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ENVIRONMENTAL CONTAMINANTS IN BALD EAGLE EGGS FROM THE ALEUTIAN ARCHIPELAGO

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Abstract—We collected 136 fresh and unhatched eggs from bald eagle (*Haliaeetus leucocephalus*) nests and assessed productivity on eight islands in the Aleutian archipelago, 2000 to 2002. Egg contents were analyzed for a broad spectrum of organochlorine (OC) contaminants, mercury (Hg), and stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). Concentrations of polychlorinated biphenyls (ΣPCBs), *p,p′*-dichlorodiphenyldichloroethylene (DDE), and Hg in bald eagle eggs were elevated throughout the archipelago, but the patterns of distribution differed among the various contaminants. Total PCBs were highest in areas of past military activities on Adak and Amchitka Islands, indicating local point sources of these compounds. Concentrations of DDE and Hg were higher on Amchitka Island, which was subjected to much military activity during World War II and the middle of the 20th century. Concentrations of ΣPCBs also were elevated on islands with little history of military activity (e.g., Amlia, Tanaga, Buldir), suggesting non–point sources of PCBs in addition to point sources. Concentrations of DDE and Hg were highest in eagle eggs from the most western Aleutian Islands (e.g., Buldir, Kiska) and decreased eastward along the Aleutian chain. This east-to-west increase suggested a Eurasian source of contamination, possibly through global transport and atmospheric distillation and/or from migratory seabirds. Eggshell thickness and productivity of bald eagles were normal and indicative of healthy populations because concentrations of most contaminants were below threshold levels for effects on reproduction. Contrary to our predictions, contaminant concentrations were not correlated with stable isotopes of carbon ($\delta^{13}C$) or nitrogen ($\delta^{15}N$) in eggs. These latter findings indicate that contaminant concentrations were influenced more by point sources and geographic location than trophic status of eagles among the different islands.

Keywords—Alaska Bald eagles Environmental contaminants Productivity Stable isotopes

INTRODUCTION

The Aleutian archipelago is a 1,900-km island chain that extends westward from the Alaskan Peninsula, Alaska, USA. It comprises a series of remote and physically similar volcanic islands that separate the North Pacific Ocean and the Bering Sea. Although the archipelago is remote from human populations, agriculture, and industry, it has been subjected to significant anthropogenic influences. For example, military activities have occurred on some islands during World War II [1] and the ensuing cold war; introduced arctic foxes (*Alopex lagopus*) have depleted breeding seabird populations, leading to substantially altered terrestrial ecosystems [2]; and various marine mammal and fish species have been harvested extensively from the surrounding marine environment [3]. In addition, elevated concentrations of polychlorinated biphenyls (PCBs), *p,p′*-dichlorodiphenyldichloroethylene (DDE), and heavy metals have been reported in sea otters (*Enhydra lutris*) [4], bald eagle eggs [5], internal organs of bald eagles [6], and pelagic cormorants (*Phalacrocorax pelagicus*) [7]. These reports of contaminants in various levels of the food chain have raised concerns about their potential effects on near-shore ecosystems.

Bald eagles are apex or high trophic–level predators throughout their geographic range. In the Aleutian archipelago, their diet is comprised mostly of fish and seabirds, and the majority (>90% by number and biomass) of their prey comes from near-shore marine ecosystems [5]. Because of their high trophic status, bald eagles tend to accumulate higher concentrations of environmental contaminants than other birds that occupy the same environments [8]. For example, Elliott et al. [9] reported that bald eagle eggs contained about a 10-fold higher DDE concentration than other fish-eating birds such as great blue herons (*Ardea herodias*) and double-crested cormorants (*P. auritus*). Consequently, bald eagles accumulate some of the highest concentrations of contaminants in aquatic ecosystems and can be used to assess the more severe and potential impacts to these systems [8]. The effect of DDE on productivity of regional populations of bald eagles is well documented [8,10], and various studies have indicated that the species is sensitive to low concentrations of DDE [8,11,12]. Also consensus is broad that impairment of reproduction by DDE was the major factor that caused declines of bald eagle populations throughout much of North America during the middle of the 20th century [8]. With the ban of DDT from use in the United States in the 1970s, there was subsequent recovery of reproductive success of the species [13]. The effects of PCBs and mercury (Hg) on bald eagle reproduction are less certain because concentrations of these contaminants usually are correlated positively with concentrations of DDE in eggs [10], so their effects are not easily separated from those of DDE [8]. Based on the bald eagle's diet, sensitivity to DDE and other organochlorines (OCs) [8], and its tendency to bioaccumulate environmental contaminants [10], the species has been used to monitor environmental contaminants in fresh-

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water, estuarine, and marine ecosystems [14]. White-tailed sea eagles (*Haliaeetus albicilla*) and Bonelli's eagles (*Hieraaetus Fasciatus*) have been used for the same purpose in Europe [15,16].

Recently, elevated concentrations of DDE, PCBs, and mercury in bald eagle eggs were reported from Adak, Tanaga, Amchitka, and Kiska Islands, and these elevated levels were associated with lower reproduction on Kiska Island during 1993 to 1994 [5]. At the time, these results were not expected, and they raised concern for bald eagle populations in the region. However, the spatial scale and size of sample collections limited inferences about the potential impact and source(s) of contaminants. The potential sources of these contaminants are local point sources, migratory seabirds that may be acquiring contaminants throughout the North Pacific Ocean, and/or global transport via oceanic or atmospheric deposition from Europe and Asia [5]. Understanding the source of environmental contaminants to the Aleutian Islands is vital to understanding the potential impacts to marine ecosystems [17].

The purpose of this study was threefold. First, we wanted to assess whether environmental contaminants represented a potential threat to reproduction and stability of bald eagle populations in the Aleutians. Second, we wanted to describe the geographic pattern and potential sources of contaminants in bald eagle eggs from a number of widely distributed islands in the Aleutian archipelago. Last, we wanted to determine if contaminant levels in eagle eggs were related to trophic status of bald eagles among the islands. Previous studies have shown that concentrations of environmental contaminants are related to the trophic level at which a species forages [18,19]. The heavy isotope of nitrogen (^{15}N) is preferentially incorporated into the tissues of consumers from their diet, which results in a systematic enrichment in the nitrogen-isotope ratio ($^{15}N/^{14}N$) with each trophic level [20]. Consequently, we predicted that concentrations of contaminants in bald eagle eggs would be correlated positively with $\delta^{15}N$ in eggs. In contrast, relatively little trophic enrichment occurs among carbon isotope ratios ($^{13}C/^{12}C$), so $\delta^{13}C$ is a reliable indicator of primary productivity among trophic levels due to the differential fractionation of carbon during photosynthesis in terrestrial versus marine plants [20]. Furthermore, variation in water turbulence in marine ecosystems allows partitioning of pelagic phytoplankton versus near-shore algal communities [21]. Recent studies have shown that $\delta^{13}C$ decreases from east to west along the Aleutian archipelago in zooplankton [22] and pelagic cormorants [7]. We predicted a similar east-to-west decrease in $\delta^{13}C$ in bald eagle eggs because they tend to occupy relatively small breeding territories [23] and forage on local prey species. Herein, we report on contaminant concentrations and stable isotopes of carbon and nitrogen in bald eagle eggs from eight islands. We also discuss the possible sources of environmental contaminants and their potential impacts on bald eagle productivity in the Aleutian archipelago.

METHODS

Study area

The Aleutian archipelago comprises >200 islands extending westward from the tip of the Alaska Peninsula towards Asia (Fig. 1). The Aleutians were strategically important during World War II and for subsequent Cold War military activities. Islands with a history of military activities include Attu, Shemya, Kiska, Amchitka, Adak, Umak, and Unalaska. The U.S. Naval Base on Adak closed in 1996 and now houses a small fish processing plant and support community. Currently, nonmilitary human activities are more common in the eastern Aleutians. Large commercial fish processing and fleet operations are located primarily in the eastern Aleutians at Dutch Harbor on Unalaska Island and at a smaller port at Sand Point in the Shumagin Islands.

Egg collections and productivity surveys

We determined locations of nests for egg collections and nesting status of bald eagles by surveying approximately 1,130 km of shoreline from inflatable skiffs during the egg-laying and incubating phase of the breeding season (mid-April to early May), 2000 to 2002. The Aleutians are virtually treeless, so the open terrain and species' close association with water allowed us to reliably count pairs and identify nests. Active nests were recorded and climbed when possible. We collected one egg from each nest, placed it in a clean 500-ml plastic container padded with nest material, kept it refrigerated, and removed the contents within a few days. We obtained 109 fresh eggs: 30 from Adak (15 each from the east and west sides), 15 each from Kiska, Amchitka, and Tanaga, 14 from Unalaska (including Akun and Akutan), and 15 from the Shumagin Islands (Fig. 1). One additional fresh egg was collected in 2004 at Buldir Island, the western-most island where bald eagles nest. We also collected 27 unhatched eggs from nests during productivity surveys in June. All collections during this study were done in accordance with the U.S. Geological Survey's Animal Care and Use committee and authorized by permits from the U.S. Fish and Wildlife Service (permit MBO14922-1) and Alaska Department of Fish and Game (permit 01-027).

Terminology used to define nest success and productivity followed that of Postupalsky [24] and Anthony et al. [5]. We determined nesting success and productivity at 282 occupied territories during 2000 to 2002: 106 on Adak, 77 on Kiska, 72 on Amchitka, and 27 on Tanaga; some of these were the same nesting territories/pairs sampled in different years. We also searched the nests for unhatched eggs and collected six from Kiska, four from Amchitka, eight from west Adak, and nine from East Adak. In 1993 to 1994, we surveyed 181 nests (69 on Adak, 43 on Kiska, 39 on Amchitka, 30 on Tanaga) and collected 25 unhatched eggs in an identical manner [5].

Sample preparation and analytical chemistry

We excised each egg along its equator and extracted all contents into certified chemically cleaned jars. Jars were sealed and frozen until chemical analyses were performed. We measured combined thickness of eggshell and membrane at four approximately equidistant locations along the equator of each egg using a Starrett 1010M dial thickness gauge (L.S. Starrett Company, Athol, MA, USA). We calculated Ratcliffe's index (eggshell weight/[egg length $\times$ egg width]) as a surrogate for eggshell density.

Fresh eggs were analyzed for 97 congener-specific PCBs, 4 PCB Aroclors (1242, 1248, 1254, 1260), and 27 chlorinated pesticides by the Geochemical and Environmental Research Group, Texas A&M University, College Station, Texas, USA. Unhatched eggs were analyzed for the same suite of compounds and elements except for the specific PCB congeners. Elemental mercury (Hg) was analyzed in all eggs by the Trace Element Research Laboratory, Texas A&M University, College Station, Texas, USA. Egg samples were prepared for organic analyses following the National Oceanic and Atmo-

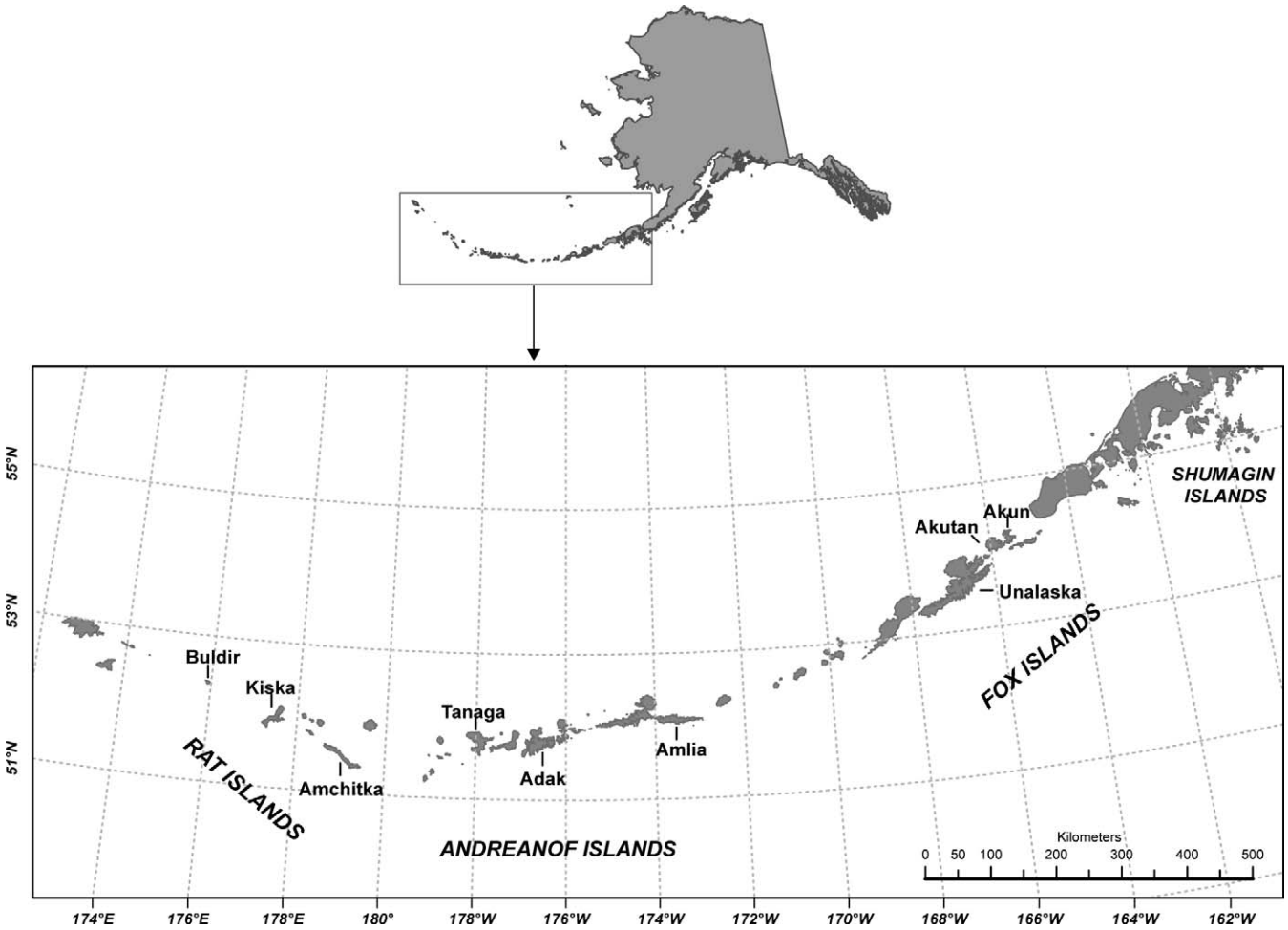

Fig 1. Map of the Aleutian archipelago, Alaska, USA, illustrating islands where bald eagle eggs were collected from 2000 to 2002.

spheric Administration Status and Trends Method [25], with slight revisions [26,27]. A 1- to 10-g sample (wet weight) was extracted with a Teckmar Tissumizer (Tekmar, Cincinnati, OH, USA) by adding surrogate standards, Na_2SO_4, and methylene chloride in a centrifuge tube. Extracts were purified by silica/alumina column chromatography to isolate pesticide and PCB fractions, which were further purified by high-performance liquid chromatography to remove interfering lipids. Quantitative analyses then were performed by capillary gas chromatography with an electron capture detector. Coeluting pesticides and congeners were analyzed and confirmed using capillary gas chromatography with a mass spectrometer operated in select ion monitoring mode. Total PCB concentrations that we report are the sum of the four Aroclors as reported by the laboratory. Mercury was determined with a direct mercury analyzer whereby a sample aliquot was combusted in a stream of oxygen, and Hg became trapped on a gold column. Mercury then was released by electro-thermal heating and analyzed by atomic absorption. Standard reference materials were mussel tissue (National Institute of Standards and Technology 2974) for organic analyses and dogfish tissue (National Research Council Canada, Dogfish Reference Material-2) for Hg analysis. The analytical laboratories were authorized under the quality assurance and quality control standards and guidelines of Patuxent Wildlife Research Center, U.S. Geological Survey, Laurel, Maryland.

Limits of detection for contaminants averaged 0.1 ng/g (standard deviation [SD] = 0.4) for PCB congeners, 2.7 ng/g (SD = 1.4) for chlorinated pesticides, 29.4 ng/g (SD = 11.8) for PCB Aroclors, and 4.8 (SD = 3.3) ng/g for Hg. Analytical accuracy and precision were assessed using spiked sample recovery and duplicate analyses on 5% of all samples. For organic analyses, spiked recoveries averaged 86.7% (SD = 10.4), and relative percent difference for duplicate samples averaged 8.3% (SD = 15.2). For Hg, spiked recoveries averaged 99.6% (SD = 4.5), and relative percent difference for duplicate samples averaged 2.3% (SD = 2.6). Information regarding analytical chemistry and quality assurance for eggs collected during 1993 to 1994 are provided by Anthony et al. [5]; lower limits of detection in the earlier study were ~10× higher because of the state of analytical technology available at that time.

Stable isotope analysis

We determined stable isotopes of nitrogen (^{15}N) and carbon (^{13}C) in all bald eagle eggs collected for contaminant analysis. A 6- to 7-g subsample was extracted from individual frozen and homogenized whole egg samples, dried at 60°C for 24 to 48 h, and ground into a fine powder with a mortar and pestle. Lipids were extracted from dried and ground egg homogenates using diethyl ether in a Soxhlet apparatus for 48 h [28], and samples were freeze dried for 12 h to remove any remaining solvent. Aliquots (1.0–1.5 mg) were sealed into 5 × 9 mm tin capsules and analyzed with an Europa Hydra 20/20 (Europa

Scientific, Cambridge, UK) continuous flow isotope ratio mass spectrometer at the University of California, Davis, Stable Isotope Facility. We expressed stable isotope ratios in delta notation

$$\delta X = ([R_{sample}/R_{standard}] - 1) \times 1{,}000$$

where δX is ^{13}C or ^{15}N (parts per thousand) and R is the corresponding ratio of $^{13}C/^{12}C$ or $^{15}N/^{14}N$. The $R_{standard}$ values were based on the PeeDee Belemnite and atmospheric N_2 for ^{13}C and ^{15}N, respectively. Measurement error determined from replicate analysis of internal laboratory standards was 0.1% and 0.05% for ^{13}C and ^{15}N, respectively.

Data analysis

Productivity estimates. We calculated productivity as the number of young produced per number of occupied territories [24]. Previous studies have demonstrated that bald eagles may abandon nests if eggs are collected during the incubating phase [29], so we adjusted our estimates of productivity by excluding a failed nest from the total number of occupied sites if we collected a fresh egg from that nest during the same year. We also adjusted productivity calculations by adding one young to a successful nest if we collected an egg and the nest was successful during the same breeding season. This accounted for our effect on productivity.

Contaminants. We pooled concentrations of OC compounds into related chemical groups to summarize overall contaminant patterns. Contaminant groups were ΣPCBs, ΣDDT (DDE, DDT, and dichlorodiphenyldichlorethane [DDD]), Σchlordanes ([CHLORD], alpha and gamma chlordane, oxychlordane, heptachlor epoxide, cis and trans nonachlor), Σchlorobenzenes ([CBZ], hexachlorobenzene and 1,2,3,4- and 1,2,4,5-tetrachlorobenzene), Σhexachlorocyclohexane ([HCH], alpha, beta, delta, and gamma HCH), Σcyclodiene pesticides (aldrin, dieldrin, endrin), Σother compounds ([OTH], mirex, toxaphene, and endosulfan II), and Hg. In most cases, only concentrations greater than the limit of detection were included in group totals to avoid overestimation of rare compounds. However, we substituted ½ limit of detection when a particular analysis did not allow a missing value. For statistical hypothesis testing, we separated *p,p′*-DDE from ΣDDT due to its well-known effects on eagle reproduction [8,10]. Percent lipid varied with concentrations among all contaminant groups ($p < 0.02$), but correlations were weak ($R^2 < 0.22$) given the large sample size of eggs ($n = 136$). We expressed concentrations of OC compounds on a wet weight basis (μg/g) to facilitate comparison to previous studies. We expressed concentrations of Hg on a dry weight basis (μg/g) unless noted otherwise.

We constructed profile charts to visually examine relative proportions of individual PCB congeners and chlorinated pesticides comprising ΣPCBs and ΣOC groups, respectively. We used principal components ordination in PC–ORD software (MSM, Gleneden, OR, USA) to quantify overall patterns of PCB congeners among islands and sites. We used correlation analysis to examine relations among contaminants and multivariate analysis of variance to test for overall differences in contaminant concentrations among islands. If a significant difference was found among mean vectors in the multivariate analysis of variance, we used univariate analysis of variance to determine which contaminants differed among islands. This procedure was followed by Tukey-Kramer mean separation tests to determine how concentrations differed among islands. Prior to this analysis, we tested for overall differences in contaminant concentrations between the east and west sides of Adak because one of our objectives was to determine how east Adak, the location of a previous U.S. Naval Base, differed from the remainder of the archipelago. Overall concentrations differed between east and west Adak (Wilk's $\lambda = 0.23$, $F = 7.97$, $p < 0.0001$), so we treated them separately in subsequent analysis of variance. We also tested for differences in contaminant concentrations between fresh and unhatched eggs from islands where both egg types were collected (Kiska, Amchitka, Adak). An overall egg type effect (Wilk's $\lambda = 0.60$, $F = 5.23$, $p < 0.0001$) occurred for only ΣCBZ ($F = 32.7$, $p < 0.0001$) and ΣHCH ($F = 5.9$, $p = 0.02$). Concentrations did not differ between fresh and unhatched eggs for all other contaminant groups ($F \leq 1.77$, $p \geq 0.18$), so we combined the two samples in the tests for differences among islands. We did not discriminate between fresh and unhatched eggs for concentrations of ΣCBZ and ΣHCH because these groups comprised only a small percentage of total OC composition (see *Results* section). All contaminant concentrations were $\log_e$-transformed prior to analysis [30]. Mean $\log_e$ concentrations from analyses of variance were back-transformed and presented as geometric mean concentrations. The lack of significant differences in concentrations of contaminant groups between fresh and unhatched eggs in the 2000 to 2002 sample justified a comparison of contaminant concentrations in this study to those in 1993 and 1994 [5], because the earlier study was based on the analysis of unhatched eggs.

We used multiple regression to examine the relation between contaminants and stable isotopes. We controlled for differences among island groups because baseline isotopic food web signatures may not be constant across all food webs in the Archipelago. We used results from 1993 and 1994 and this study to regress average productivity for each island and study period against $\log_e$-transformed mean concentrations of ΣPCBs, DDE, and Hg. We used multiple regression to examine the relation between concentrations of each contaminant group and stable isotopes in each egg sample while controlling for differences among island groups (Rat, Andreanof, and Fox-Shumagin). We pooled values from the Fox and Shumagin island groups into a single group to represent the eastern Aleutians. The Rat Islands included Buldir. We also regressed eggshell thickness on concentrations of ΣPCBs, *p,p′*-DDE, and Hg in each egg to determine if any of the contaminants were likely to have caused thinning of eggshells.

RESULTS

OC and Hg composition and concentrations

All eggs contained detectable concentrations of ΣPCBs and Hg. Total DDT and chlordane compounds were detected in ≥54% of all eggs except DDE and hepatachlor, respectively. The only HCH compound detected was β-HCH (99%). Mirex and endosulfan II (ΣOTH) were detected in >91% of all eggs, except for the egg from Buldir in which neither compound was detectable. Aldrin and endrin (Σcyclodiene pesticides) and 1,2,3,4-TCBZ (ΣCBZ) were detected infrequently (≤43%). Toxaphene was not detected in any of the samples.

Proportional composition of OC compounds in eggs was similar among islands. Total PCBs (56%) and ΣDDT (29%) comprised the majority of organochlorines in eggs from all islands. Notably, ΣPCBs comprised 81% of organochlorines at east Adak, and ΣDDT comprised 41% at Buldir. Total CHLORDs comprised 8% of organochlorines in eggs, and ΣCBZ, HCH, cyclodiene pesticides, and OTH comprised ≤2%

from all islands. Within organochlorine groups, DDE comprised ≥91% of ΣDDTs in eggs from each island. Chlordane composition generally was similar among islands and mostly was comprised of the metabolic by-products transnonachlor (39–62%), oxychlordane (21–51%), and *cis*-nonachlor (4–10%). Chlorobenzenes and cyclodienes primarily were comprised of HCB (45–94%) and dieldrin (82–100%), respectively. Mirex comprised the majority (68–88%) of other compounds.

Concentrations of most organochlorines and Hg were significantly correlated with each other; however, most r values were <0.70 but significant due to the large sample size (n = 136). However, concentrations of ΣPCB and ΣDDT ($r = 0.82$, $p < 0.001$); DDE and ΣCHLORD ($r = 0.89$, $p < 0.001$); and DDE and ΣOTH ($r = 0.83$, $p < 0.001$) in eggs were most strongly correlated. Concentrations of ΣPCBs and DDE ($r = 0.55$, $p < 0.001$) and DDE and Hg ($r = 0.48$, $p < 0.001$) also were correlated positively. The correlation between ΣPCBs and Hg was much weaker ($r = 0.26$, $p = 0.003$).

Differences among islands

Overall, contaminant concentrations in bald eagle eggs differed among islands (Wilk's $\lambda = 0.04$, $F = 8.1$, $p < 0.001$) for all contaminant groups except ΣCHLORD ($F = 1.9$, $p = 0.07$; Table 1). Mean concentrations of ΣPCBs in eggs were highest at east Adak (3.6 μg/g) and lowest at Amlia (1.0 μg/g) and the Shumagins (1.3 μg/g). Mean concentrations of DDE (1.2 μg/g) and Hg (2.5 μg/g) were highest at Kiska and declined eastward. Mean concentrations of ΣDDTs in eggs were highest at east Adak and Kiska, and ΣCBZ (0.06–0.07 μg/g) and ΣHCH (0.04–0.05 μg/g) were highest at Unalaska and the Shumagin Islands. The egg from Buldir had the highest concentrations of ΣPCBs (11.1 μg/g), DDE (8.3 μg/g), and Hg (5.3 μg/g; Table 1).

PCB composition and concentrations

Eighty-seven percent of the PCB congeners were detected in >50% of all fresh eggs. Congeners 7/9, 15, 29, 30, 39, 45, 46, 63, 69, 114, and 200 rarely were detected (Fig. 2). Forty-nine percent of ΣPCBs were comprised of congeners 118, 138/160, 153, and 180, which typically bioaccumulate in marine food webs [31]. All the other congeners comprised <5% of ΣPCBs. A pattern of high proportional composition (>90%) of *penta-, hexa-,* and *hepta*-chlorinated PCB homologue groups and low composition of lighter and less chlorinated PCB homologues existed, which was similar among all islands. Total PCBs were composed almost exclusively of Aroclor 1260 and 1254; PCB 1260 was highest in eggs from east Adak and Buldir (≥ 80%), though PCB 1254 was highest in eggs from Amchitka (53%). Composition of Aroclor 1248 in eggs was <5% from any island, and PCB 1242 was only detected in eggs from Tanaga.

Principal component analysis of PCB congeners identified subtle differences in PCB concentrations in eggs among islands, and the first two axes explained 68% of the cumulative variance in congener concentrations (Fig. 3). Axis 1 was correlated positively with concentrations of all congeners, particularly the more highly chlorinated congeners such as 138, 153, and 180 ($r > 0.93$). Axis 2 was correlated negatively with the lower chlorinated congeners such as 1, 18, 25, 40, and 92 ($r > -0.54$) and positively correlated with the highly chlorinated congeners ($r > 0.23$). Concentration in the egg from Buldir was an outlier in ordination space with high concentrations of 138, 153, 180, and lower chlorinated congeners compared to all other islands. Higher concentrations of lower chlorinated congeners were found in eggs from Kiska and Tanaga, although higher concentrations of higher chlorinated congeners were found in eggs from east Adak. Low concentrations of lower chlorinated congeners were associated with west Adak, Amlia, and the Shumagin islands.

Comparison of concentrations between study periods

Overall contaminant concentrations in eggs differed between 1993 and 1994 and 2000 to 2002 (Wilk's $\lambda = 0.40$, $F = 17.9$, $p < 0.001$) and among islands (Wilk's $\lambda = 0.22$, $F = 5.7$, $p < 0.001$), but differences between study periods were not consistent among islands (period × island interaction: Wilk's $\lambda = 0.48$, $F = 2.5$, $p < 0.001$; Fig. 4). For example, concentrations of ΣPCBs ($F = 7.2$, $p = 0.008$) and Hg ($F = 3.8$, $p = 0.05$) in eggs were higher in the 2000 to 2002 sample, whereas concentrations of DDE were higher in the 1993 and 1994 sample ($F = 5.8$, $p = 0.02$). Concentrations of all of these contaminants differed among islands ($F > 2.6$, $p < 0.03$), and differences between study periods were consistent across islands (period × island interaction: $F < 1.3$, $p > 0.29$). No within-island study period interaction differed statistically ($p > 0.06$) for any contaminant group. However, higher concentrations in the 2000 to 2002 sample appeared to be driven mostly by increased ΣPCBs in eggs from Tanaga and east Adak and increased Hg in eggs from Tanaga, although lower concentrations of DDE largely were due to the nearly 50% reduction from 1993 to 1994 concentrations in eggs from Kiska (Fig. 4). Concentrations of mirex (ΣOTH) were lower in the 1993 and 1994 sample ($F = 6.8$, $p < 0.0001$), but differences between study periods varied across islands (period × island interaction: $F = 2.6$, $p = 0.04$), where mirex concentrations were ~3× higher in eggs from Kiska and Amchitka Islands during 2000 to 2002 versus 1993 and 1994.

Geographic differences in contaminants and stable isotopes

Concentrations of Hg and ΣDDT in eagle eggs were highest in the western Aleutians and declined linearly to the east regardless of the inclusion of Buldir (Fig. 5). Concentrations of *p,p*-DDE and ΣCHLORD also were highest in the western Aleutians, declined in the central Aleutians, and increased slightly in the eastern Aleutians conforming to a marginally significant ($F = 5.1$, $p = 0.06$) quadratic relation (Fig. 5). Neither linear nor quadratic relations between relative longitude and concentrations were statistically significant ($F \leq 4.6$, $p \geq 0.07$, $r^2 < 0.51$) for all other contaminant groups. In contrast to contaminant concentrations, mean $\delta^{15}N$ was lowest in the western Aleutians and increased linearly going east (Fig. 6A). In contrast, mean $\delta^{13}C$ only varied by about 2.3 mg/g among islands and was not significantly correlated with longitude (Fig. 6B).

We identified two local point sources of contaminants in eagle eggs. Concentrations of ΣPCBs in eggs were significantly elevated in Kuluk Bay, east Adak Island (Fig. 7), and concentrations were particularly high in Sweeper Cove, the site closest to the former military base, and declined with distance from this site. These elevated concentrations on east Adak were in contrast to the relatively low concentrations in the Bay of Islands, west Adak (Fig. 7). In addition, concentrations of Hg, DDE, and ΣPCBs were elevated significantly in eggs collected from the south end of Amchitka Island from

Table 1. Geometric mean concentrations (and ranges) of organic contaminant groups (μg/g, wet wt) and Hg (μg/g, dry wt) in bald eagle eggs collected during 2000 through 2004 in the Aleutian archipelago, Alaska, USA. Mean values sharing common letters are not significantly different. Islands are listed in order from west to east

Contaminant group[a]	Buldir[b] (n = 1)	Kiska (n = 21)	Amchitka (n = 19)	Tanaga (n = 15)	West Adak (n = 23)	East Adak (n = 24)	Amlia (n = 5)	Unalaska (n = 14)	Shumagins (n = 15)
ΣPCB	11.076	2.340 B	2.231 B	1.565 BC	1.668 BC	3.664 A	1.034 C	1.904 BC	1.279 C
	NA[b]	(0.890–4.168)	(1.05–8.47)	(1.02–3.8)	(0.429–3.83)	(1.67–10.917)	(0.579–1.77)	(0.731–3.86)	(0.544–2.89)
p,p′-DDE	8.363	1.239 A	0.848 AB	0.679 B	0.673 B	0.576 B	0.534 B	0.755 AB	0.602 B
	NA	(0.449–2.794)	(0.447–6.66)	(0.246–2.3)	(0.228–1.917)	(0.274–1.011)	(0.355–0.99)	(0.288–2.56)	(0.221–1.38)
ΣDDT[c]	0.135	0.048 AB	0.05 AB	0.035 BC	0.042 ABC	0.061 A	0.029 ABC	0.032 BC	0.026 C
	NA	(0.018–0.124)	(0.019–0.332)	(0.016–0.07)	(0.013–0.157)	(0.038–0.099)	(0.014–0.043)	(0.014–0.131)	(0.016–0.045)
Hg	5.27	2.495 A	1.926 AB	1.555 BC	1.549 BC	1.369 C	1.323 BCD	1.119 CD	0.814 D
	NA	(1.76–3.8)	(0.897–3.92)	(0.993–2.62)	(0.736–3.25)	(0.833–2.39)	(0.749–2.24)	(0.513–1.91)	(0.499–1.62)
ΣCHLORD	0.651	0.263 A	0.217 A	0.201 A	0.210 A	0.180 A	0.141 A	0.230 A	0.182 A
	NA	(0.116–0.741)	(0.1–1.71)	(0.112–0.663)	(0.047–0.602)	(0.111–0.264)	(0.087–0.212)	(0.091–0.477)	(0.085–0.297)
ΣCBZ	0.109	0.050 ABC	0.034 BC	0.029 C	0.032 BC	0.039 BC	0.024 BC	0.074 A	0.055 AB
	NA	(0.026–0.117)	(0.016–0.076)	(0.014–0.053)	(0.009–0.126)	(0.014–0.54)	(0.014–0.044)	(0.03–0.204)	(0.026–0.111)
ΣDRIN	0.075	0.031 A	0.028 A	0.025 A	0.024 A	0.021 A	0.006 B	0.026 A	0.031 A
	NA	(0.01–0.055)	(0.013–0.179)	(0.014–0.057)	(0.005–0.079)	(0.014–0.036)	(0.002–0.013)	(0.012–0.056)	(0.015–0.072)
ΣHCH	ND[d]	0.036 ABC	0.027 ABC	0.022 CD	0.029 BCD	0.021 D	0.017 CD	0.050 A	0.045 AB
	NA	(0.016–0.073)	(0.012–0.091)	(0.011–0.053)	(0.005–0.084)	(0.012–0.038)	(0.009–0.034)	(0.016–0.139)	(0.017–0.103)
ΣOTH	0.366	0.072 A	0.053 AB	0.034 B	0.041 B	0.043 B	0.033 B	0.05 AB	0.035 B
	NA	(0.026–0.122)	(0.026–0.199)	(0.016–0.082)	(0.015–0.122)	(0.024–0.076)	(0.021–0.055)	(0.016–0.121)	(0.015–0.099)

[a] PCB = total polychlorinated biphenyls; *p,p′*-DDE = dichlorodiphenyldichloroethylene; Hg = mercury; CHLORD = alpha and gamma chlordane, oxychlordane, heptachlor expoxide, cis and trans nonachlor; CBZ = hexachlorobenzene 1,2,3,4- and 1,2,4,5-tetrachlorobenzene; CYCLO = aldrin, dieldrin, and endrin; HCH = alpha, beta, delta, and gamma cyclodiene pesticides; and OTH = mirex and endosulfan II.

[b] Buldir excluded from analysis of variance because n = 1, illustrated for visual comparison only.

[c] Concentration of *p,p′*-DDE not included.

[d] All analytes comprising contaminant group were below limits of detection.

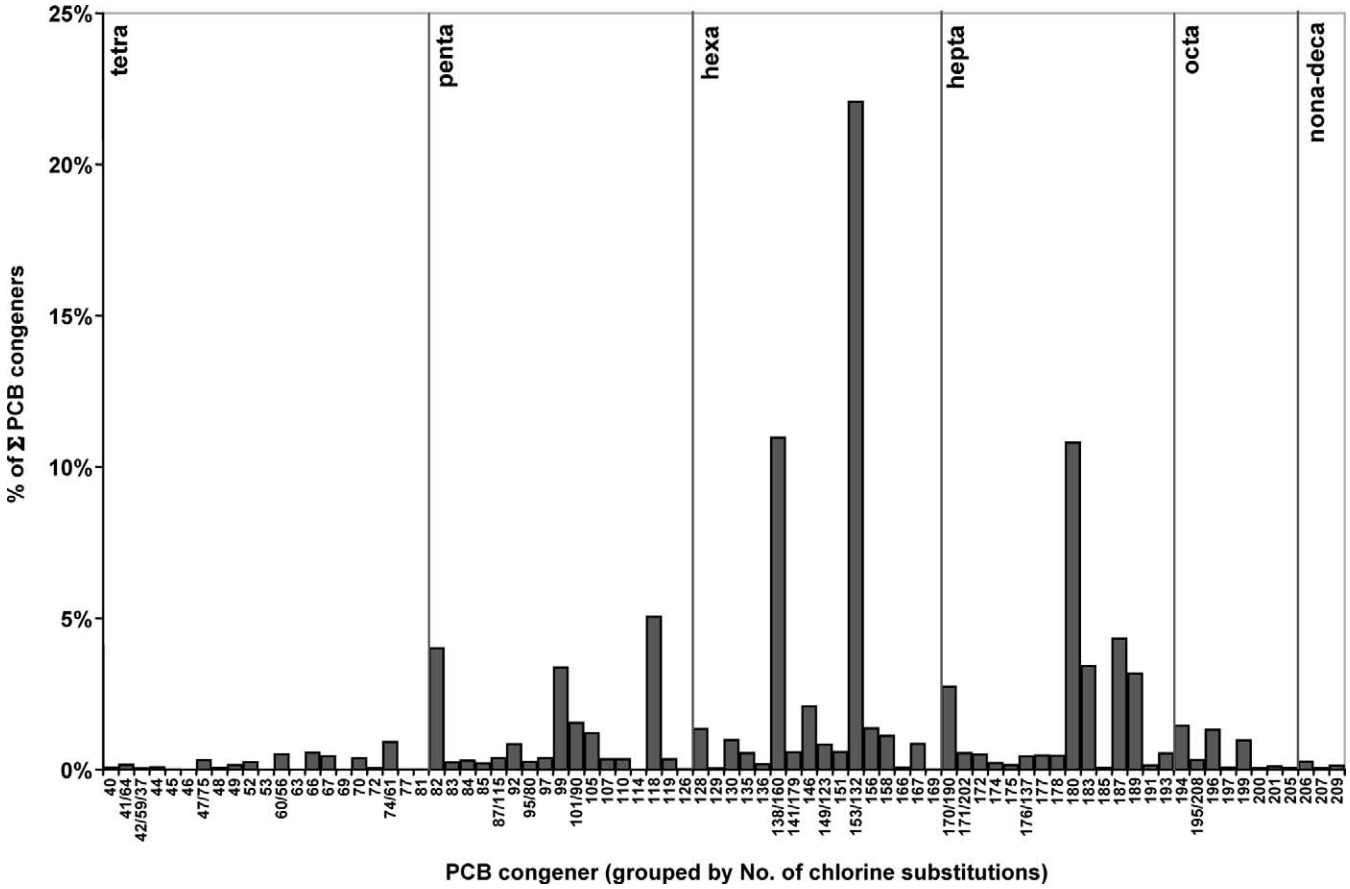

Fig. 2. Polychlorinated biphenyl (PCB) congener profiles in fresh bald eagle eggs (n = 110) collected during 2000 through 2002 in the Aleutian archipelago, Alaska, USA. The mono, di, and tri groups have been omitted because they comprised <2% of total congeners.

Makarius Bay to East Cape (Fig. 8). Although the concentrations in eagle eggs were somewhat different among the three contaminants, the data indicate several likely point sources of contaminants along this shoreline. On Unalaska, ΣPCBs were elevated (3.9 μg/g) in one egg collected near Dutch Harbor and in eggs from nearby Akun and Akutan Islands (2.5–3.3 μg/g). In addition, one egg from Akun contained 2.6 μg/g DDE.

Association of contaminants to stable isotopes

Variation in concentrations of contaminants in eggs was not influenced by trophic status of eagles as estimated by δ^{15}N. No significant associations were found between concentrations of most contaminant groups in eggs and δ^{15}N ($t \leq -1.9$, $p \geq 0.06$, $r^2 \leq 0.02$) when controlling for variation among island groups. The only exceptions were negative associations between δ^{15}N and ΣCBZ ($t = -2.71$, $p = 0.007$, $r^2 = 0.05$) and ΣOTH ($t = -2.1$, $p = 0.04$, $r^2 = 0.03$), which were weak and contrary to our original predictions. In contrast, there were significant but weak ($r^2 < 0.09$) negative relations between concentrations of most contaminant groups and δ^{13}C, particularly for ΣPCB ($t = -2.7$, $p < 0.01$, $r^2 = 0.13$), DDE ($t = -3.3$, $p < 0.001$, $r^2 = 0.20$) and ΣDDT ($t = -3.6$, $p < 0.001$, $r^2 = 0.20$).

Productivity and eggshell thickness

Breeding success, productivity, and clutch size were high during this study. Productivity ranged from 1.08 young/occupied territory on east Adak during 2001 to 1.71 young/occupied territory on Amchitka during 2001. Mean productivity with years and islands combined was 1.36 young/occupied territory. Breeding success ranged from 63% on Amchitka in 2000 to 94% on Amchitka in 2001. Neither productivity nor breeding success differed significantly among years ($F < 2.95$, $p > 0.11$) or islands ($F < 0.92$, $p > 0.50$) during the study. Clutch size averaged 2.3 eggs per clutch across the archipelago and did not differ significantly among islands ($F < 1.0$, $p = 0.63$). Reduced breeding success was associated with egg collections during 2000 to 2002, as 53% of nests with egg collections failed compared to 35% failure for nests without egg collections.

Fresh eggs were slightly thicker ($x = 0.64$ mm, SE = 0.01) than unhatched eggs ($x = 0.61$ mm, SE = 0.01), but the difference was not statistically significant when accounting for variable concentrations of DDE and ΣPCBs (y intercepts: $t \leq 1.5$, $p \geq 0.14$). Eggshell thickness decreased with increasing concentrations of DDE ($t = -2.2$, $p = 0.03$), but with low predictability (partial $r^2 = 0.04$). Eggshell thickness was not associated with concentrations of ΣPCBs ($t = -1.8$, $p = 0.08$). Ratcliffe indices for eggshell density were similar between fresh (mean = 3.21, SE = 0.02) and unhatched eggs (mean = 3.20, SE = 0.02) and did not differ significantly with variable concentrations of DDE and ΣPCBs (y intercepts: $t \leq -0.4$, $p \geq 0.59$). Shell density declined with increasing DDE ($t = -2.0$, $p = 0.04$) but with low predictability (partial $r^2 = 0.03$). A nonsignificant ($r^2 = 0.15$, $p = 0.18$) relation existed between mean island productivity and DDE concentrations in eggs for the two study periods. Productivity was not related

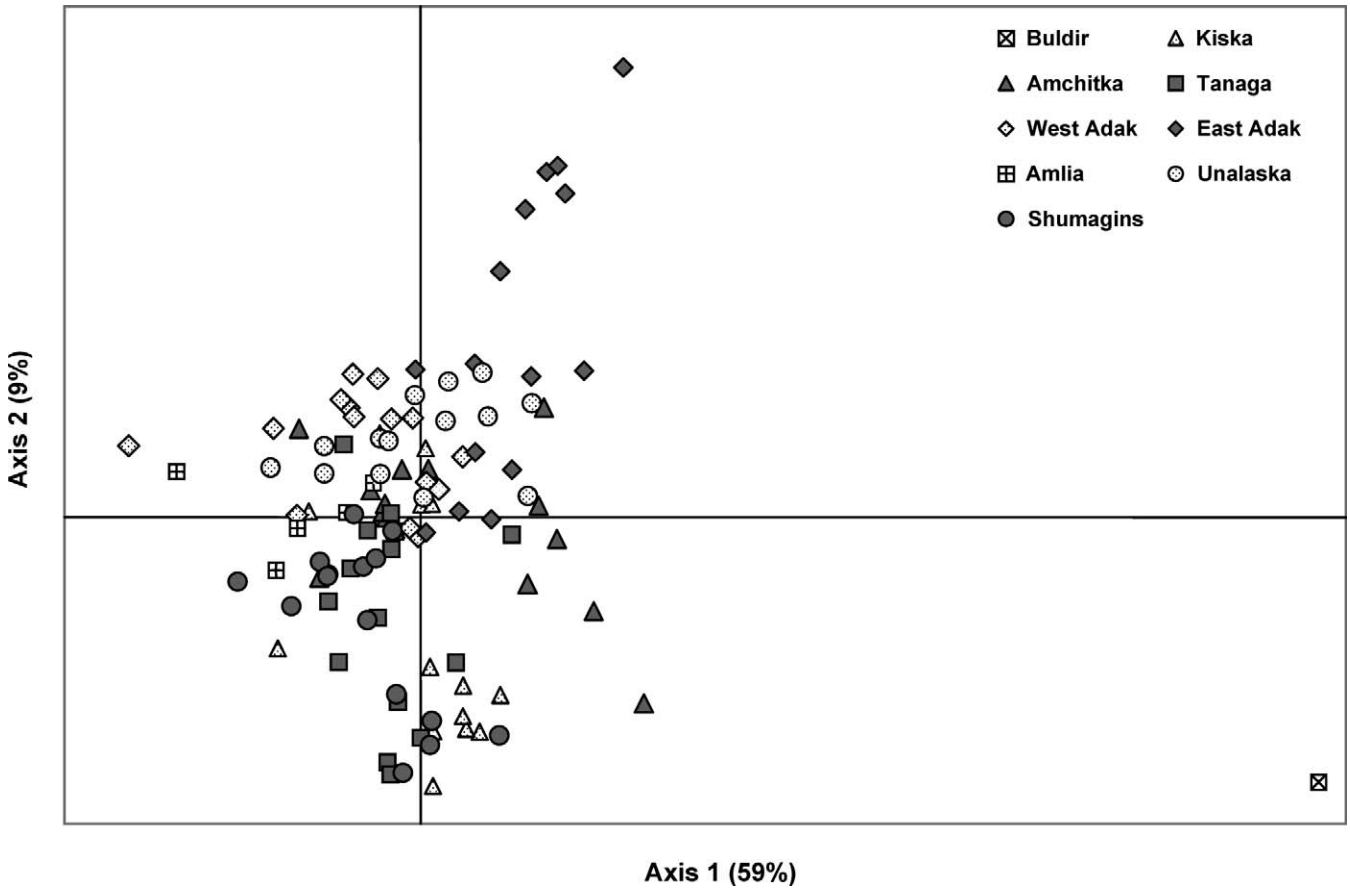

Fig. 3. Principal components analysis for polychlorinated biphenyl (PCB) congeners in fresh bald eagle eggs (n = 110) collected during 2000 through 2002 in the Aleutian archipelago, Alaska, USA. Sample units are individual eagle eggs, and scales are identical for each graph.

to concentrations of ΣPCBs (r^2 = 0.00, p = 0.47) or Hg (r^2 = 0.00, p = 0.94) across the two study periods, although it was significantly depressed (0.65 young/occupied site) on Kiska Island in 1993 and 1994.

DISCUSSION

Concentrations of PCBs, DDE, and Hg in bald eagle eggs were elevated in the Aleutian archipelago in this study, which allowed us to assess the potential impact and suggest the possible sources of these contaminants. Our results exemplified the utility of bald eagles as a monitoring species for environmental contaminants and support the results of others who have used the species similarly [8,11,14,32]. Bald eagles are a good sentinel species for environmental contaminants because they forage at the top of the food chain, accumulate high concentrations of contaminants [10], are relative sedentary as breeding adults [23], and are sensitive to moderate levels of contamination [8]. In addition, several studies have documented the effect of elevated concentrations of DDE in conjunction with PCBs and Hg on reproductive success of bald eagles [8,10,12,33]. The correlation between productivity and average concentrations of DDE in bald eagle eggs has been used to predict average productivity of local and regional bald eagle populations [8,10,12]. This relationship is expressed by the equation $Y = 1.070 - 0.489 \log_{10}X$, where Y is mean productivity (young produced per breeding pair) and X is mean DDE concentration in eggs [8]. Concentrations of DDE in the range of 3.0 to 12.0 μg/g in eggs have been shown to affect productivity of bald eagles [8,10], and concentrations of DDE >12 μg/g result in severely decreased reproduction and declines in local populations. A threshold value of 6 μg/g DDE in eggs has been suggested by Elliott and Harris [8] for effects on reproduction.

Contaminants, eggshell thickness, and productivity

The majority (>98%) of bald eagle eggs in this study had DDE concentrations below the threshold of 6 μg/g except for one egg from each of Amchitka and Buldir Islands. In addition, the low percentage of DDT in all samples indicated weathered rather than recent deposition of this compound. Furthermore, we found little evidence for eggshell thinning or reduced productivity of bald eagles during this study with the exception of Buldir Island. The egg from Buldir was the most contaminated with 8.4 μg/g DDE, 11.0 μg/g ΣPCBs, and 5.3 μg/g Hg, which may explain the apparent low reproduction of bald eagles there (J. Williams, U.S. Fish and Wildlife Service, Homer, AK, USA, personal communication). Our results were in contrast to those of Anthony et al. [5], who found reduced productivity on Kiska Island associated with elevated concentrations of DDE in eggs during 1993 and 1994. Why have DDE concentrations in bald eagle eggs declined and productivity increased on Kiska Island in such a short time frame? We offer three possible explanations for these differences. First, the sample of eggs from Kiska Island during 1993 and 1994 was small (n = 6) and may not have been representative of the population. Second, the sample of bald eagle eggs collected during 1993 and 1994 may have been from older females who had accumulated high levels of DDE with age, and these

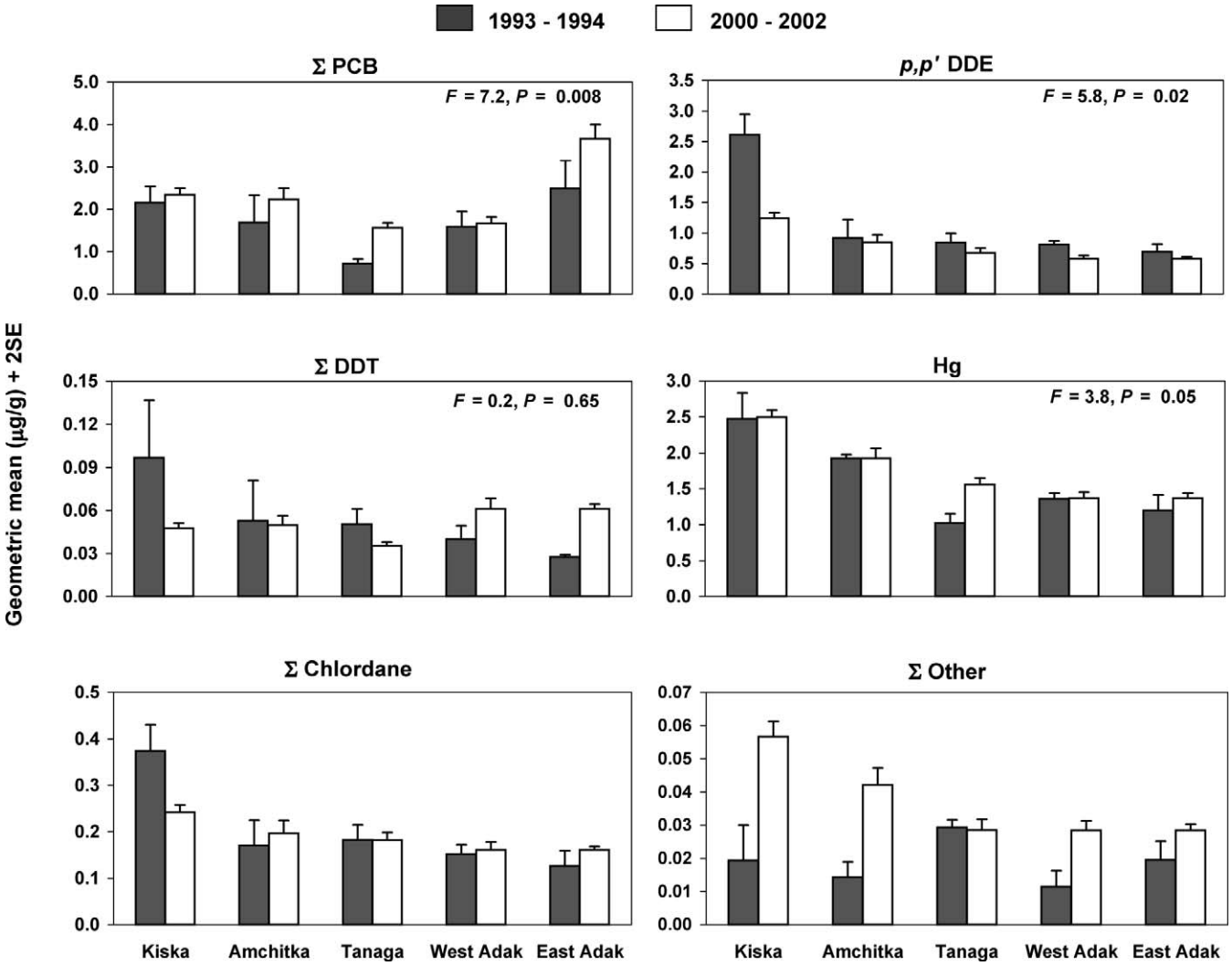

Fig. 4. Comparison of geometric mean concentrations of various contaminant groups in bald eagle eggs collected during 1993, 1994, and 2000 through 2002 in the Aleutian archipelago, Alaska, USA. *P* values refer to differences between study periods; no within-island study period combination differed significantly ($p \geq 0.06$); PCB = polychlorinated biphenyl; DDE = dichlorodiphenyldichloroethylene.

females were no longer living in 2000 to 2002. Third, the source of contaminants in bald eagles in 1993 and 1994 may have been from scavenging of marine mammal carcasses, which would be ephemeral in nature (see *Source of contaminants* section). Nonetheless, concentrations of DDE, chlordanes, and HCHs were lower in 2000 to 2002, and productivity was not depressed on Kiska Island. Productivity in 2000 to 2002 was indicative of healthy populations on all islands except Buldir during this study.

Source of contaminants

Concentrations of DDE, ΣPCBs, and Hg were elevated and sufficiently variable among the islands, so we were able to suggest some possible sources of these contaminants in food chains of the Aleutian archipelago. First, our results provide strong evidence for point sources of some contaminants. Concentrations of ΣPCBs in eagle eggs were highest in Kuluk Bay, particularly Sweeper Cove, at east Adak Island and were comprised by a higher proportion of the heavier PCB congeners. The pattern of ΣPCBs concentrations in bald eagle eggs from Kuluk Bay was strikingly similar to those in blue mussels from the same area (S.L. Reese, University of California, Santa Cruz, CA, USA, Master's thesis). This area had considerable military activity during World War II [1] and was the site of a U.S. Naval Base for approximately five decades thereafter. In addition, concentrations of DDE, ΣPCBs, and Hg in eagle eggs from the southern end of Amchitka Island were elevated. The southern end of Amchitka also had considerable military activity during World War II and was the site of various other military activities thereafter, including an atomic test site by the U.S. Atomic Energy Commission during the 20th century. Our results suggest that military activities were the likely source of these high concentrations of contaminants at specific locations on Adak and Amchitka Islands. Similar conclusions were made about the source of organochlorine contaminants in pelagic cormorants from the Aleutian archipelago [7]. We also found slightly elevated concentrations of DDE, ΣPCBs, and/or Hg in eagle eggs from Dutch Harbor on Unalaska Island and around nearby Akutan and Akun Islands. The source of contaminants at these sites was not apparent, but Dutch Harbor supports the largest fish processing industry in western Alaska and has a considerable amount of shipping activity.

The other possible sources of contaminants were complex and not easily partitioned between point and non–point sources. Nonetheless, our data provide evidence for non–point

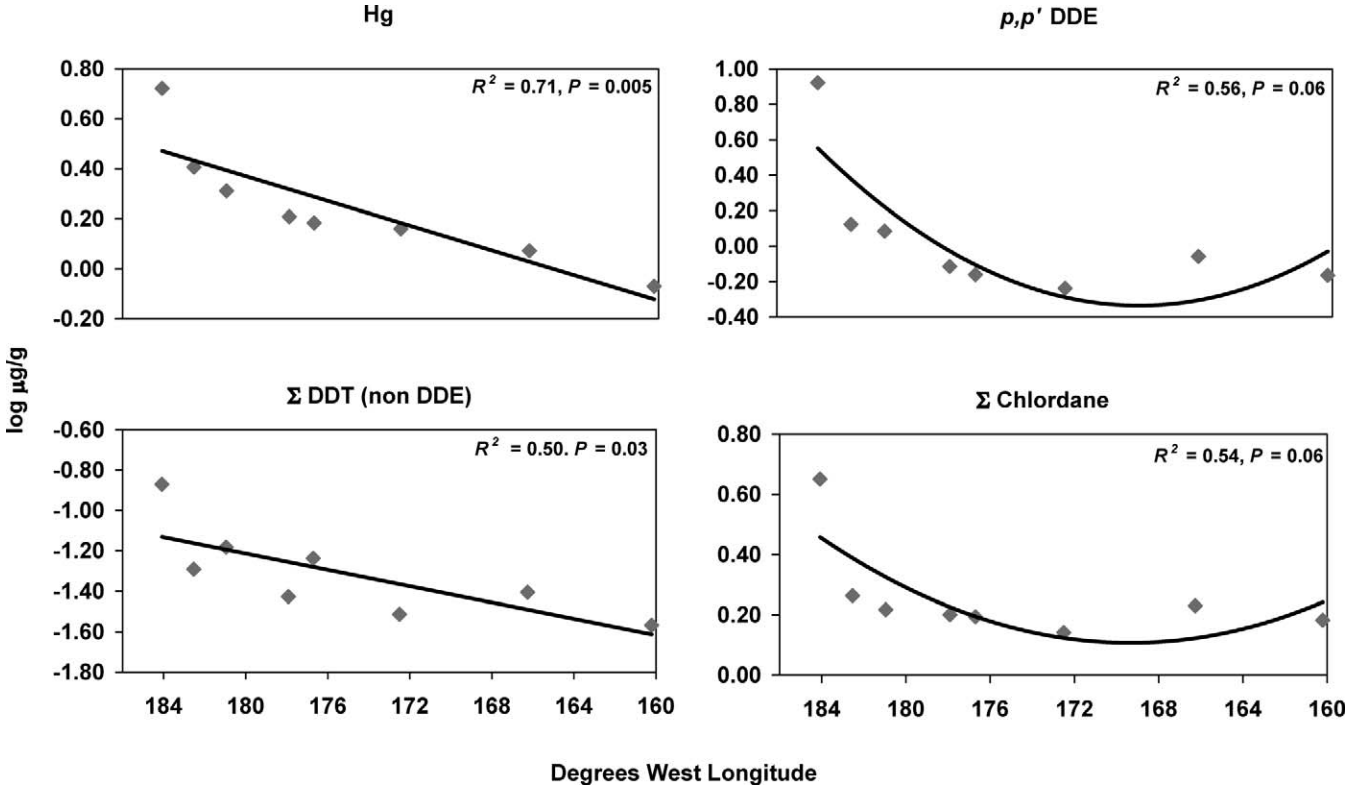

Fig. 5. Relations between longitude and log mean concentrations of various contaminant groups in bald eagle eggs collected during 2000 through 2004 in the Aleutian archipelago, Alaska, USA, including Buldir; DDE = dichlorodiphenyldichloroethylene.

sources of contaminants from atmospheric transport and distillation, oceanic currents, or migratory seabirds. First, concentrations of DDE, ΣPCBs, and Hg were elevated in eagle eggs from islands that had little military or other human activity (e.g., Amlia, Tanaga, Buldir) indicating non–point sources of contaminants. Second, our results show a distinct pattern of east-to-west increases in DDE and Hg in eagle eggs in the Aleutian Islands. Third, higher concentrations of lighter molecular weight PCB congeners and Hg were detected at the more westerly islands (e.g., Kiska and Buldir). The higher concentrations of the lighter more volatile compounds in the western Aleutians support the hypothesis of global transport and atmospheric deposition of these contaminants from Eurasia. Contaminant residues originating from agricultural or industrial activities often are transported long distances by the atmosphere and deposited into arctic regions through global distillation [34–36]. Compounds with DDT have been used recently throughout most of the world, particularly in Japan, Russia, and China, so it is possible that DDE and Hg are being transported to the Aleutian archipelago via atmospheric and oceanic currents from eastern Eurasia [37].

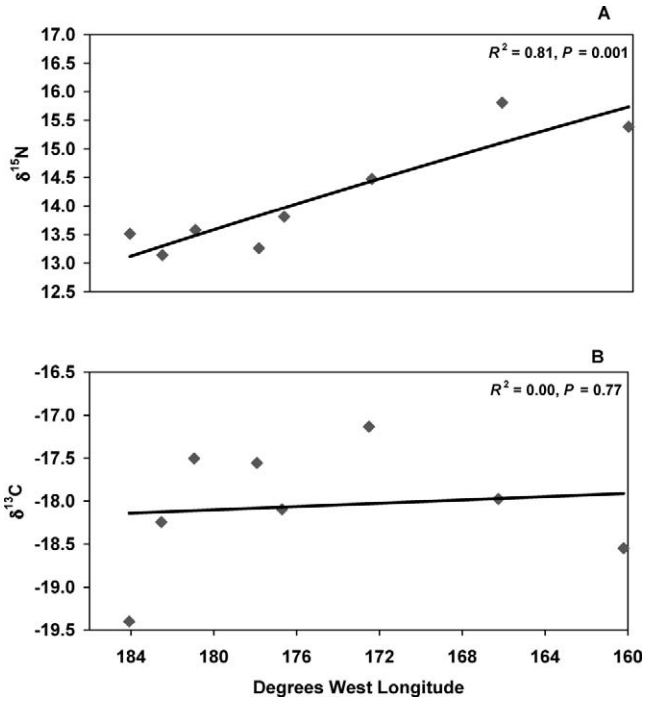

Fig. 6. Relationship between longitude and mean δ^{15}N (**A**) and δ^{13}C (**B**) in bald eagle eggs collected during 2000 through 2004 in the Aleutian archipelago, Alaska, USA, including Buldir.

Our data provide two lines of evidence that implicate migratory seabirds as a non–point source for contaminants in bald eagles. First, the lack of significant relations between δ^{13}C and longitude and the slight negative trend between contaminant concentrations and δ^{13}C suggests a pelagic source of contaminants (see below). Second, we found the highest concentrations of DDE and Hg in eagle eggs from Kiska and Amchitka Islands, where marine birds comprised a higher portion of their diet compared to Adak and Tanaga Islands [5]. Admittedly, this latter pattern is somewhat confounded by the east-to-west increase and possible atmospheric source of these contaminants. Rocque and Winker [7] found no evidence that migratory prey were a source of contaminants in cormorants in the Aleutian archipelago; however, cormorants feed locally on small fish, whereas bald eagles consume a wider range of prey, including marine birds [5]. Data on contaminant concentrations in seabirds along with the geographic distribution

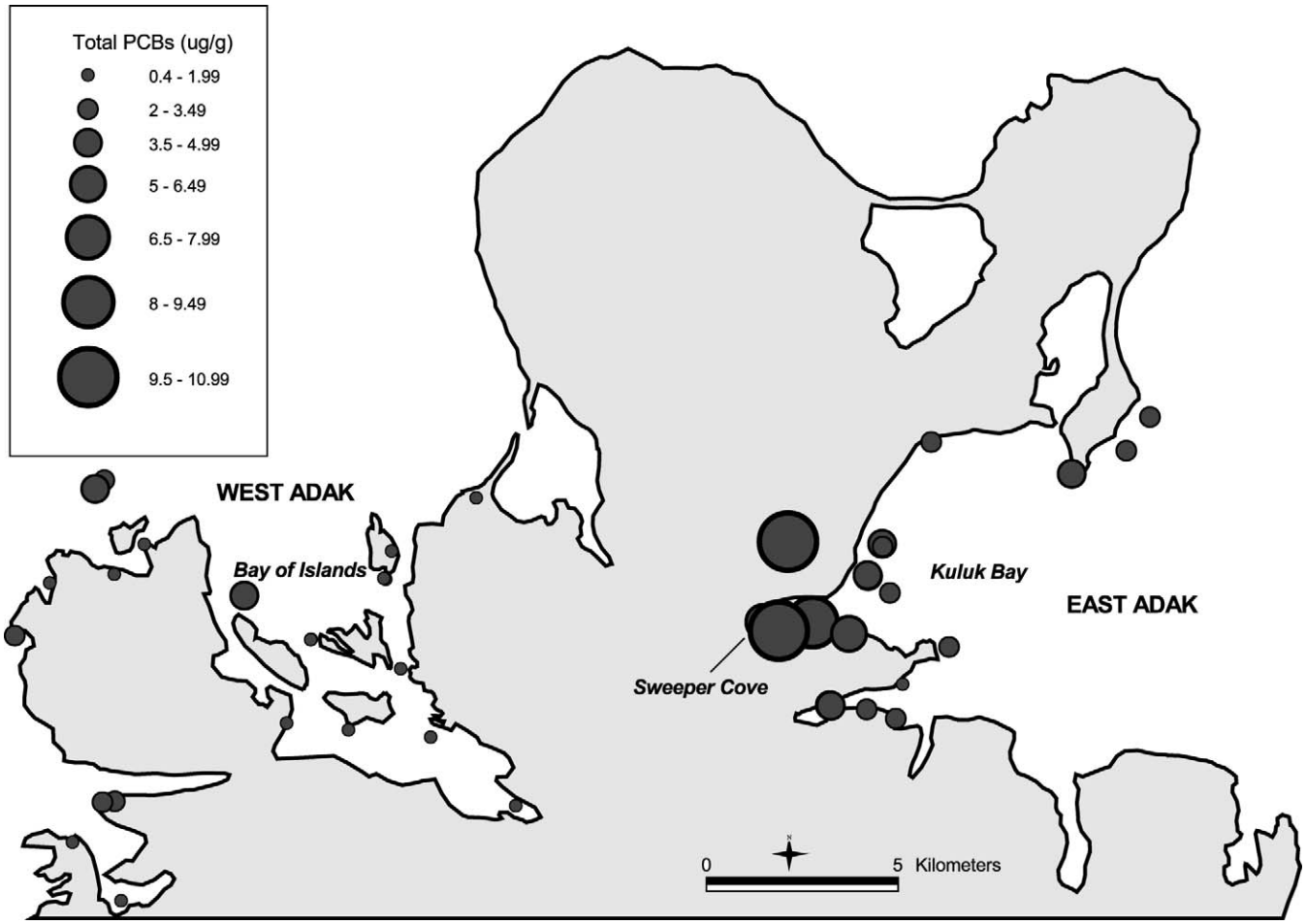

Fig. 7. Spatially explicit concentrations of Σpolychlorinated biphenyls (PCBs) in bald eagle eggs collected from Adak Island, Alaska, USA, 2000 through 2002.

of these contaminants is necessary to fully assess this potential source of contaminants to bald eagles in the Aleutian archipelago.

Another potential source of contaminants to bald eagles is the scavenging of marine mammal carcasses. Marine mammals often contain high concentrations of contaminants [38–40], and bald eagles are known to scavenge on dead carcasses of many species of animals. For example, we observed up to 20 individual bald eagles scavenging on a dead killer whale (*Orcinus orca*) on the south side of Kiska Island in the spring of 2001, and carcasses of harbor seals (*Phoca vitulina*), Steller's sea lions, and various whale species are likely available from time to time. This source of contaminants is highly variable spatially and temporally and difficult to trace, but it could be an important source to bald eagle populations in the Aleutian Islands.

Association between contaminant concentrations and stable isotopes

We predicted higher $\delta^{15}N$ in eagle eggs from the western Aleutian Islands, which would be correlated positively to contaminant concentrations, because seabirds comprise a higher portion of their diet than in the western Aleutians [5]. We found no support for this prediction, which indicated that contaminant uptake was influenced more by longitude and/or proximity to point sources than trophic status of bald eagles among islands. Another study of environmental contaminants and stable isotopes in bald eagles also failed to find a positive correlation between $\delta^{15}N$ and ΣPCBs, DDE, or Hg in blood plasma from nestling bald eagles in Newfoundland [41]. In contrast, Hg concentrations and $\delta^{15}N$ in blood of adult bald eagles but not eaglets in British Columbia, Canada, were positively correlated [42]. Concentrations of Hg were correlated positively with the proportion of secondary consumers in the diet of Bonelli's eagles from Southwest Portugal [16], but they did not characterized trophic position with stable isotopes. At least three reasons explain why contaminant concentrations in eagle eggs were not positively related to $\delta^{15}N$ in our study. First, isotope contaminant studies usually examine biomagnification over multiple species/trophic levels [19], whereas we restricted our investigation to a single species. Second, analysis of relations between contaminants and stable isotopes in eggs may be problematic because egg isotopes likely reflect dietary input during egg formation and relatively little endogenous input [43], although contaminant concentrations often represent accumulation of body burdens over a longer time frame [18]. Finally, we have to assume relatively constant levels of $\delta^{15}N$ in phytoplankton that form the base of near-shore food webs across the Aleutians Islands in order to implicate point or distant sources outweighed trophic effects on contaminant uptake. The significant eastward enrichment in $\delta^{15}N$ in our study suggests that either bald eagles in the eastern Aleutians foraged at a higher trophic level or baseline ^{15}N varied among nearshore food webs. Information on diets of bald eagles in the Aleutians

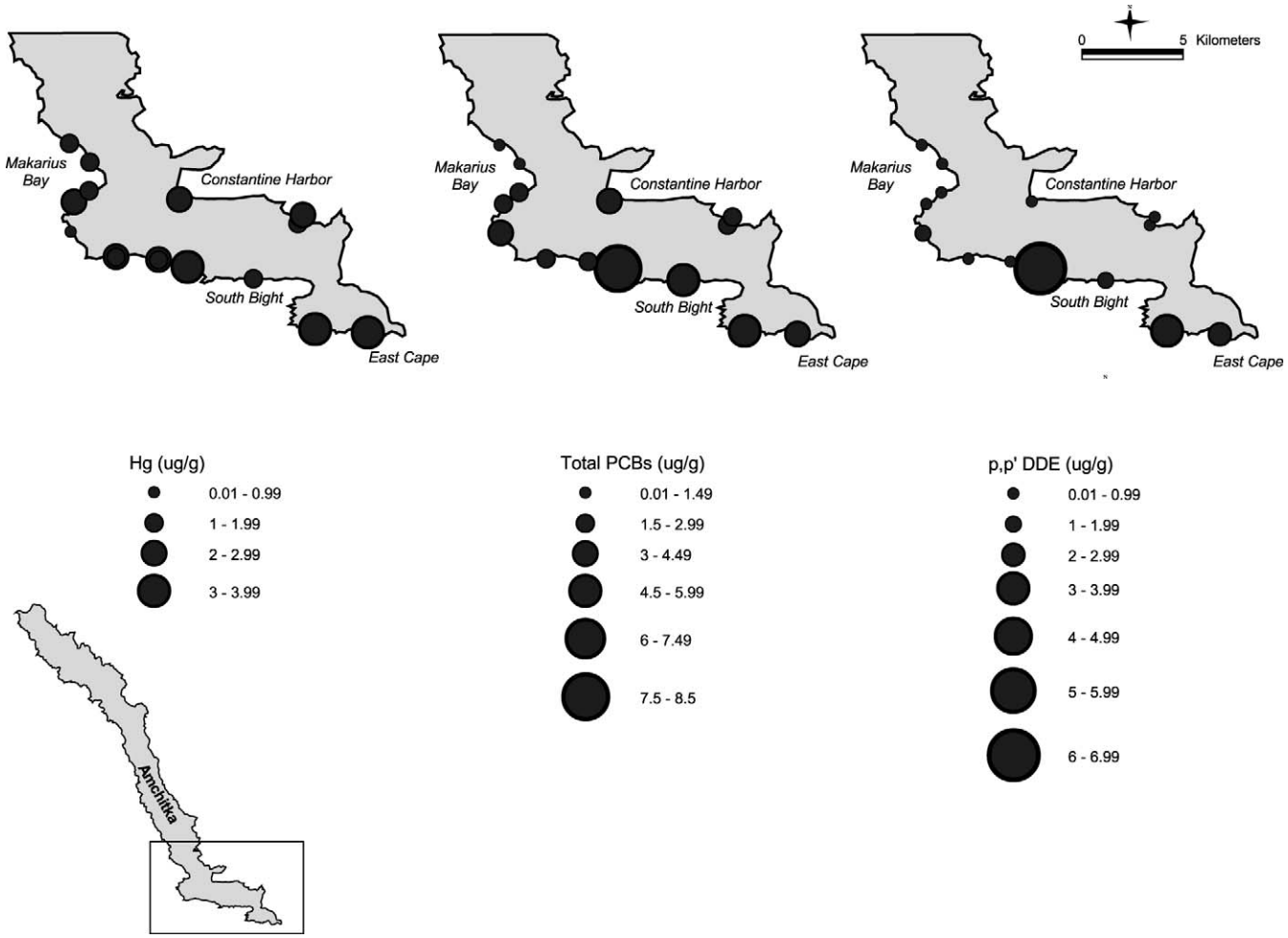

Fig. 8. Spatially explicit concentrations of Hg, ΣPCBs, and *p,p′*-dichlorodiphenyldichloroethylene (DDE) in fresh bald eagle eggs collected from Amchitka Island, Alaska, USA, during 2000–2002. Note concentration scale differs among contaminants.

suggests the former is not true [5], but we have little data on diets of bald eagles in the eastern Aleutians. Isotopic baselines of food webs may be lower in the western Aleutians due to slower growth rates of phytoplankton and/or excess nutrients in surface waters, so values of nitrogen isotopes across large geographic areas should be interpreted with caution. Although trophic effects may have been masked by elevated $\delta^{15}N$ in the eastern Aleutian and Shumagin Islands, our statistical analyses of contaminant concentrations versus $\delta^{15}N$ and $\delta^{13}C$ controlled for variation among island groups. This provides stronger support for point or distant sources of contaminant input than trophic level of foraging by bald eagles (see above).

We also predicted a decrease in $\delta^{13}C$ in eagle eggs from east to west similar to that reported for zooplankton [22] and pelagic cormorants [7]. This eastward enrichment of $\delta^{13}C$ in cormorants [7] tracked trends in plankton [22] and suggested that cormorants feed in localized food webs with minimal input from migratory prey in their diet. In contrast, the lack of a significant relation between $\delta^{13}C$ and longitude and the weak relation between $\delta^{13}C$ and contaminant concentrations in our study suggests that bald eagles were acquiring their food from more distant sources, notably migratory seabirds. Also, higher proportions of piscivorous seabirds have been observed in the diets of bald eagles nesting in the western Aleutian Islands where concentrations of contaminants were highest (this study and [5]). Our carbon and nitrogen isotope data provided evidence that geography of egg collections, due to either local point or distant sources, explained more variation in contaminants than trophic status of eagles.

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REFERENCES

1. Garfield B. 1969. *The Thousand Mile War: World War II in Alaska and the Aleutians.* University of Alaska Press, Fairbands, AK, USA.
2. Croll DA, Maron JL, Estes JA, Danner EM, Byrd GV. 2005. Introduced predators transform subarctic islands from grassland to tundra. *Science* 307:1959–1961.
3. Merritt ML, Fuller RG. 1977. The environment of Amchitka Island, Alaska. Publication TID-26712. National Technical Information Service, Springfield, VA, USA.
4. Estes JA, Bacon CE, Jarman WM, Nordstrom RJ, Anthony RG, Miles AK. 1997. Organochlorines in sea otters and bald eagles from the Aleutian Archipelago. *Mar Pollut Bull* 34:1–5.
5. Anthony RG, Miles AK, Estes JA, Isaacs FB. 1999. Productivity,

diets, and environmental contaminants in nesting bald eagles from the Aleutian Archipelago. *Environ Toxicol Chem* 18:2054–2062.
6. Stout JH, Trust KA. 2002. Elemental and organochlorine residues in bald eagles from Adak Island, Alaska. *J Wildl Disease* 38: 511–517.
7. Roque DA, Winker K. 2004. Biomonitoring of environmental contaminants in birds from two trophic levels in the North Pacific. *Environ Toxicol Chem* 23:759–766.
8. Elliott JE, Harris ML. 2001. An ecotoxicological assessment of chlorinated hydrocarbon effects on bald eagle populations. *Rev in Toxicol* 4:1–60.
9. Elliot JE, Wilson LK, Langelier KW, Norstrom RJ. 1996. Bald eagle mortality and chlorinated hydrocarbon contaminants in livers from British Columbia, Canada, 1989–1994. *Environ Pollut* 94:9–18.
10. Wiemeyer SN, Lamont TG, Bunck CM, Sindelar CR, Gramlich RJ, Fraser JD, Byrd MA. 1984. Organochlorine pesticide, polychlorobiphenyl, and mercury residues in bald eagle eggs (1969–1979) and their relationships to shell thinning and reproduction. *Arch Environ Contam Toxicol* 13:529–549.
11. Kozie KD, Anderson RK. 1991. Productivity, diet, and environmental contaminants in bald eagles nesting near the Wisconsin shoreline of Lake Superior. *Arch Environ Contam Toxicol* 20: 41–48.
12. Anthony RG, Garrett MG, Schuler CA. 1993. Environmental contaminants in bald eagles in the Columbia River estuary. *J Wildl Manage* 57:10–19.
13. Grier JW. 1982. Ban of DDT and subsequent recovery of reproduction in bald eagles. *Science* 218:1232–1234.
14. Bowerman WW, Best DA, Grubb TG, Zimmerman GM, Giesy JP. 1998. Trends of contaminants and effects in bald eagles of the Great Lakes basin. *Environ Monitor Assess* 53:197–212.
15. Kenntner N, Krone O, Oehme G, Heidecke D, Tataruch F. 2003. Organochlorine contaminants in body tissue of free-ranging white-tailed eagle from northern regions of Germany. *Environ Toxicol Chem* 22:1457–1464.
16. Palma L, Beja P, Tavares PC, Monteiro LR. 2005. Spatial variation of mercury levels in nesting Bonelli's eagles from southwest Portugal. *Environ Pollut* 134:549–557.
17. Bacon CE, Jarman WM, Estes JA, Simon M, Norstrom RJ. 1999. Comparison of organochlorine contaminants among sea otter (*Enhydra lutris*) populations in California and Alaska. *Environ Toxicol Chem* 18:452–458.
18. Jarman WM, Hobson KA, Sydeman WJ, Bacon CE, McLaren EB. 1996. Influence of trophic position and feeding location on contaminant levels in the Gulf of the Farallones food web revealed by stable isotope analysis. *Environ Sci Technol* 30:654–660.
19. Fisk AT, Hoekstra PF, Gagnon J, Duffe J, Norstrom RJ, Hobson KA, Kwan M, Muir DCG. 2003. Influence of habitat, trophic ecology and lipids on, and spatial trends of, organochlorine contaminants in Arctic marine invertebrates. *Mar Ecol Progr Ser* 262:201–214.
20. Kelly JF. 2000. Stable isotopes of carbon and nitrogen in the study of avian and mammalian trophic ecology. *Can J Zool* 78:1–27.
21. France RL. 1995. Carbon-13 enrichment in benthic compared to planktonic algae: Food web implications. *Mar Ecol Progr Ser* 124:307–312.
22. Schell DM, Barnett BA, Vinette KA. 1998. Carbon and nitrogen isotope ratios in zooplankton of the Bering, Chukchi, and Beaufort Seas. *Mar Ecol Progr Ser* 162:11–23.
23. Garrett MG, Watson JW, Anthony RG. 1993. Bald eagle home range and habitat use in the Columbia River estuary. *J Wildl Manage* 57:10–19.
24. Postupalsky S. 1974. Raptor reproductive success: Some problems with methods, criteria, and terminology. In Hamerstrom FN Jr, Harrell BE, Ohlendorff RR, eds, *Management of Raptors.* Raptor Research Foundation. Vermillion, SD, USA, pp 21–31.
25. MacLoed WD, Brown KW, Friedman AJ, Burrow DG, Mayes O, Pearce RW, Wigren CA, Bogar RG. 1985. Standard analytical procedures of the NOAA National Analystical Facility 1985–1986. Extractable toxic organic compounds, 2nd ed. NOAA Technical Memorandum NMFS F/NWRC-92. U.S. Department of Commerce, Washington, DC, USA.
26. Wade TL, Atlas EL, Brooks JM, Kennicutt MC, Fox RG, Sericano J, Garcia B, Dereitas D. 1988. NOAA Gulf of Mexico status and trends program: Trace organic contaminant distribution in sediments and oysters. *Estuaries* 11:171–179.
27. Brooks JM, Wade TL, Atlas EL, Kennicutt MC, Pressley BJ, Fay RR, Powell EN, Wolff G. 1989. Analysis of bivalves and sediments for organic and trace elements. Third Annual Report, NOAA's National Status and Trends Program, Contract 50-DGNC-5-00262. Washington, DC.
28. Dobush GR, Ankney CD, Krementz DG. 1985. The effect of apparatus, extraction time, and solvent type on lipid extractions of snow geese. *Can J Zool* 63:1917–1920.
29. Anthony RG, Frenzel RW, Isaacs FB, Garrett MG. 1994. Probable causes of nesting failures in Oregon's bald eagle population. *Wildl Soc Bull* 22:576–582.
30. Gilbert RO. 1987. *Statistical Methods for Environmental Pollution Monitoring.* Van Nostrand Reinhold, New York, NY, USA.
31. Malcolm HM, Osborn D, Wright J, Wienberg CL, Sparks TH. 2003. Polychlorinated biphenyl (PCB) congener concentrations in seabirds found dead in mortality incidents around the British coast. *Arch Environ Contam Toxicol* 45:136–147.
32. Bowerman WW, Best DA, Grubb TG, Sikarskie JG, Giesy JP. 2000. Assessment of environmental endocrine disruptors in bald eagles of the Great Lakes. *Chemosphere* 41:1569–1574.
33. Bowerman WW, Best DA, Giesy JP, Shieldcastle MC, Myer MW, Postupalsky S, Sikarskie JG. 2003. Associations between regional differences in polychlorinated biphenyls and dichloroidphenyldichloroethylene in blood of nestling bald eagles and reproductive productivity. *Environ Toxicol Chem* 22:371–376.
34. Barrie LA, Gregor D, Hargrave B, Lake R, Muir D, Shearer R, Tracey B, Bidleman T. 1992. Arctic contaminants: Sources, occurrence, and pathways. *Sci Total Environ* 122:1–74.
35. Muir D, Wagemann R, Hargrave BT, Peakall DJ, Norstrom RJ. 1992. Arctic marine ecosystem contamination. *Sci Total Environ* 122:75–134.
36. Iwata HS, Tanabe S, Sakai N, Tatsukawa R. 1993. Distribution of persistent organochlorines in the oceanic air and surface seawater and the role of ocean on their global transport and fate. *Environ Sci Technol* 27:1080–1098.
37. Arctic Monitoring Assessment Program. 2004. *AMAP Assessment 2002: Persistent organic pollutants (POPs) in the Arctic.* (AMAP), XVI. Oslo, Norway.
38. Vetter W, Luckas B, Heidemann G, Skirnisson K. 1996. Organochlorine residues in marine mammals for the northern hemisphere. A consideration of the composition of organochlorine residues in the blubber of marine mammals. *Sci Total Environ* 186:29–39.
39. Becker PR. 2000. Concentrations of chlorinated hydrocarbons and heavy metals in Alaska Arctic marine mammals. *Mar Pollut Bull* 40:819–829.
40. Hoekstra PF, O'Hara TM, Fisk AT, Borga K, Solomon KR, Muir DCG. 2003. Trophic transfer of persistent organochlorine contaminants (OCs) within an Arctic marine food web from the southern Beaufort and Chukchi Seas. *Environ Pollut* 124:509–522.
41. Dominguez L, Montevecchi WA, Burgess NM, Brazil J, Hobson KA. 2003. Reproductive success, environmental contaminants, and trophic status of nesting Bald Eagles in eastern Newfoundland, Canada. *J Raptor Res* 37:209–218.
42. Weech SA, Scheuhammer AM, Elliott JE. 2006. Mercury exposure and reproduction in fish-eating birds breeding in the Pinchi Lake region, British Columbia, Canada. *Environ Toxicol Chem* 25:1433–1440.
43. Hobson KA, Sirois J, Gloutney ML. 2000. Tracing nutrient allocation to reproduction with stable isotopes: A preliminary investigation using colonial waterbirds at Great Slave Lake. *Auk* 117:760–774.