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PRODUCTIVITY, DIETS, AND ENVIRONMENTAL CONTAMINANTS IN NESTING BALD EAGLES FROM THE ALEUTIAN ARCHIPELAGO

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Abstract—We studied productivity, diets, and environmental contaminants in nesting bald eagles from the western Aleutian Islands, Alaska, USA, during the summers of 1993 and 1994. Productivity on Adak, Tanaga, and Amchitka Islands ranged from 0.88 to 1.24 young produced per occupied site and was comparable to that of healthy populations in the lower 48 United States. However, productivity on Kiska Island was depressed, averaging 0.67 young per occupied site. The lower reproductive success on Kiska was associated with elevated levels of dichlorodiphenyldichloroethylene and other organochlorine pesticides. Many of the organochlorine pesticides were elevated in bald eagle eggs from the four islands, but concentrations of these contaminants and Hg were significantly higher in eggs from Kiska Island than in eggs from the other islands. In contrast, polychlorinated biphenyl concentrations were higher in eggs from Adak, Amchitka, and Kiska (where military facilities have been installed) than in those from Tanaga (which has had little military activity). The most likely source of these contaminants in bald eagles was from their diets, which were variable spatially and temporally. Fish made up most (56%) of the eagles' diet on Adak and Tanaga Islands, followed by birds (25%) and mammals (19%). In contrast, birds comprised the majority (60%) of bald eagle diets on Amchitka and Kiska Islands, followed by mammals (30%) and fish (10%). The high proportion of seabirds in the diet of eagles from Kiska Island could be the major source of organochlorine and Hg contamination. Elevated concentrations of organochlorines in bald eagle eggs from the Aleutian Archipelago was surprising, because of the distance to agricultural areas. The results indicate that these contaminants can be transported long distances and affect wildlife populations in remote and pristine areas. We also discuss potential sources and transport mechanisms of these contaminants to the Aleutian Islands.

Keywords—Aleutian Islands Bald eagle Contaminants Diets Productivity

INTRODUCTION

Most regions of the earth are susceptible to deposition of volatile contaminants, such as certain organic insecticides or inorganic metals. Toxic residues originating from agricultural and industrial activities are transported long distances by the atmosphere and sea and deposited into polar regions through global distillation [1–3]. However, Simonich and Hites [4] concluded that some less volatile compounds, such as DDT, are not elevated in the polar regions by global transport, and their presence in these remote environments may result more from local deposition or discharge. Other toxic elements in the Arctic are believed to originate from natural weathering or volcanic deposition, but recent studies on global transport of volatile elements, particularly Hg, also indicate anthropogenic sources. For example, elevated levels of dichlorodiphenyldichloroethylene (DDE) and polychlorinated biphenyls (PCBs) recently have been found in sea otters (*Enhydra lutris*) and bald eagles (*Haliaeetus leucocephalus*) at Adak Island, located in the central Aleutian Islands, Alaska, USA [5]. These contaminants may have entered the food chain from local point sources on Adak Island and/or more distant sources.

Birds of prey, including bald eagles, peregrine falcons (*Falco peregrinus*), and ospreys (*Pandion haliaeetus*), have been the focus of studies on the effects of organochlorines for the last three decades. These species have been used as indicators of contamination because they feed at the top of the food chain, are sensitive to organic insecticides, and bioaccumulate these contaminants. Several studies have documented the negative relationship between productivity of bald eagles and environmental contaminants in North America [6–8]. Specifically, certain organochlorine pesticides, especially DDE (a metabolite of DDT), cause lower reproductive success of bald eagles by interfering with eggshell formation [8]. In response to the increased use of DDT as an insecticide, bald eagle populations declined substantially from 1950 to 1970 and remained depressed until the mid-1970s, when use of DDT was banned in the United States. Declines in most populations of bald eagles led to the species being listed as threatened or endangered in the contiguous United States. Many of the declines were attributed to environmental contaminants, either by circumstantial evidence or by presence of contaminant residues in eggs [8–11]. Since DDT was banned, the distribution and abundance of bald eagles have increased throughout most of the contiguous United States. However, DDE and PCBs are persistent in the environment and have been reported to affect reproductive success of localized populations as late as the 1980s [6,8].

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The western Aleutian Islands comprise the western extent of the breeding range of bald eagles, and there are substantial breeding populations on many of the larger islands [V. Byrd and J. Williams, unpublished report]. Because of the inaccessibility of the Aleutian Islands, surveys of breeding populations have been sporadic in space and time, and there are few published articles on the species from this vast area. Murie [12,13] provided the first detailed accounts of diets and general abundance of bald eagles in the Aleutian Islands. Sherrod et al. [14] described their natural history on Amchitka Island, and Hehnke [15] reported on their nesting ecology and foraging behavior on the Alaskan Peninsula. Because the Aleutian Islands are extremely remote from industrial or agricultural activity, we predicted that the likelihood of exposure from these sources would be low and that bald eagles in this region would be relatively free of contaminants. The possible exception to this prediction is PCBs, which are known to be global in their transport and distribution. Therefore, we hypothesized that this population would be devoid of organochlorine pesticides while containing elevated levels of PCBs. If this prediction were true, we would have the opportunity to evaluate the potential effects of PCBs alone on productivity of bald eagles. At present, this has not been possible because concentrations of PCBs and DDE have been positively correlated in eggs [6,8], so the effects of each contaminant could not be assessed separately. In addition, we were aware that intensive military activities on some of the islands may have been the source of contaminants, so we were interested in comparing contaminant levels from those islands to islands with no history of military occupation. We report bald eagle productivity, diets, and contaminant concentrations in eggs. Our overall goal was to determine whether diet varied among islands, whether contaminants varied with diet, and whether reproductive success was associated with contaminant concentrations.

STUDY AREA

The Aleutian Archipelago, which defines the border between the North Pacific Ocean and Bering Sea, comprises numerous islands stretching between North America and Asia. Temperatures are moderated by the oceanic environment such that summers are cool and winters are mild. The terrestrial environment supports a subarctic maritime tundra ecosystem lacking woody vegetation, except for dwarf willow (*Salix* spp.). Most organic production in this region is from the sea, which is reflected by a generally depauperate terrestrial biota but an abundance of marine fishes, birds, and mammals. Many terrestrial consumers, including bald eagles, obtain most of their food from the marine environment.

The Aleutians have been of strategic importance to the U.S. military since World War II. Military outposts were subsequently established at several islands, including Attu (a small U.S. Coast Guard Loran Station where combat between U.S. and Japanese forces occurred), Shemya (U.S. Air Force Base), Amchitka (the staging areas for the planned invasion of Japan and later an underground nuclear test site), Adak (U.S. Navy Base), and Kiska (occupied by Japanese forces). A more detailed account of this region is provided by Merritt and Fuller [16].

METHODS

We studied bald eagles on Adak, Tanaga, Amchitka, and Kiska Islands (Fig. 1) from May to July of 1993 and 1994 via the research vessel *Alpha Helix.* We determined productivity at 181 nesting sites, collected prey remains from 109 productive nests, and collected 25 unhatched eggs and one dead nestling for contaminant analyses.

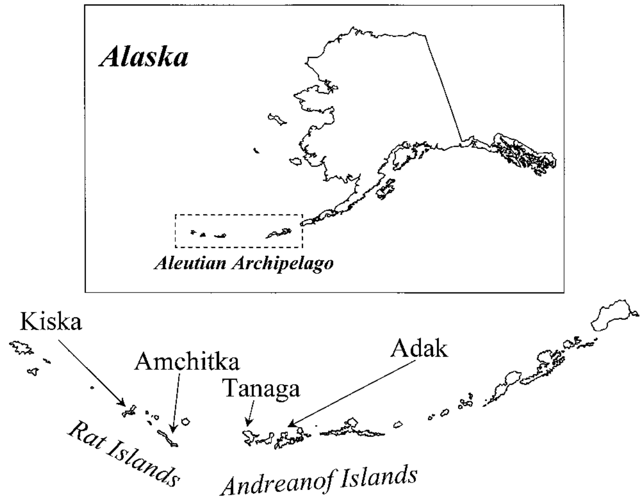

Fig. 1. Study area in the western Aleutian Islands, Alaska, USA.

Diets

Diets were determined from 128 prey remains collected from nests on Adak (45 nests), 96 prey from Tanaga (18 nests), 132 prey from Amchitka (28 nests), and 116 prey from Kiska (17 nests). Avian food items were identified by comparison with museum specimens at the Aleutian Maritime National Wildlife Refuge, Adak, Alaska, USA; fish were identified using Kessler's [17] guide. Mammalian pelts and fur were identified by visual inspection because only sea otters and Norway rats (*Rattus norwegicus*) occurred in the diet. The minimum number of individuals in any nest was determined by the greatest number of identical bones or feathers per taxon [18]. Data were summarized by island, year, and taxon for comparison among years and islands.

Productivity

We determined productivity of 69 nest sites on Adak, 30 on Tanaga, 39 on Amchitka, and 43 on Kiska Islands during the 2 years. Productivity was determined by surveying the shorelines by small boats during the nestling phase of the breeding season. On these surveys, we recorded the number of breeding pairs, successful (with live young) and unsuccessful (no living young observed) nests, number of young in successful nests, single adults, and subadults. Because of the inaccessibility of the area, we could not survey the breeding populations twice per year as is done in most surveys of productivity [19]. However, the Aleutian Islands are virtually treeless, so the open terrain and the species' close association with water allowed us to easily count the number of unsuccessful pairs and estimate breeding success and productivity (number of young produced per pair). Unsuccessful pairs were identified as two adults in proximity (<500 m) to a nest that did not contain live young in the year surveyed. Terminology used to describe nesting success and productivity follows that of Postupalsky [20]. Adult bald eagles were identified by their white head and tail feathers; subadults lacked these features.

Contaminant samples and analyses

Twenty-five unhatched but intact eggs and one dead nestling were collected from nests in 1993 and 1994. Eggs were wrapped in clean aluminum foil and refrigerated until processed. Egg volume and shell thickness measurements followed the methods of Krantz et al. [10] and Stickel [21]. We measured eggshell thickness (shell and membrane) at four locations at approximately the equator of each egg. A mean was computed from these measurements and compared with the mean eggshell thickness (0.6088 mm) of bald eagle eggs before the use of DDT in 1946 [22]. The amount of eggshell thinning was computed as the difference (%) between mean thickness of each egg and mean thickness before 1946.

Organochlorines. Each egg was excised along the equator, and the liquid contents were extracted, sealed in a chemically cleaned jar, and frozen. All eggs were analyzed for 23 organochlorine compounds, including four PCB Aroclors and 19 elements, by Hazelton Environmental Services, Madison, Wisconsin, USA. Tissue samples were prepared for analyses as described by the U.S. Environmental Protection Agency [23]. Briefly, for organochlorines, a 20-g (wet-weight basis) subsample of each homogenized egg liquid was blended with 40 g or more of anhydrous sodium sulfate until the sample appeared granular. A 500-μl pesticide spiking solution was added, then 100 μl of a 2,4,5,6-tetrachloro-*m*-xylene surrogate spiking solution was added to all samples, and the sample was dried. This process was repeated on quality-control samples. Each prepared sample was then loaded into a Soxhlet® extractor, and after a process of heating and mixing with methyl chloride, the resulting filtered extract was concentrated in a Kuderna-Danish apparatus (Wheaton Science Products, Millville, NJ, USA), adjusted to volume with methyl chloride, and analyzed on a Gel-Permeation Chromatography system (Surface Science Laboratories, Mountain View, CA, USA). An additional silica gel cleanup method was used to separate PCBs from organochlorine pesticides.

Elements. For inorganic analyses, a subsample of egg tissue was digested in Teflon® vessels with HNO_3 in a microwave digester, diluted with Triton X-100 solution (J.T. Baker, Phillipsburg, NJ, USA), and filtered. Most elements in the digestate were determined by ICP–AAS. Additional subsamples were analyzed for As and Se using graphite furnace AAS. Mercury was determined by digestion of an egg subsample in H_2SO_4 and HNO_3 with heat, and then the digestate was reduced with sodium borohydride for determination using cold-vapor AAS. Dogfish muscle was used as reference material for Hg, and bovine and dogfish livers were used for the remaining elements.

The limit of detection (LOD) for organic compounds was 0.01 μg/g (or ppm) wet weight and for inorganic elements, 0.1 to 7.0 μg/g dry weight, depending on the analyte and amount of sample available. Analytical accuracy and precision were assessed using spiked sample recovery and duplicate analysis for 8% of the egg samples. For duplicate analysis, the estimated 95% confidence interval for analyses at concentrations less than twice the LOD was ±200% and for concentrations between two and 10× the LOD was ±15%. For detected analytes, spiked recoveries ranged from 82.5 to 135.0% for organic compounds and from 79.7 to 111.1% for inorganic elements, and the relative percentage of difference of duplicate samples averaged 8.3% for organic and 2.1% for inorganic analytes.

Data analysis

Breeding success was calculated as the percentage of breeding pairs that were successful in raising young to the feathered stage. Productivity was calculated as the number of feathered young produced per number of breeding pairs observed (number of young produced per occupied site). Arithmetic means, ranges, and standard errors were computed for eggshell thickness. Geometric means were computed for the concentrations of organochlorines and heavy metals in eagle eggs and carcasses after correction for moisture content. Concentrations of organochlorines in eggs were expressed as parts per million wet weight, because these measurements provided the best comparison to the results of Wiemeyer et al. [8]. Pearson product moment correlations were used to describe the relationship between DDE and PCBs in eggs and those of eggshell thickness to concentrations of DDE, PCBs, and Hg. We used multivariate analysis of variance to test for differences in concentrations of all contaminants collectively among islands. If a significant difference was found among mean vectors, then we proceeded to use univariate tests. One-way analysis of variance (ANOVA) was used to test for significant differences in concentrations of each contaminant in eggs and eggshell thickness among different islands. Concentrations were log normalized for ANOVA [24]. Specific contaminants in some samples were below the LOD. If a contaminant concentration was lower than the LOD in fewer than 50% of the samples collected, a value of one-half the LOD was assigned to each of those samples, and a geometric mean or ANOVA was computed. Neither means nor ANOVA was computed for contaminant concentrations lower than the LOD in 50% or more of the samples. The Tukey-Kramer mean separation test was used to determine significantly different concentrations in eggs among islands. All statistical tests were performed at the 0.05 level of significance.

RESULTS

Productivity

Clutch size varied from 1.6 to 2.7 and averaged 2.2 among the islands and between years (Table 1), but there was no consistent or significant difference among islands and years. Nesting success varied from 48 to 86% during the 2 years; Amchitka had the highest nest success (86%) in 1994, and Kiska had the lowest (48%) in 1994. Productivity varied from 0.65 to 1.24 young per occupied site among the different islands and years; lowest productivity occurred on Kiska Island (0.65 young per occupied site) in 1993, and highest productivity (1.24 young per occupied site) occurred on Amchitka in 1994. Productivity was similar on Adak, Tanaga, and Amchitka Islands (1.09, 0.96, and 1.22 young per occupied site, respectively) over the 2 years, but productivity at Kiska Island (0.67 young per site) was depressed compared with the other islands. Depressed productivity on Kiska Island was associated with lower breeding success in 1994 and low clutch sizes in 1993 (Table 1).

Diets

Diets of eagles varied between years and among islands, exemplifying the diverse diet and opportunistic foraging behavior of the species (Table 2). In the Western Adreanof Islands (Adak and Tanaga), most of the diet consisted of fish (56%) with lesser amounts of birds (25%) and mammals (19%); however, there was considerable difference between 1993 and 1994. The difference between years was due to the high availability of smooth lumpsuckers (*Aptocyclus ventricosus*) that were washed ashore in 1993, when they comprised 27% of

Table 1. Productivity of bald eagles in the Aleutian Islands, Alaska, USA, 1993–1994

	Western Andreanof Islands					Rat Islands				
	Adak		Tanaga			Amchitka		Kiska		
	1993	1994	1993	1994	Subtotal	1993	1994	1993	1994	Subtotal
Sites surveyed	27	42	10	20	99	7	30	18	25	82
Clutch size[a]	2.13	2.00	2.67	1.89	2.17	1.56	2.38	1.57	1.80	1.79
Nest success[b] (%)	70	73	70	56	67	86	69	62	48	63
Young per occupied site[c]	1.04	1.14	1.10	0.88	1.05	1.14	1.24	0.69	0.65	0.88
Subtotal[d]	1.09		0.96			1.22		0.67		

[a] Number of nestlings plus number of unhatched or broken eggs.
[b] Number of successful nests divided by number of occupied sites (breeding pairs).
[c] Number of young produced divided by number of occupied sites (breeding pairs).
[d] Weighted mean young per occupied site between years.

the diet on both Adak and Tanaga Islands. However, smooth lumpsuckers did not occur in the diet on Adak or Tanaga Island in 1994, nor did they occur in the diet on Amchitka or Kiska Island for either year. In 1993, fish comprised 82% of the diet on Adak and 63% on Tanaga. Overall, rock greenling (*Hexagrammos lagocephalus*) (22%), Pacific cod (*Gadus macrocephalus*) (16%), and smooth lumpsuckers (13%) were the most important fish species in the diet on Tanaga and Adak Islands. Although birds comprised a lower portion of the diet, the number of species (22) was large. Northern fulmars (*Fulmarus glacialus*) (7%) and glaucous-winged gulls (*Larus glaucescens*) (4%) were the most common avian species in the diet on Adak and Tanaga Islands. Sea otters pups (14%) and Norway rats (5%) were the only mammals in the diet and comprised 19% of the diet over the 2 years on Adak and Tanaga Islands.

Diets of eagles on the Rat Island group (Amchitka and Kiska Islands) also were variable (Table 3), and there were striking differences between these islands and the Western Adreanof Islands. In contrast to the diet on Adak and Tanaga Islands, birds comprised most (60%) of the prey species on Amchitka and Kiska Islands, followed by mammals (30%) and fish (10%). There were 26 species of marine birds in the diet on Amchitka and Kiska Islands, of which glaucous-winged gulls (12%) and northern fulmars (11%) were the most prevalent. Mammals comprised a larger portion (30%) of the diet

Table 2. Diets of bald eagles in the Western Andreanof Islands group, Aleutian Islands, Alaska, USA, 1993–1994[a]

Prey species	Adak Island 1993	Adak Island 1994	Tanaga Island 1993	Tanaga Island 1994	Total
Fish					
Pacific cod	18	29	1	7	55 (16)
Rock greenling	40	16	16	2	74 (22)
Smooth lumper fish	32		11		43 (13)
Dolly Varden	4	5			9 (3)
Other species[b]	3	6	1		10 (3)
Subtotal	97 (82)	56 (44)	29 (63)	9 (18)	191 (56)
Mammals					
Sea otter	4	17	12	15	48 (14)
Norway rat	11	4		1	16 (5)
Subtotal	15 (13)	21 (16)	12 (26)	16 (32)	64 (19)
Birds					
Northern fulmar	2	13		8	23 (7)
Glaucous-winged gull	1	7	3	2	13 (4)
Tufted puffin	1	1		3	5 (1)
Rock ptarmigan		5		1	6 (2)
Auklets[c]	1	4	1		6 (2)
Cormorants[d]		2		3	5 (1)
Shearwaters[e]		4		2	6 (2)
Other species[f]	2	15	1	6	21 (6)
Subtotal	7 (5)	51 (40)	5 (11)	25 (50)	88 (25)
Total	119	128	46	50	343

[a] Values are the number of individual prey items (% of total is in parentheses).
[b] Pacific halibut, giant sculpin, and rockfish (*Sebastes* spp.).
[c] Least, Cassin's, parakeet, and crested auklets.
[d] Pelagic, red-faced cormorants.
[e] Sooty, short-tailed shearwaters.
[f] Mallard, green-winged teal, common murre, common eider, black-legged kittiwake, Laysan albatross, common raven, fork-tailed storm petrel, ancient murrelet, red-breasted merganser, and pigeon guillemot.

Table 3. Diets of bald eagles in the Rat Island group, Aleutian Islands, Alaska, USA, 1993–1994[a]

Prey species	Amchitka Island		Kiska Island		Total
	1993	1994	1993	1994	
Fish					
Pacific cod		4	2	4	10 (4)
Rock greenling	1	3		1	5 (2)
Smooth lumper fish			2		2 (1)
Rockfish		1		1	2 (1)
Other species[b]	2		4		6 (2)
Subtotal	3 (9)	8 (8)	8 (15)	6 (9)	25 (10)
Mammals					
Sea otter	9	15	7	11	42 (17)
Norway rat	1	20	1	10	32 (13)
Subtotal	10 (29)	35 (36)	8 (15)	21 (33)	74 (30)
Birds					
Northern fulmar	2	13	2	11	28 (11)
Glaucous-winged gull	4	11	6	8	29 (12)
Tufted puffin	1	1	3	3	8 (3)
Rock ptarmigan	1	5	1	4	11 (4)
Auklets[c]	2	4	3	3	12 (5)
Cormorants[d]	1	2	3	2	8 (3)
Shearwaters[e]	4	6		3	13 (5)
Other species[f]	6	13	18	3	40 (16)
Subtotal	21 (62)	55 (56)	36 (70)	37 (58)	149 (60)
Total	34	98	52	64	248

[a] Values are the number of individual prey items (% of total in parentheses).
[b] Pacific halibut, rockfish (*Sebastes* spp.), and unknown species.
[c] Crested, least, parakeet, and Cassin's auklets.
[d] Pelagic, red-faced cormorants.
[e] Sooty, short-tailed shearwaters.
[f] Mallard, pintail, green-winged teal, common murre, common eider, black-legged kittiwake, harlequin duck, ancient murrelet, Canada goose, red-breasted merganser, fork-tailed petrel, least petrel, pigeon guillemot, and peregrine falcon.

on Amchitka and Kiska Islands than on Adak and Tanaga Islands and consisted of sea otters pups (17%) and Norway rats (13%). In contrast to diets on the Western Andreanof Islands, fish comprised a much lower percentage (10%) of the diet on the Rat Island group. Pacific cod (4%) and rock greenling (2%) were the most common fish species. Part of the difference in diets between the Western Adreanof and Rat Island groups was due to the high occurrence of smooth lumpsuckers in the diets in 1993; however, fish were still more prevalent in the diets on the Western Andreanof Islands during 1994. These differences likely reflect differences in availability of prey species between years and among islands.

Environmental contaminants and eggshell thickness

Organochlorines. Concentrations of PCB-1260 (Aroclor or commercially made mixture of chlorinated biphenyls with an average chlorinated content of 60%), *p,p*-DDE, β-1,2,3,4,5,6-hexachlorocyclohexane (β-BHC), hexachlorobenzene, oxychloradane, *trans*-nonachlor, dieldrin, and mirex were detected in most eggs (Table 4 and Fig. 2). Heptachlor epoxide, and

Table 4. Geometric means or ranges (μg/g) of common organochlorine contaminants or elements detected in eggs of bald eagles collected in 1993 and 1994 that did not differ significantly[a] among four Aleutian Islands, Alaska, USA

Contaminant	Kiska	Amchitka	Tanaga	Adak	*p*
β-BHC[b]	0.05	0.02	0.03	0.02	0.090
Dieldrin	0.04	0.02	0.02	0.01	0.135
Hexachlorobenzene	0.04	0.02	0.02	0.02	0.252
Heptachlor epoxide	0.01	LOD–0.03	0.01	LOD–0.01	—[c]
Cr	0.82	1.29	1.01	0.69	0.832
Cu	3.53	3.60	3.32	4.09	0.204
Fe	77.6	77.1	87.3	69.5	0.328
Mg	546	654	562	589	0.459
Mn	0.57	LOD–1.26	0.79	LOD–1.30	—
Ni	LOD–3.72	LOD–1.04	0.87	LOD–2.78	—
Se	4.43	4.93	3.98	3.92	0.440
Sr	9.23	11.2	10.2	9.74	0.950
Zn	38.3	38.7	43.6	41.3	0.553

[a] No statistics were calculated if concentrations in 50% or more of all samples were lower than the limit of detection (LOD) for an analyte.
[b] β-HC = β-1,2,3,4,5,6-hexachlorocyclohexane.
[c] A range from the LOD to maximum concentration detected is provided if 50% or more of the egg samples were below the LOD at any island.

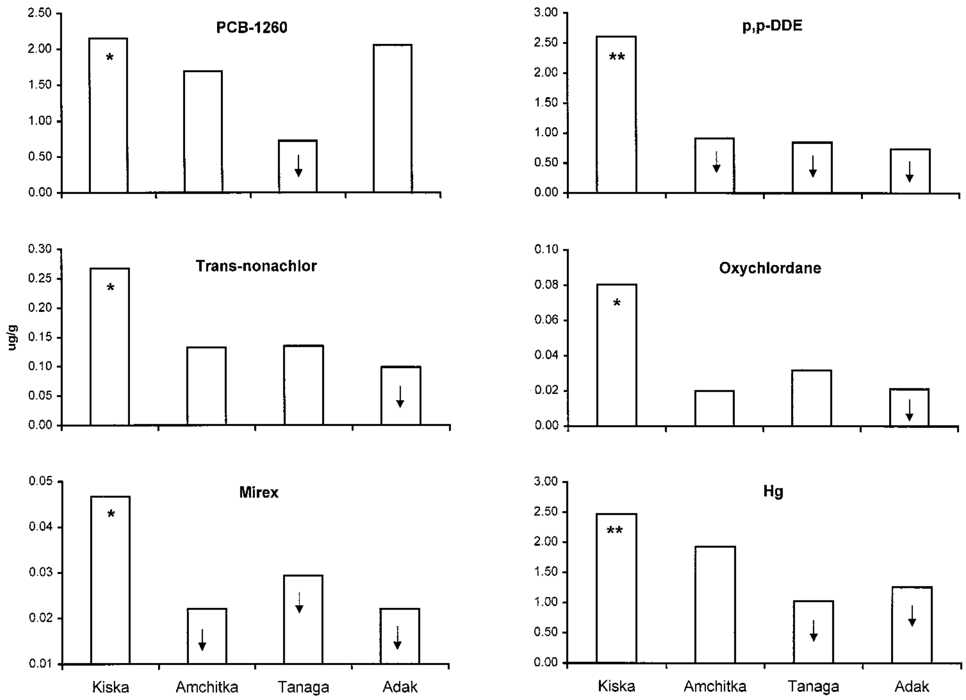

Fig. 2. Geometric mean concentrations of certain organochlorines (μg/g wet weight) and Hg (μg/g dry weight) in bald eagle eggs in the Aleutian Islands, Alaska, USA. Asterisks indicate concentrations in eggs from islands that were significantly higher than those from islands indicated by ↓; ** = $p < 0.001$; * = $p < 0.05$. Note the different scales on the *y* axes.

p,p-DDT were detected but were generally uncommon. The remaining organochlorines (PCB-1242, -1248, and -1254; toxaphene; α-BHC and δ-BHC; α-chlordane and δ-chlordane; endrin; *o,p,*-DDT, *o,p,*-DDE, *o,p*-DDD, and *p,p*-DDD) were rare (≤3 eggs) or not detected in any eggs. Concentrations of PCB-1260 and DDE were highest among the organochlorines (Fig. 2); the concentration of PCB-1260 ranged from 0.1 to 9.9 μg/g in samples from Adak Island, and that of DDE ranged from 0.3 to 4.1 μg/g.

Patterns of PCB and DDE concentrations among the islands were strikingly different. A multivariate ANOVA indicated that there was a significant difference (Wilks' $\lambda = 0.451$, $p = 0.010$) in contaminant concentrations in bald eagle eggs among the islands; therefore, we proceeded with univariate statistical analyses for each organochlorine separately. Accordingly, PCB-1260 concentrations were highest in eggs from Adak, Kiska, and Amchitka Islands (geometric mean = 2.1, 2.0, and 1.7 μg/g wet weight, respectively) but much lower (0.70 μg/g) on Tanaga Island ($F = 3.68$, $p = 0.03$) (Fig. 2). Concentrations of DDE were significantly ($F = 9.52$, $p < 0.0004$) higher in eggs from Kiska Island than in those from the other islands (Fig. 2), and the concentrations from Kiska Island (1.5 to 4.1 μg/g) were within the range of concentrations known to cause reproductive impairment in bald eagles [8]. These differences also represented an increase in mean DDE concentrations from east to west (Fig. 1). Similarly, concentrations of mirex, oxychlordane, and *trans*-nonachlor were significantly ($p < 0.05$) higher in eggs from Kiska Island than in those from the other

Table 5. Pearson product moment correlations among common organochlorine contaminants in bald eagle eggs from the Aleutian Archipelago, Alaska, USA[a]

Organochlorine	PCB-1260	β-BHC	Dieldrin	Oxychlordane	*p,p*-DDE	*Trans*-nonachlor	Mirex
Hexachlorobenzene	0.322 (0.117)	0.759 (0.000)	0.688 (0.000)	0.739 (0.000)	0.750 (0.000)	0.828 (0.000)	0.366 (0.072)
PCB-1260		0.042 (0.842)	0.218 (0.209)	0.207 (0.320)	0.291 (0.169)	0.266 (0.200)	−0.040 (0.849)
β-BHC			0.856 (0.000)	0.638 (0.000)	0.728 (0.000)	0.868 (0.000)	0.186 (0.372)
Dieldrin				0.541 (0.005)	0.672 (0.000)	0.830 (0.000)	0.082 (0.698)
Oxychlordane					0.903 (0.000)	0.730 (0.000)	0.770 (0.000)
p,p-DDE						0.840 (0.000)	0.672 (0.000)
Trans-nonachlor							0.302 (0.142)

[a] *p* values are in parentheses.

Table 6. Pearson product moment correlations among common inorganic contaminants in bald eagle eggs from the Aleutian Archipelago, Alaska, USA[a]

	Elements						
Element	Fe	Hg	Mg	Se	Sr	Zn	Cr
Cu	0.564 (0.003)	−0.190 (0.364)	0.182 (0.383)	−0.230 (0.268)	−0.026 (0.904)	0.462 (0.020)	0.377 (0.063)
Fe		−0.029 (0.891)	0.238 (0.253)	−0.007 (0.937)	0.025 (0.905)	0.702 (0.000)	0.667 (0.000)
Hg			0.030 (0.887)	0.463 (0.020)	−0.025 (0.904)	−0.132 (0.531)	−0.149 (0.478)
Mg				0.239 (0.250)	0.521 (0.008)	0.385 (0.058)	0.064 (0.760)
Se					−0.016 (0.940)	−0.122 (0.562)	−0.133 (0.527)
Sr						0.217 (0.298)	−0.223 (0.283)
Zn							0.147 (0.483)

[a] *p* values are in parentheses.

islands (Fig. 2), and these differences were strikingly similar and consistent among the islands for all organochlorines except PCBs.

Elements. Most of the frequently detected elements were similar in concentrations among the islands (Wilks' $\lambda = 0.589$, $p = 0.288$); Cr, Cu, Fe, Mg, Sr, and Zn were at background concentrations, but Hg and Se were elevated (Table 4). Mercury concentrations were significantly ($F = 7.28$, $p = 0.0016$) higher in eggs from Kiska Island compared with the other islands (Fig. 2). These differences and patterns were consistent and similar to the differences in organochlorines in eggs from the different islands. Selenium also was elevated, but this and the other common elements were not significantly different among islands (Table 4). Of the remaining elements, Mn and Ni were uncommon, and Al, As, B, Ba, Be, Cd,, Mo, and Pb were rarely detected (≤5 eggs) or below the LOD (range, 0.06–8.20 μg/g) in all egg samples.

Eggshell thickness and relationships among contaminants. Eggshell thickness was not significantly ($F = 1.457$, $p = 0.255$) different among the islands, nor was eggshell thickness correlated with DDE concentrations ($r = -0.029$, $P = 0.889$) or mercury concentrations ($r = -0.047$, $p = 0.823$). However, eggshell thickness was negatively correlated with PCB concentrations ($r = -0.418$, $p = 0.037$). Concentrations of PCBs and DDE in eggs were not significantly correlated ($r = -0.291$, $p = 0.159$). Concentrations of all organochlorines (Table 5) except PCBs were significantly and positively correlated with each other in eggs ($r = 0.541$–0.903, $p < 0.05$); therefore, there was a single and consistent pattern of organochlorine concentrations in eggs among the islands. In contrast, PCB concentrations were not significantly correlated with those of the other organochlorines ($r = 0.042$–0.321). Concentrations of most elements were not significantly correlated (Table 6), which suggests different sources and/or exposures to these contaminants than the organochlorines. However, there were significant correlations between Se and Hg ($r = 0.463$, $p = 0.015$) concentrations in eggs.

DISCUSSION

We found elevated concentrations of PCBs, DDE, mirex, oxychlordane, *trans*-nonachlor, dieldrin, hexachlorobenzene, and Hg in bald eagle eggs from four islands in the Aleutian Archipelago. A striking feature of the results was the similarity in relative differences in concentrations of most contaminants among the different islands. Concentrations of all of the above contaminants except PCBs were higher in eggs from Kiska Island than in eggs from the other islands; PCB-1260 was high in eggs from three of the four islands. Concentrations of DDE and Hg were particularly high in eggs from Kiska Island and were associated with lower productivity of breeding pairs. As a result, we rejected our initial hypothesis that bald eagles in the Aleutian Islands were free of organochlorine contamination. These findings surprised us and have raised some important questions that we address below.

Concentrations of PCBs, specifically Aroclor 1260, were significantly elevated in bald eagle eggs from the four islands; therefore, we were correct in our initial hypothesis that levels of PCBs would be elevated in bald eagles from the Aleutian Archipelago. However, the differences among the islands displayed a different pattern than that of the other contaminants, particularly DDE and Hg. Concentrations of PCBs were significantly higher in bald eagle eggs from Adak, Amchitka, and Kiska Islands than in those from Tanaga Island, a pattern consistent with previous military activity. Our results for PCB concentrations in eagle eggs suggest two important conclusions. First, the elevated concentrations of PCBs from all islands suggest that these contaminants are being transported globally by air and/or sea and deposited into polar regions due to the global distillation effect [1–3]. This supports the findings of several other studies [25,26] and has significant implications for the health of wildlife populations around the globe, particularly mammals that are sensitive to PCB contamination. Second, the significantly higher concentrations of PCBs on Adak, Amchitka, and Kiska Islands suggests that the primary source of these contaminants has been from local military activities. This is evidenced further by the fact that highest concentrations of PCBs were detected in eggs from Kuluk Bay (Adak Island) and Kiska Harbor (Kiska Island), where the most intense military activities have taken place over the last 50 years and during World War II, respectively. One egg from Kuluk Bay contained 9.9 μg/g wet weight PCBs, and one from Kiska Harbor had 3.6 μg/g wet weight, which are particularly high compared with our other samples.

The most important question raised by our results is the source of the other contaminants, particularly DDE and Hg, in the food chain of the Aleutian Archipelago. One possibility is that bald eagles migrate to more southern latitudes during the winter and accumulate organochlorines from their food in those areas. This seems unlikely because bald eagles are resident on Adak Island (J. Williams, personal communication) and Amchitka Island [14] year around and because the distance to southern latitudes associated with agricultural or industrial pollution seems prohibitive. Second, it is possible that bald eagles in the Aleutian Archipelago are acquiring contaminants from avian prey species that migrate to southern latitudes in North America or Asia during the winter. This possibility is supported by the fact that we found the highest levels of DDE and Hg in eagle eggs from Amchitka and Kiska Islands, where marine birds comprised a higher portion of their diet than on Adak and Tanaga Islands. A diet of piscivorous marine birds would result in a higher potential for food chain biomagnification than a diet strictly of fish. Similar findings have been noted for bald eagles nesting along the shores of Lake Superior [27]. We have no evidence that marine birds from the Aleutian Archipelago are carrying elevated levels of organochlorines, but we suggest that some of these species, particularly northern fulmars and glaucous-winged gulls, be sampled for contaminants. Northern fulmars and glaucous-winged gulls occurred consistently in the diets of bald eagles from all of the islands and are likely candidates as the source of organochlorines. Third, there was an east-to-west increase in organochlorine concentrations, which suggests an Asiatic source of these pollutants. Migration of avian prey to these areas could play a role in this potential source also. Also, DDT is still used throughout much of the world, particularly in Japan and the former Soviet Union, so it is possible that this and other organochlorines are being transported to the Aleutian Archipelago via atmospheric or oceanic currents from eastern Eurasia. This potential source of organochlorines could be confirmed or refuted by more intensive and extensive collections of fresh bald eagle eggs during incubation throughout the Aleutian Islands. Additional egg samples from white-tailed sea eagles (*Haliaeetus albicilla*) and Steller's sea eagle (*H. pelagicus*) from Eurasia also would help verify or refute this potential source of contaminants. The latter two species are closely related to bald eagles taxonomically and ecologically and would be expected to have similar accumulation rates with similar diets and exposure rates. Lastly, higher concentrations of DDE in eggs from Kiska Island could have resulted from storage or usage of DDT by the military; however, we have no information that would verify this possibility.

Reproductive success and productivity of bald eagles on Kiska Island were depressed compared with populations at Adak, Tanaga, and Amchitka Islands, and this was associated with significantly higher levels of DDE and Hg in eagle eggs from Kiska Island. We also found elevated concentrations of DDE and PCBs (1.65 and 1.05 ppm dry weight, respectively) in a dead nestling from Kiska Island, indicating that it had been exposed to these contaminants early in life. We suspect that the lower reproductive success at Kiska Island was due primarily to the presence of high levels of DDE because (1) levels of Hg were below those found to have effects in other studies [8] and (2) DDE concentrations in eggs were in the range of concentrations known to affect bald eagle productivity [8,28]. Wiemeyer et al. [28] also predicted rates of productivity (5-year average) of bald eagle populations from average levels of DDE concentrations in eggs. This relationship was significant ($p < 0.05$) and expressed by the equation $Y = 1.199 - 0.804 \log_{10}X$, where Y is mean productivity (young produced per breeding pair), and X is mean DDE concentration in eggs. Anthony et al. [6] and Grubb et al. [7] found that an earlier version of this equation [8] accurately predicted productivity of bald eagles based on DDE concentrations in eggs from the Columbia River estuary and in Arizona, respectively. If we apply this equation to our data from Kiska Island with mean DDE = 2.75 ppm, the predicted level of productivity would be 0.85 young per breeding pair. This value is higher than the productivity we observed (0.67 young per breeding pair) and suggests that levels of DDE may actually be higher on Kiska Island than we found and/or that other contaminants (e.g., PCBs and Hg) also were having an effect on productivity. Our mean concentrations were based on only six eggs, so additional sampling of bald eagle eggs at Kiska Island would be valuable to elucidate the extent and degree of organochlorine contamination in the population. Eggs from other bald eagle populations in the Aleutian Islands also would be valuable for comparison.

Our findings of elevated concentrations of mercury, DDE, and other organochlorines in bald eagle eggs from the Aleutian archipelago indicates a wider distribution of these contaminants than has been documented previously. These findings raise concerns for the health of Aleutian ecosystems and the possible effect of organochlorines on population viability of several top predators. Populations of pinnipeds, seabirds, and sea otters have declined substantially over the last several decades [29], and although the declines have been generally attributed to overfishing and temperature regime shifts [30], the possibility of contaminant-related effects should be investigated further. Most importantly, our findings exemplify the need for international controls on the use of contaminants. Their transport and effects, particularly of DDT and its metabolite DDE, know no political or continental bounds, so they should be banned from production and use globally to protect human health as well as wildlife resources.

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