taxa, and are also known for their scavenging behavior (Anthony et al. 1999, Collins et al. 2005, Dooley et al. 2005). This presents a broad variety of potential sources from which contaminants could contribute to body burden of resident eagles.

Metals can cause morbidity and fatality of individuals and populations of eagles (Falandysz et al. 2001, Kenntner et al. 2001, Stauber et al. 2010). Bald Eagles reported in this study were exposed to a wide variety of metals, but only lead was found at found at concentrations associated with potential adverse effects. Bald Eagle lead exposure in this study was associated with individual age and time spent on SRI (Table 2). Lead ammunition left in carcasses and offal was likely the main source of lead in Bald Eagles within this sample. The small amount of lead found in eagles that did not go to SRI could have been acquired from birds, fish, or from dead marine mammals. There may have been movement of lead from SRI through the food chain as corvids and gulls fed on deer and elk carcasses and then moved among the NCI.

Lead has been amply documented to negatively affect wildlife, including raptors (Lumeij 1985, Franson 1996, Kramer and Redig 1997, Wayland et al. 1999, Pattee and Pain 2003, Wayland et al. 2003, Fisher et al. 2006, Cade 2007, Pain et al. 2007, Gangoso et al. 2009, Stauber et al. 2010). Pattee et al. (1981) experimentally dosed Bald Eagles with lead shot and found bone lead levels (femur) above 7.8 ppm d.w.

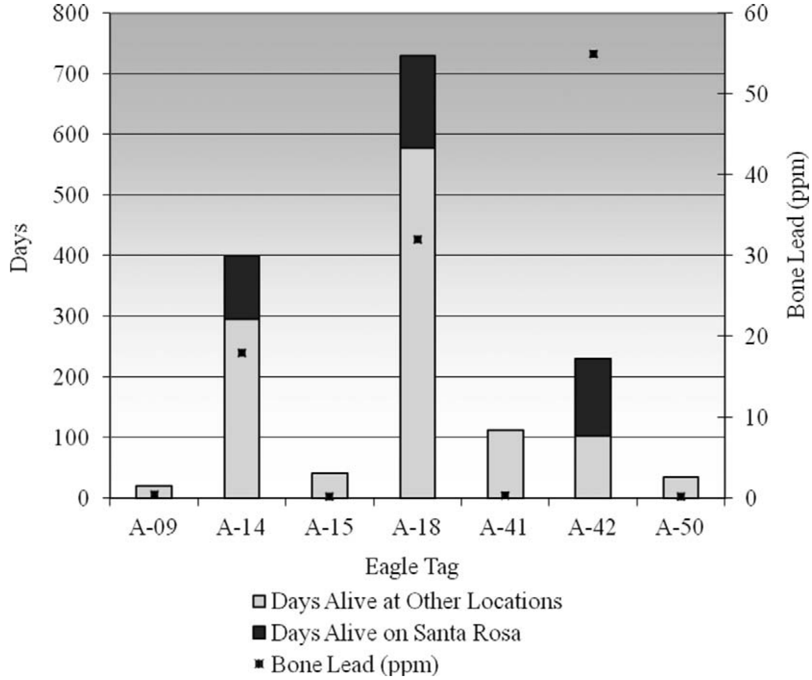

Figure 2. Bone lead analysis relative to Bald Eagle lifespan from the northern Channel Islands, California: 2002–06.

may be associated with mortality. Kramer and Redig (1997) conducted a retrospective study of 654 Bald and Golden eagles (*Aquila chrysaetos*) admitted to rehabilitation centers during a 16-yr period and found 138 cases of lead poisoning. Eagles with blood lead concentrations between 0.2–0.6 ppm were classified as having subclinical lead exposure and birds with concentrations between 0.61–1.2 ppm were classified as having clinical lead poisoning. The lead concentration in A-35 found on Santa Rosa Island was 0.522 ppm, which was indicative of lead exposure. According to Redig (1979), subclinical lead poisoning may weaken raptors and leave them unable to hunt or more susceptible to mortality from vehicles, power lines, steel traps, etc. Kramer and Redig (1997) determined that despite the 1987 Minnesota and 1991 federal lead ammunition ban for waterfowl, lead toxicity of eagles persisted at comparable pre-ban levels due to the eagles' reliance on other animals hunted with lead ammunition. They posited that an additional potential lead source may be ''deer offal containing lead fragments that are left in the field after evisceration by hunters'' (Kramer and Redig 1997).

Offal and non-recovered animal carcasses associated with hunting have been attributed to increasing the body burden of lead in raptors (Bloom et al. 1989, Fisher et al. 2006). Hunt et al. (2006) empirically showed friable lead fragments in a high percentage of deer carcasses and offal piles (94% and 90%, respectively) that were killed during periods of licensed sport hunting. Bloom et al. (1989) noted high levels of lead in Golden Eagles within the range of California Condors (*Gymnogyps californianus*) and suggested morbidity effects on this species via carcass scavenging. Cade (2007) synopsized the evidence of lead ammunition as a primary cause of mortality of free-flying California Condors in California and Arizona which, when not fed stillborn calves and other lead-free carrion by wildlife managers, feed on offal piles and hunter-killed game.

Concentrations of metals other than lead in Bald Eagle bones used in this study were comparable to or slightly higher than those measured in bones of seabirds (Kim et al. 1998, Nam et al. 2005), waterfowl (Taggart et al. 2009), and passerines (Deng et al. 2008). The concentrations reported in Table 2 appeared to be low; however, toxicological assessments cannot be made based on their concentration in bone.

Lead ammunition is no longer used on any of the NCI, but was used by hunters between 2002 and 2006 on SRI during the fall deer and elk hunting seasons and was thus available to eagles in carcass remains. Nontoxic ammunition was used during the feral pig

Table 2. Metal levels in ppm (wet weight and dry weight) found in Bald Eagle femurs from the Channel Islands, California, 2002–06.

Heavy Metal	Eagle ID (Age of Death) A-50 (4 mo.)		A-09 (4 mo.)		A-15 (6 mo.)		A-41 (8 mo.)		A-14 (18 mo.)		A-42 (22 mo.)		A-18 (28 mo.)	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Al	25.0	39.8	115.0	228.63	184.0	370.97	13.0	19.91	12.0	13.7	7.0	15.42	35.0	54.77
As	<0.10	<0.16	<0.10	<0.20	0.20	0.40	<0.10	<0.15	<0.20	<0.23	<0.09	<0.20	<0.10	<0.16
B	2.0	3.19	3.0	5.96	3.2	6.45	<1.0	<1.53	<2.0	<2.28	2.0	4.41	<1.0	<1.56
Ba	1.6	2.55	3.0	5.96	12.3	24.80	2.2	3.37	8.1	9.25	3.2	7.05	6.3	9.86
Be	<0.06	<0.10	<0.05	<0.10	<0.05	<0.10	<0.07	<0.11	<0.09	<0.10	<0.05	<0.11	<0.06	<0.09
Cd	<0.06	<0.10	<0.05	<0.10	<0.05	<0.10	<0.07	<0.11	<0.09	<0.10	<0.05	<0.11	<0.06	<0.09
Cr	<0.3	<0.48	0.8	<1.59	3.1	6.25	0.4	0.61	0.5	0.57	0.4	0.88	1.0	1.56
Cu	0.62	0.48	0.60	1.19	0.77	1.55	0.93	1.42	0.80	0.91	0.80	1.76	0.67	1.05
Fe	30.0	47.85	99.0	196.82	245.0	493.95	17.0	26.03	44.0	50.23	26.0	57.27	41.0	64.16
Hg	0.09	0.14	<0.05	<0.10	<0.05	<0.10	0.68	1.04	0.1	0.11	0.10	0.22	0.08	0.13
Mg	2470.0	3939.39	2050.0	4075.55	1410.0	2842.74	2160.0	3307.81	3120.0	3561.64	1360.0	2995.59	2120.0	3317.68
Mn	2.3	3.67	5.4	10.74	6.3	12.70	1.9	2.91	4.8	5.48	1.6	3.52	3.9	6.10
Mo	<1.0	<1.59	<1.0	<1.99	<1.0	<2.02	<1.0	<1.53	<2.0	<2.28	<0.9	<1.98	<1.0	<1.56
Ni	0.4	0.64	0.6	1.19	1.6	3.23	0.5	0.77	0.6	0.68	0.5	1.10	0.7	1.10
Pb	<0.10	<0.16	0.2	0.40	<0.1	<0.20	0.2	0.31	16.0	18.26	25.0	55.07	20.0	31.30
Se	<0.10	<0.16	0.1	0.20	0.1	0.20	0.1	0.15	0.3	0.34	0.1	0.22	<0.10	<0.16
Sr	116.0	185.01	211.0	419.48	26.8	54.03	196.0	300.15	236.0	269.41	26.2	57.71	152.0	237.87
V	0.40	0.64	0.50	0.99	0.87	1.75	0.70	1.07	1.40	1.60	0.40	0.88	0.95	1.49
Zn	130.0	207.34	106.0	210.74	73.1	147.38	93.3	142.88	179.0	204.34	98.8	217.62	170.0	266.05

[a] Percent moisture values were 37.3 (A-50), 49.7 (A-09), 50.4 (A-15), 34.7 (A-41), 12.4 (A-14), 54.6 (A-42), and 36.1 (A-18).

eradication program on SCI in 2005, thus eliminating that effort as a potential source of lead. Our small sample size revealed that Bald Eagles exposed to carcasses where lead ammunition had been used can accumulate considerable body burdens of lead.

Metal contaminants are additive to the preeminent cause of depressed eagle productivity on the Channel Islands, i.e., DDT/DDE (Garcelon et al. 1989, Sharpe and Garcelon 2005). Hunting does not occur on any of the other NCI. No known natural sources of lead exist on any of the islands, nor are we aware of historic lead sources (such as expended military ammunition, or lead-acid battery dumping), which may have leached into water sources or presented a delivery route into eagle prey. Further, during the time of this study (2002–06), there was no program in place to cause hunters to remove or bury lead contaminated offal from kills. Following the collection of the dead eagles for this study, Vail and Vickers Company on SRI imposed a requirement for lead-free ammunition for all guided hunts starting in 2007.

Further testing of eagles may be necessary to determine whether the recent ban on lead bullets on SRI has been effective in reducing the eagle lead levels. Although the sample size of this study was small, we documented the exposure of Bald Eagles to lead on the northern Channel Islands. Elevated levels of lead were found in the femurs of three Bald Eagles that spent time on SRI, and one eagle (A-35) had elevated lead levels in her blood after being recovered alive with a broken wing on SRI. These data suggested that the use of lead ammunition for hunting of deer and elk on Santa Rosa Island may have resulted in or contributed to elevated lead concentrations in the resident eagles.

ACKNOWLEDGMENTS

We appreciate the support given to Bald Eagle restoration by the Montrose Settlements Restoration Program, Channel Islands National Park, The Nature Conservancy, U.S. Fish and Wildlife Service, and the Ventura County Office of Education. D. Rempel and J. Dooley were helpful in collecting samples in the field. K. Zeeman, J. Gibson, E. Luciani, S. Sobiech, B. Bridges, G. Wallace, R. Nagel, and T. McKinney assisted with review and collecting background material for this study. We also thank J. Linthicum and P.H. Bloom for their informal review of earlier drafts of this manuscript. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

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Received 3 March 2011; accepted 21 September 2011