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CHANGES IN PRODUCTIVITY AND CONTAMINANTS IN BALD EAGLES NESTING ALONG THE LOWER COLUMBIA RIVER, USA

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Abstract—Previous studies documented poor productivity of bald eagles (*Haliaeetus leucocephalus*) in the lower Columbia River (LCR), USA, and elevated *p,p′*-dichlorodiphenyldichloroethylene (DDE), polychlorinated biphenyls (PCBs), dioxins, and furans in eagle eggs. From 1994 to 1995, we collected partially incubated eggs at 19 of 43 occupied territories along the LCR and compared productivity and egg contaminants to values obtained in the mid-1980s. We found higher productivity at new nesting sites along the river, yet productivity at 23 older breeding territories remained low and was not different ($p = 0.713$) between studies. Eggshell thickness at older territories had not improved ($p = 0.404$), and eggshells averaged 11% thinner than shells measured before dichlorodiphenyltrichloroethane use. Decreases in DDE ($p = 0.022$) and total PCBs ($p = 0.0004$) in eggs from older breeding areas occurred between study periods. Productivity was not correlated to contaminants, but DDE, PCBs, and dioxin-like chemicals exceeded estimated no-effect values. Some dioxin-like contaminants in eggs were correlated to nest location, with highest concentrations occurring toward the river's mouth where productivity was lowest. Although total productivity increased due to the success of new nesting pairs in the region, egg contaminants remain high enough to impair reproduction at older territories and, over time, may alter productivity of new pairs nesting near the river's mouth.

Keywords—*Haliaeetus leucocephalus* *p,p′*-Dichlorodiphenyldichloroethylene Polychlorinated biphenyls Dioxins Toxic equivalents

INTRODUCTION

The lower Columbia River (LCR), located along the border of Oregon and Washington, USA (Fig. 1), provides an important foraging and nesting habitat for bald eagles (*Haliaeetus leucocephalus*), which currently are listed in Oregon and Washington as threatened under the Endangered Species Act of 1973 (http://endangered.fws.gov/esa.html). Bald eagle nesting territories and productivity along the LCR have been monitored since the early 1970s, and the number of occupied nesting territories has increased each year. By 1997, 60 resident pairs of bald eagles occupied sites along the LCR, along with a wintering population of over 100 birds ([1], F.B. Isaacs et al., Oregon State University, Corvallis, OR, USA, unpublished data). However, five-year running productivity averages of eagles in the LCR have been nearly half that of statewide averages for eagles nesting elsewhere in Washington and Oregon (F.B. Isaacs et al., Oregon State University, Corvallis, OR, USA, unpublished data), where many of the recovery goals required to remove the species from the Endangered Species List have been achieved.

Organochlorine (OC) pesticides, including dichlorodiphenyltrichloroethane (DDT), dieldrin, and their analogs, have been implicated in causing declines in bald eagle populations, either through direct mortality or by impacting breeding success [2–4]. Bald eagle populations have rebounded nationwide since the ban of DDT and other OC pesticides in the 1970s [2]. However, the reproductive success of some subpopulations of bald eagles has not improved substantially [5–7]. During a study conducted along the LCR from 1985 to 1987, Anthony et al. [5] found elevated concentrations of *p,p′*-dichlorodiphenyldichloroethylene (DDE) and polychlorinated biphenyls (PCBs) in partially incubated (fresh) bald eagle eggs, in blood obtained from eight- to 10-week-old nestlings, and in eagle carcasses collected near the river. The presence of DDE and PCBs in blood of eagle nestlings provided evidence of exposure from contaminated prey from the river [5]. Addled eagle eggs collected in 1991 and fresh eggs from 1987 also exhibited elevated concentrations of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD) and 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDF) [5]. By 1987, eagles occupied 23 territories along the river and experienced five-year running productivity averages 30 to 50% lower than statewide values for every year evaluated.

In this study, we determined if OC contaminants continued to accumulate in bald eagles along the LCR, and assessed whether dioxin-like compounds could be contributing to the poor reproductive success observed in eagles in this area. Specifically, the objectives were to compare OC contaminants in bald eagle eggs to estimated no-effect threshold concentrations, evaluate the relationship between contaminant concentrations, productivity, and nest location along the river, and determine if contaminant concentrations and productivity changed over time.

MATERIALS AND METHODS

Productivity surveys and egg collection

Productivity (the number of young produced per occupied territory) was determined for bald eagles along the LCR (Fig.

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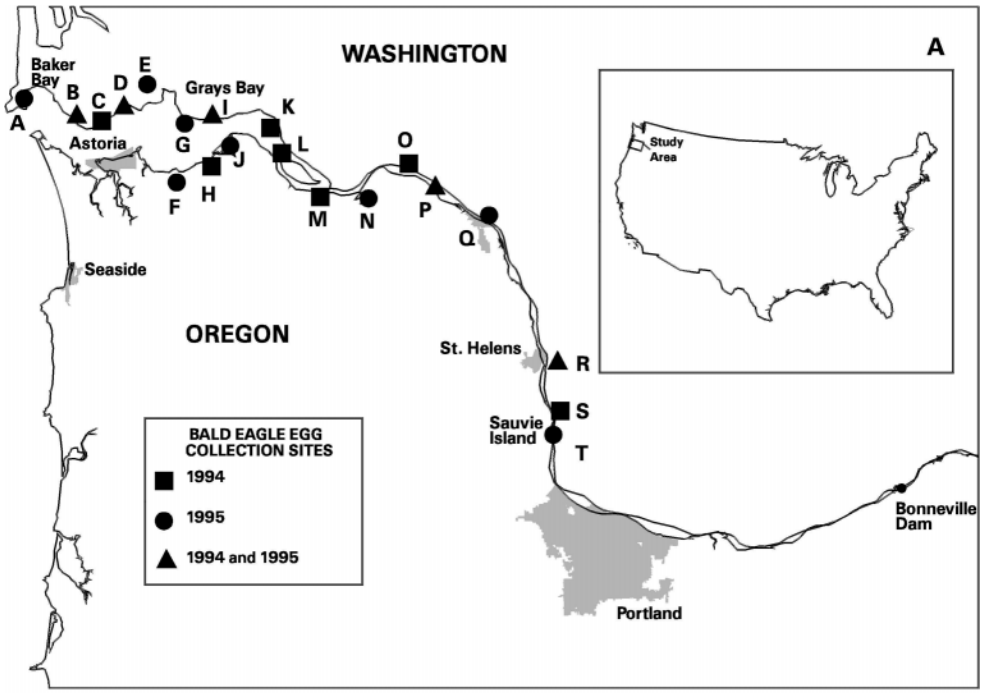
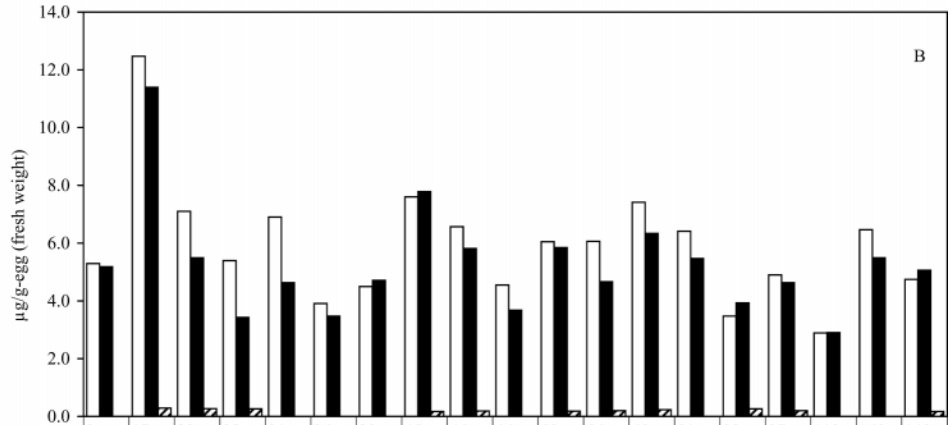




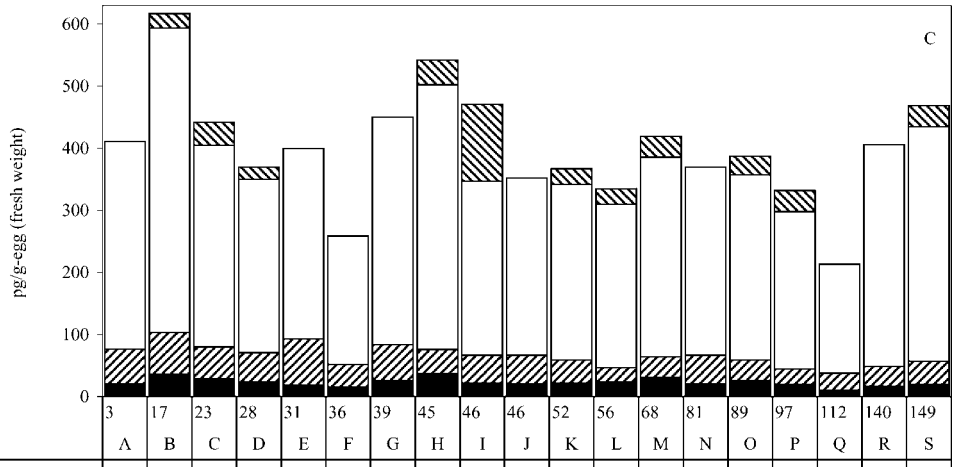
	3	17	23	28	31	36	39	45	46	46	52	56	68	81	89	97	112	140	149
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
□ p,p' DDE	5.29	12.5	7.10	5.39	6.90	3.91	4.50	7.60	6.57	4.55	6.05	6.06	7.41	6.41	3.47	4.90	2.89	6.46	4.74
■ Total PCBs	5.18	11.4	5.49	3.43	4.63	3.47	4.71	7.78	5.81	3.68	5.84	4.66	6.34	5.47	3.93	4.63	2.90	5.49	5.06
▨ Mercury		0.29	0.27	0.26				0.17	0.19		0.18	0.20	0.23		0.26	0.20			0.17

Fig. 1. Bald eagle nest site locations along the lower Columbia River, USA, where eggs or shell fragments were collected (**A**) and contaminant concentrations in eggs from individual nest sites (**B** and **C**). Data table below *x* axis (**B** and **C**) contains river kilometer, map letter, and egg-contaminant concentrations listed from top to bottom of column (DDE = *p,p′*-dichlorodiphenyldichloroethylene). Toxic equivalents (TEQ) were calculated using dioxins and furans (D/F), non-*ortho*–substituted polychlorinated biphenyls (nPCB), and non- and mono-*ortho*–substituted PCBs (nmPCB). Eggshell fragments only were collected at site T. TCDD = 2,3,7,8-tetrachlorodibenzo-*p*-dioxin.

1) using methods and terminology described by Postupalsky [8]. An occupied breeding territory was the area surrounding one or more nest trees used by one breeding pair of bald eagles [8]. Territories were surveyed by helicopter three times from April to July, in combination with information gained from trained ground crews, to determine site occupancy and final nest outcome.

A total of 25 eggs from 19 of 43 different breeding territories were collected over the two-year study, representing nearly half the population of eagles nesting along the lower river. Nine fresh and five addled eggs were collected from 12 territories in 1994, and eight fresh and three addled eggs from 11 territories in 1995. Nest trees were climbed by a professional tree climber, and collected eggs were wrapped in aluminum foil, transported on wet ice to a field office, and stored at 3°C. Length, breadth, whole egg mass, and volume by water displacement were measured on each egg within 24 h of collection. Eggs were opened by cutting along the equator and contents placed into a chemically clean glass jar. Eggshells were rinsed and set aside to dry and egg contents were stored at −20°C pending overnight shipment to analytical laboratories.

Eggshell thickness (shell and membranes) was determined using a dial micrometer with ball contacts on 25 bald eagle eggs collected intact, and on eggshell fragments from four damaged eggs with pieces large enough to approximate the equator region. An average of 10 measurements was collected on eggshell halves from whole eggs, and five measurements



	3 A	17 B	23 C	28 D	31 E	36 F	39 G	45 H	46 I	46 J	52 K	56 L	68 M	81 N	89 O	97 P	112 Q	140 R	149 S
TEQ-nmPCB		617	442	370				542	471		367	335	419		387	332			469
TEQ-nPCB	411	594	405	350	400	259	450	502	347	352	342	310	386	370	357	298	213	406	435
TEQ-D/F	77	103	80	71	93	52	84	76	67	67	59	47	64	67	59	45	38	49	57
2378-TCDD	21	36	29	24	19	16	26	37	22	21	22	24	31	21	26	20	10	17	20

Fig. 1. Continued.

on damaged eggshells. Membrane thickness was estimated as 0.13 mm (S. Wiemeyer, U.S. Fish and Wildlife Service, Reno, NV, personal communication) for eggshells with detached membranes and added to the mean thickness measurement. Eggshell thinning was estimated as the percent difference between the eggshell thickness of each LCR egg and the mean bald eagle eggshell thickness (0.6088 mm) determined on museum specimens collected in the Northwest before 1947 (pre-DDT; D. Anderson, University of California, Davis, CA, USA, personal communication).

Chemical analysis

Organochlorine pesticides and total PCBs in 1994 egg samples were analyzed at Hazleton Laboratories America (Madison, WI, USA) as described by the U.S. Environmental Protection Agency [9]. These compounds were analyzed in 1995 samples at the U.S. Geological Survey's Columbia Environmental Research Center (Columbia, MO) following methods of Schmitt et al. [10]. Briefly, samples were cleaned up using gel-permeation chromatography and silica gel was used to separate PCBs from OC pesticides. Analytes were determined by capillary gas chromatography/electron capture detection. The detection limits for 1994 samples were 20 ng/g for most OC pesticides and 90 ng/g for total PCBs and toxaphene. For 1995 samples, detection limits ranged from 0.05 to 0.13 ng/g for OC pesticides and 29 ng/g for total PCBs.

Total mercury was analyzed only in eggs collected in 1994. Mercury was analyzed at Hazelton Laboratories following procedures by Monk [11], including digestion with a mixture of sulfuric and nitric acids and reduction of mercury using sodium borohydride. Mercury was determined by cold-vapor atomic absorption [12]. The detection limit for this procedure was <0.01 μg/g.

Dioxin-like compounds, including the polychlorinated dibenzo-*p*-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and non- and mono-*ortho*–chlorine–substituted PCBs (planar PCBs), were analyzed according to Feltz et al. [13] at the Columbia Environmental Research Center. Due to limited funding, the mono-*ortho* PCB congeners were analyzed only in 1994 samples. Extracts were treated by a two-stage reactive cleanup using silica gel and purified with high-performance gel-phase chromatography. Analytes were separated by an automated C-18/PX-21 carbon column high-performance liquid chromatography system (Perkin-Elmer, Boston, MA, USA) [13] and potential cocontaminants (polychlorinated diphenyl ethers and residual polychlorinated naphthalenes and PCBs) were removed from the PCDD/PCDF fraction using basic alumina. Mono-*ortho* PCBs were determined by capillary gas chromatography/electron capture detection [14], and PCDD/PCDF and non-ortho PCB fractions were determined by gas chromatography/high-resolution mass spectrometry monitoring five sequential windows of selected ions during the chromatographic separation [15]. The detection limits for most dioxin and furan congeners ranged from 0.1 to 0.9 pg/g. However, some chlorinated dibenzodioxins (CDDs), such as 1,2,3,4,6,7,8-heptaCDD in 1995 samples, were not quantitated below 3.0 or 4.0 pg/g due to inaccurate ion ratios.

Accuracy and precision, as determined by spike recovery and replicate analysis, were within specified ranges (70–120%) for most contaminants analyzed, and recoveries of the ^{13}C-labeled dioxin-like compound concentrations generally were within ±20% of expected values. Analytes with matrix-spike recoveries outside specified boundaries exhibited concentrations below or near detection limits or were reported as estimated results. In 1994 samples, detection limits for OC pesticides and total PCBs were raised due to insufficient sample material.

Bioassay

The H4IIE rat hepatoma cell bioassay was conducted on egg sample extracts following the methods of Tillitt et al. [16] as modified for 96-well microtiter plates to assess toxic potency of all planar halogenated compounds. Polyaromatic hydrocarbons exhibiting dioxin-like activity were removed from egg extracts during the two-stage reactive cleanup process and did not contribute to the total toxic potency estimates. The potency of extracts tested in the H4IIE bioassay was compared to the potency of 2,3,7,8-TCDD, and the results were expressed as TCDD-equivalents (TCDD-EQs) [16]. Replicate and positive control results from the H4IIE bioassay were acceptable for all eggs collected in 1994. However, the H4IIE results from

eggs collected in 1995 did not meet quality assurance objectives and were censored from the data set.

Data analysis

Contaminant concentrations in each egg were adjusted for moisture and lipid loss using an adjustment factor based on volume measurements [17] and data reported on a fresh-weight basis. For eggs collected in 1985, 1994, and 1995, volume was estimated as the mean of whole egg displacement and the egg content volume calculated from length and breadth measurements. Egg measurements were unavailable for eggs collected in 1986 or 1987 [5]. Therefore, an adjustment factor was derived based on data from all late-stage embryos collected from 1994 to 1995. Eggs collected from 1986 to 1987 were assumed to be in the later stages of development, which provided a conservative adjustment and prevented an overestimation of the contaminant concentrations.

Analytical chemistry and bioassay data were transformed to natural logarithms to improve normality. Concentrations below detection were assigned a value of one-half the detection limit for computational purposes. All statistical tests were performed at the $p < 0.05$ level of significance using the software program Systat® 8.0 [18]. Nomenclature for the planar PCB congeners discussed in this report is from the International Union of Pure and Applied Chemists [19].

Mean annual productivity, nest success (percentage of occupied breeding territories that successfully produced young), and five-year running productivity averages were calculated for eagles nesting along the LCR and compared to statewide values. Territories were excluded from productivity calculations during years when fresh eggs were collected. Territories along the river were defined as old or new to compare differences in productivity between breeding territories established through 1987 and investigated by Anthony et al. [5] and new breeding territories established after 1987 by new eagles moving into the area. Banding data and subadult return rates are not available for eagles nesting in the LCR, and new eagle pairs likely are the result of birds immigrating from outside the region as well as birds returning to the natal area to nest after reaching reproductive age. Old breeding territories were not necessarily occupied by the original nesting pairs, as younger eagles could have replaced one or both members of the original pairs at any time.

Total productivity (total number of young produced per breeding territory over the total years occupied) from 1982 to 1996 for eagle pairs at 21 new breeding territories was compared to total productivity at 23 old breeding territories using a two-sample *t* test. The period between 1982 and 1996 was used as a category to calculate total productivity for both new and old groups, even though the new group of eagles did not begin nesting until 1990. Only breeding territories with at least three years occupancy were used in this analysis in order to obtain a more reliable estimate of productivity. Total productivity of eagle pairs at the 23 old breeding territories also was compared over two time periods (1982–1987 and 1990–1995) using a paired *t* test to determine if reproductive success changed over time.

Mean five-year productivity [3] was compared to contaminant concentrations and eggshell thinning using linear regression. Five-year productivity values are considered a better measure of productivity because they average out other factors besides contaminants that may have effects. Data for mean five-year productivity included three years of occupancy before 1994 and two years after, although fewer years were used for 10 territories without five years of productivity data. Mean five-year productivity also was compared to river kilometer (RK) using linear regression.

Concentrations of OC pesticides, dioxin-like compounds, and mercury in LCR bald eagle eggs were compared to estimated no-observable-adverse-effect levels or lowest-observable-adverse-effect levels and to concentrations associated with adverse impacts to bald eagles or other avian species. Regression was used to evaluate relationships between DDE and eggshell thickness, and between egg contaminants and RK where the egg was collected. Using a two-sample *t* test, egg-contaminant concentrations at older breeding territories were compared to values found in eggs collected from 1985 to 1987 [5], and a paired *t* test was used to compare concentrations of DDE and total PCBs between six individual breeding territories sampled both in this study and by Anthony et al. [5]. Sample numbers were insufficient to compare reliably dioxins, furans, or planar PCBs between the two studies.

The total dioxin-like toxic potency of planar chlorinated compounds in bald eagle egg tissues was summarized as TCDD toxic equivalents (TEQs) using toxic equivalency factors based on avian endpoints adopted by the World Health Organization [20]. Toxic equivalents also were calculated using mammalian-based toxic equivalency factors [20] and designated as M-TEQs for comparison to previous studies where only mammalian-based TEQs were derived. Concentrations of dioxin-like compounds below detection or quantification limits were not used in the calculation of TEQs.

RESULTS

Productivity

Annual productivity and nest success of LCR eagles in 1994 were similar to statewide values, whereas productivity in 1995 was 37% lower than statewide values (Table 1). Many nest sites on the LCR were abandoned in 1995; at least 10 nests were abandoned at some point between incubation and hatching in territories where nest trees were not climbed (Table 1). During our two-year study, only one territory successfully produced young after tree climbing and collection of a fresh egg.

Since 1980, mean annual productivity, nest success, and running five-year productivity averages for LCR eagles consistently have been lower than values for bald eagles nesting elsewhere in Oregon, even though the number of occupied nest sites increased to 43 by 1995. From 1990 to 1996, 26 additional eagle pairs established breeding territories along the LCR. Beginning in 1993, annual productivity, nest success, and running five-year averages for LCR eagles have been higher than during any previous five-year time period for eagles along the LCR (Table 1). Total productivity (calculated for individual pairs within the period between 1982 and 1996, regardless of when nest sites were established) at 21 of these new breeding territories was higher ($p = 0.002$) than at the 23 older territories (Fig. 2A). The eagle pairs at the 23 older territories exhibited low productivity that did not change ($p = 0.713$) between the two time periods (Fig. 2B).

Mean five-year productivity for eagle pairs at each of 47 breeding territories along the LCR was not correlated ($r = 0.261$, $p = 0.077$) to nest location as RK, although the significance value was suggestive of a linear relationship (Fig. 3). The slope indicated poorer productivity for eagles nesting along the lower estuary below RK 97, where most of the older breeding territories were located (Fig. 3). Mean five-year pro-

Table 1. Success and productivity (prod) of bald eagle nest sites along the lower Columbia River and in Oregon, USA, from 1980 to 1997 (F.B. Isaacs et al., Oregon State University, Corvallis, Oregon, USA, unpublished data)

	1980	1981	1982	1983	1984	1985	1986[a]	1987[a]	1988	1989	1990	1991	1992	1993	1994[a]	1995[a]	1996	1997
Lower Columbia River[b]																		
No. of occupied sites	6	9	8	11	16	21	17	24	23	20	22	30	37	36	33	35	48	54
No. of young produced	0	5	4	7	11	10	16	9	10	9	13	18	30	32	32	22	39	32
Mean annual prod[c]	0	0.56	0.50	0.64	0.69	0.48	0.94	0.38	0.43	0.45	0.59	0.60	0.81	0.89	0.97	0.63	0.81	0.59
% Nest success	0	44	38	45	44	33	71	25	30	35	50	47	57	58	52	43	58	39
Five-year running prod	0.61	0.59	0.50	0.48	0.54	0.57	0.66	0.60	0.55	0.51	0.54	0.50	0.61	0.70	0.79	0.78	0.82	0.76
Oregon[b]																		
No. of occupied sites	77	92	99	99	103	121	126	131	148	152	156	165	180	191	201	213	230	248
No. of young produced	67	92	68	86	99	109	125	115	138	125	141	175	183	158	199	214	215	244
Mean annual prod[c]	0.87	1.00	0.69	0.87	0.96	0.90	0.99	0.88	0.93	0.82	0.90	1.06	1.02	0.83	0.99	1.00	0.93	0.98
% Nest success	58	63	48	59	65	60	64	60	61	52	63	66	61	56	58	63	62	63
Five-year running prod	1.02	0.99	0.91	0.87	0.88	0.88	0.89	0.92	0.93	0.90	0.90	0.92	0.95	0.93	0.96	0.98	0.95	0.95

[a] Sites where fresh eggs were collected were excluded from the analysis during these years.
[b] All parameters refer to occupied sites with known outcome.
[c] Young per occupied site with known outcome.

Fig. 2. Arithmetic mean (bar) and standard deviation (line) of total productivity (number of young produced per occupied breeding territory) for lower Columbia River, USA, bald eagles at (**A**) 23 old and 21 new breeding territories for the period 1982 to 1996 and (**B**) 23 old breeding territories during two time periods (1982–87 and 1990–95). Old territories refer to sites occupied by eagle pairs since 1982, and new territories refer to previously unoccupied areas established and defended by new eagle pairs moving into the region after 1987.

ductivity was not related to any detectable contaminants except dieldrin and 1,2,3,7,8,9-hexaCDD, which exhibited positive correlations (Table 2).

Organochlorine pesticide, total PCB, and mercury concentrations

All LCR bald eagle eggs contained detectable concentrations of OC pesticides or degradation products and total PCBs (Table 2, Fig. 1B). Total PCBs and DDE were the most elevated contaminants in eggs, exhibiting geometric means of 5.0 and 5.63 μg/g, respectively. In addition to OC compounds, mercury was found in all 1994 eggs and total polybrominated diphenyl ethers were detected in all 1995 eggs; these contaminants were analyzed only for the year reported (Table 2). Total

Fig. 3. Relationship between mean five-year productivity (number of young produced per occupied territory) and nest location as river kilometer for bald eagles at old breeding territories (solid circles) and new breeding territories (open circles) along the lower Columbia River, USA.

Table 2. Egg-contaminant concentrations (fresh wt) and correlation coefficients (r) with significance levels (p) for relationships between five-year productivity and river kilometer (nest location along the river) for bald eagles nesting along the lower Columbia River, USA, in 1994 to 1995

Contaminant group	Geometric mean[a]	Range	Contaminant and productivity		Contaminant and river kilometer	
			r	p	r	p
Contaminants reported as μg/g[b]						
Total PCBs	5.0	2.9–11.4	0.007	0.979	−0.213	0.381
p,p′-dichlorodiphenyltrichloroethane (DDT)	0.007	<0.00006–0.034	0.131	0.592	−0.026	0.915
p,p′-dichlorodiphenyldichloroethylene (DDE)	5.63	2.89–12.5	−0.126	0.608	−0.371	0.117
p,p′-dichlorodiphenyldichloroethane (DDD)	0.273	0.149–0.498	−0.111	0.65	0.007	0.979
o,p′-DDT	NC[c]	<0.018	NC	NC	NC	NC
o,p′-DDE[d]	0.002	0.0006–0.007	0.035	0.92	0.443	0.172
o,p′-DDD[d]	0.002	<0.00006–0.006	−0.111	0.272	0.235	0.487
Dieldrin	0.046	0.019–0.081	0.592	0.008	0.118	0.629
Endrin[d]	0.002	0.0006–0.003	−0.138	0.686	−0.12	0.725
Hexachlorobenzene	0.012	<0.017–0.027	−0.133	0.588	−0.289	0.231
Oxychlordane	0.014	<0.022–0.031	0.232	0.338	−0.145	0.552
trans-Chlordane[d]	0.002	0.001–0.004	−0.05	0.883	0.033	0.924
Alpha-chlordane[e]	NC	<0.018–0.03	NC	NC	NC	NC
Gamma-chlordane[e]	NC	<0.018	NC	NC	NC	NC
Cis-chlordane/octa-chlordane[d]	0.131	0.091–0.293	0.528	0.214	−0.145	0.67
Trans-nonachlor	0.133	0.087–0.238	0.005	0.983	0.058	0.813
Cis-nonachlor[d]	0.043	0.031–0.103	−0.007	0.985	−0.181	0.595
Methoxychlor[d]	NC	<0.00006	NC	NC	NC	NC
Heptachlor[d]	NC	<0.0001	NC	NC	NC	NC
Heptachlor epoxide[d]	0.011	0.005–0.029	−0.001	0.997	−0.611	0.046
Alpha-BHC	NC	<0.018	NC	NC	NC	NC
Beta-BHC[d]	0.006	0.002–0.043	−0.007	0.983	−0.777	0.005
Gamma-BHC	NC	<0.018	NC	NC	NC	NC
Delta-BHC[d]	NC	<0.00006–0.002	NC	NC	NC	NC
Mirex[d]	0.006	0.004–0.018	0.141	0.68	−0.372	0.26
Toxaphene[e]	NC	<0.09	NC	NC	NC	NC
Total PBDEs[d]	0.745	0.446–1.21	0.217	0.521	−0.396	0.228
Total mercury[e]	0.22	0.17–0.29	−0.43	0.187	−0.481	0.134
Chlorinated dibenzodioxins (CDDs) (pg/g)						
2,3,7,8-TetraCDD	22	10–37	−0.050	0.839	−0.445	0.056
1,2,3,7,8-PentaCDD	11	5.3–21	0.139	0.569	−0.31	0.197
1,2,3,4,7,8-HexaCDD	1.2	<0.7–4.1	0.37	0.226	0.244	0.313
1,2,3,6,7,8-HexaCDD	9.1	4.4–19	0.401	0.089	0.122	0.619
1,2,3,7,8,9-HexaCDD	0.57	0.5–2.0	0.528	0.02	0.374	0.115
1,2,3,4,6,7,8-HeptaCDD	1.6	0.68–6.0	0.435	0.062	0.665	0.002
OctaCDD	19	5.3–84	0.061	0.805	−0.087	0.723
Chlorinated dibenzofurans (CDFs) (pg/g)						
2,3,7,8-TetraCDF	22	9–53	−0.166	0.498	−0.616	0.005
1,2,3,7,8-PentaCDF	1.4	0.70–2.9	0.315	0.189	−0.09	0.714
2,3,4,7,8-PentaCDF	6.2	4.0–11	0.097	0.694	−0.546	0.015
1,2,3,4,7,8-HexaCDF	0.83	<0.60–3.2	0.39	0.189	−0.097	0.692
1,2,3,6,7,8-HexaCDF	1.4	0.60–3.5	0.305	0.204	−0.112	0.649
1,2,3,7,8,9-HexaCDF	NC	<0.20–0.2	NC	NC	NC	NC
2,3,4,6,7,8-HexaCDF	2.0	0.9–4.9	0.281	0.244	0.218	0.37
1,2,3,4,6,7,8-HeptaCDF	2.1	0.9–7.8	−0.043	0.862	0.415	0.077
1,2,3,4,7,8,9-HeptaCDF	0.86	<0.5–2.5	0.178	0.465	−0.253	0.297
OctaCDF	3.7	1.6–13	0.258	0.287	0.179	0.464

Table 2. Continued

Contaminant group	Geometric mean[a]	Range	Contaminant and productivity		Contaminant and river kilometer	
			r	*p*	*r*	*p*
Non–*ortho*-chlorinated biphenyls (CBs) (pg/g)						
3,4,4′,5-TetraCB 81)[f]	339	214–491	−0.371	0.118	0.189	0.438
3,3′,4,4′-TetraCB (77)	2,580	1,820–3,810	0.207	0.395	0.002	0.992
3,3′,4,4′,5-PentaCB (126)	1,390	626–2,720	0.045	0.855	−0.271	0.262
3,3′,4,4′,5,5′-HexaCB (169)	133	49.5–353	−0.021	0.932	−0.528	0.02
Mono–*ortho*-chlorinated biphenyls (CBs)[e] (pg/g)						
2,3,3′,4,4′-PentaCB (105)	148,000	96,100–230,000	0.54	0.087	0.083	0.809
2,3,4,4′,5-PentaCB (114)	11,700	7,600–16,300	0.374	0.258	0.221	0.513
2,3′,4,4′,5-PentaCB (118)	513,100	345,000–859,000	0.402	0.22	−0.062	0.856
2,3,4,4′,5-PentaCB (123)	5,490	<200–13,100	0.301	0.368	0.096	0.779
2,3,3′,4,4′,5-HexaCB (156)	71,320	37,800–146,000	0.173	0.61	−0.289	0.388
2,3,3′,4,4′,5-HexaCB (157)	19,360	11,600–38,100	0.169	0.62	−0.278	0.408
2,3′,4,4′,5,5′-HexaCB (167)	61,700	30,900–135,000	0.055	0.872	−0.404	0.217
2′,3,3′,4,4′,5,5′-HeptaCB (189)	7,260	3,840–16,200	0.11	0.747	−0.384	0.244
Toxic equivalents[g] (TEQs) (pg/g)						
TEQ (dioxin and furan fraction)	63.9	37.6–103	−0.072	0.77	−0.684	0.001
TEQ (total)	424	332–617	0.303	0.365	−0.254	0.451
H4IIE TCDD-EQs	41	14–280	−0.123	0.685	−0.029	0.932

[a] Samples from 1994 and 1995 combined ($n = 19$) unless otherwise noted. Some analytes are reported only for 1995 because the 1994 results were at or below the detection limit of 0.018 μg/g (detection limits were elevated in 1994 samples due to insufficient amount of sample material).
[b] Group includes total polychlorinated biphenyls (PCBs), organochlorine pesticides, total polybrominated diphenyl ethers (PBDEs), and mercury.
[c] NC = not calculated because the majority of samples had results below detection limits.
[d] Reported for 1995 samples only ($n = 11$). Analyte either was not analyzed in 1994 or results were below the detection limit.
[e] Samples analyzed in 1994 only ($n = 11$).
[f] Polychlorinated biphenyl congener number based on International Union of Pure and Applied Chemists [19].
[g] TEQs calculated using avian-based TEQs from van den Berg et al. [20], and dioxin-equivalents (TCDD-EQs) derived from the H4IIE rat bioassay (1994 samples only). The TEQs were calculated based on all egg samples using the dioxin and furan contribution (TEQ dioxin and furan fraction) and based on the 1994 samples using contributions from dioxins, furans, and non- and mono-*ortho*-chlorinated PCBs (TEQ total).

Table 3. Eggshell parameters (arithmetic mean and range) and fresh weight concentrations (geometric mean and range) of selected contaminants and mammalian-based toxic equivalents (M-TEQs) in bald eagle eggs collected from old breeding territories along the lower Columbia River, USA, compared between two study periods

	1985–1987 Anthony et al. [5]	*n*	1994–1995 Old breeding territories	*n*
Eggshell parameters				
Eggshell thickness (mm)	0.552A[a] (0.497–0.618)	10	0.538A (0.454–0.623)	13
% Change[b]	−9.3 (−18–+2)	10	−11.6 (−25–+2.3)	13
Contaminants				
p,p′-Dichlorodiphenyldichloroethylene (μg/g)	9.6A (4.3–21)	10	6.3B (3.5–12.5)	13
Total polychlorinated biphenyls (PCBs) (μg/g)	10.5A (5.1–20)	10	5.4B (3.4–11.4)	13
Total mercury (μg/g)	0.21A (0.12–0.40)	10	0.22A (0.17–0.29)	9
2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (pg/g)	26 (11–38)	5[c]	24 (18–37)	13
2,3,7,8-Tetrachlorodibenzofuran (pg/g)	15 (4–38)	5[c]	22 (9–53)	13
M-TEQ (dioxin and furan fraction)[d] (pg/g)	55 (25–79)	5[c]	43 (33–68)	13
M-TEQ (total) (pg/g)	406[e] (227–574)	3	316 (223–536)	11

[a] Means with different capital letters between columns were significantly different. Concentrations of dioxins, furans, planar PCBs, and M-TEQs were not compared statistically due to insufficient sample size.
[b] Change in mean eggshell thickness below value (0.6088 mm) determined for bald eagle eggs collected prior to 1947.
[c] Includes three eggs collected in 1987 and two addled eggs collected in 1991.
[d] TEQs calculated with mammalian-based toxic equivalent factors (TEFs) from van den Berg et al. [20]. TEQs were calculated based on all egg samples using the dioxin and furan contribution (TEQ dioxin and furan fraction) and based on the 1994 samples using contributions from dioxins, furans, and non and mono-*ortho*–substituted PCBs (TEQ total).
[e] Only one mono-*ortho*–substituted congener (PCB 105) was determined.

PCBs, DDE, and mercury concentrations in individual eggs appeared consistent across nest locations along the river, although the highest concentrations of all three contaminants were in an egg from a territory near the mouth of the river at RK 17 (Fig. 1B).

Concentrations of DDE in 19 samples were correlated with other OC compounds, including total PCBs ($r = 0.887$, $p < 0.001$), 2,3,7,8-TCDD ($r = 0.700$, $p = 0.0009$), and 1,2,3,7,8-pentaCDD ($r = 0.662$, $p = 0.002$). Correlations with total PCBs also included 2,3,7,8-TCDD ($r = 0.741$, $p = 0.003$) and 1,2,3,7,8-pentaCDD ($r = 0.739$, $p = 0.003$). Of the OC pesticides and total PCBs analyzed, only heptachlor epoxide and beta-hexachlorocyclohexane exhibited significant linear relationships between concentrations in eggs and nest location (Table 2).

Only egg concentrations at the older breeding territories were used to compare results to the previous study [5], because productivity was found to be different between the old and new nesting pairs along the LCR. Total PCBs and DDE concentrations declined significantly ($p = 0.0004$ and 0.022, respectively), and mercury was not different ($p = 0.647$) between the two study periods at old breeding territories (Table 3). The DDE concentrations did not change ($p = 0.090$) at six breeding territories sampled during both studies, but total PCB concentrations were lower ($p = 0.010$) at these same six sites.

Eggshell thickness

Mean thickness of 29 LCR eagle eggshells was 0.543 mm (range = 0.454–0.682 mm), and the mean percent change from the pre-DDT average of 0.6088 mm was −11% (range = −25% to +12%). All eagle eggs collected along the LCR exhibited eggshell thinning except one from a breeding territory sampled in 1995. Eggshell thickness was not correlated to DDE ($r = 0.005$, $p = 0.985$, $n = 19$) or mean five-year productivity ($r = -0.254$, $p = 0.294$, $n = 20$). Eggshell thickness was not different ($p = 0.453$) between six new territories compared to 13 older territories sampled in 1994 to 1995. Mean eggshell thickness at 13 older territories in this study was not different ($p = 0.404$) from eggshells collected at 10 territories in 1985 to 1987 (Table 3). In addition, shell thickness did not change ($p = 0.819$) at six breeding territories sampled during both studies. Mean eggshell thickness from both studies was well below the pre-DDT average of 0.6088 mm (Table 3).

Concentrations of dioxin-like compounds

All egg samples contained dioxins and furans, and 2,3,7,8-TCDD and 2,3,7,8-TCDF were the most elevated congeners (Table 2). Mean 2,3,7,8-TCDD and 2,3,7,8-TCDF concentrations appeared similar between eggs collected in this study and the earlier study [5] along the LCR (Table 3), although differences in analytical methods and a small sample size in the earlier study precluded statistical comparisons.

Individual dioxin and furan congeners were not correlated to mean five-year productivity, with the exception of 1,2,3,7,8,9-hexaCDD (Table 2). A significant linear relationship was observed between RK and the dioxin or furan congeners 1,2,3,4,6,7,8-heptaCDD, 2,3,7,8-TCDF, and 2,3,4,7,8-pentachlorinated dibenzofuran (Table 2, Fig. 4). Concentrations of the two furan congeners increased in eggs from territories toward the lower part of the river (Fig. 4), whereas

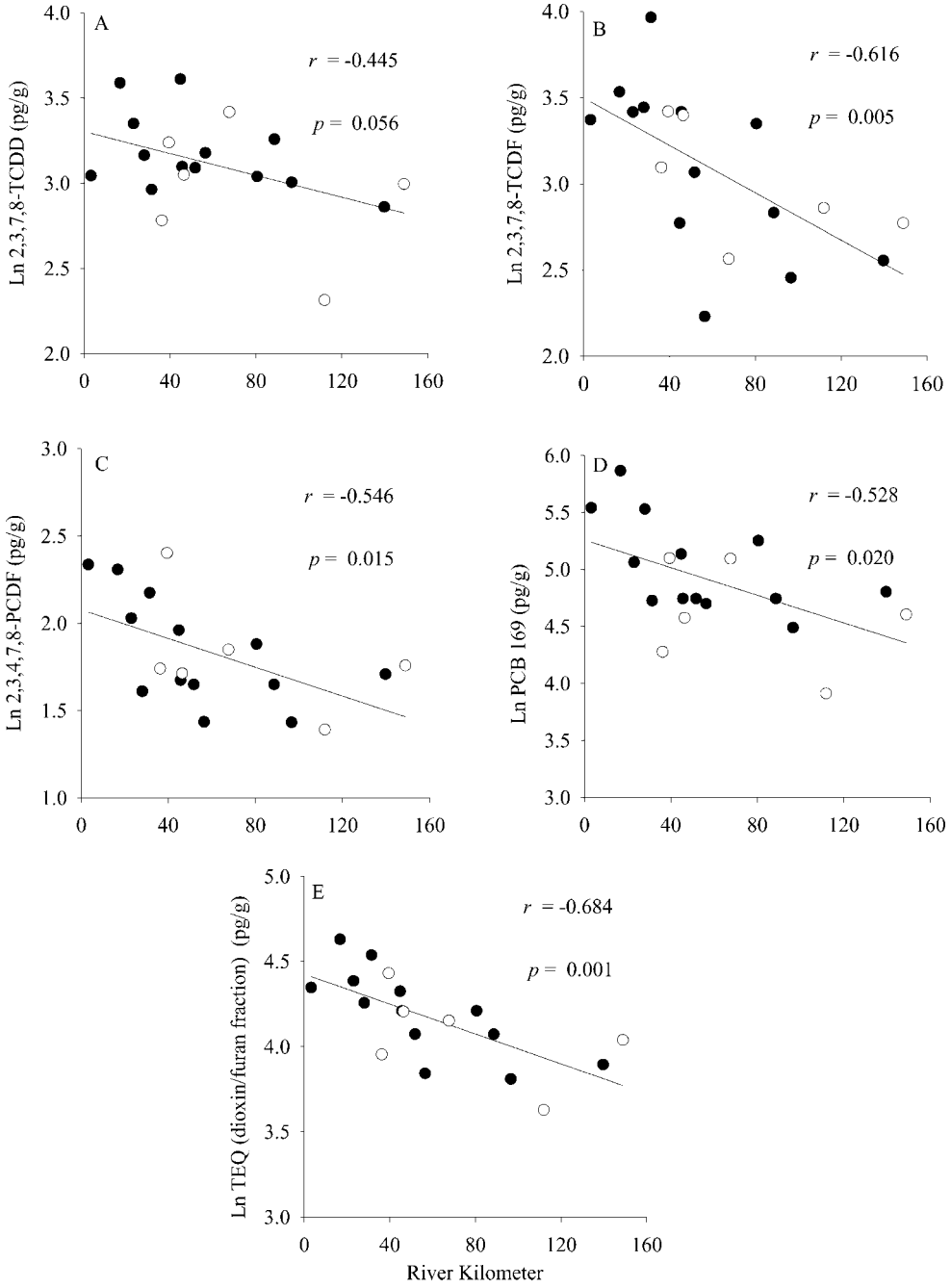


Fig. 4. Regression of the natural log of selected contaminants and toxic equivalents (TEQs) against nest location as river kilometer for 19 bald eagle egg samples along the lower Columbia River, USA (solid circles represent old breeding territories; open circles new breeding territories). Contaminants include (**A**) 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD), (**B**) 2,3,7,8-tetrachlorodibenzofuran (TCDF), (**C**) 2,3,4,7,8-pentachlorinated dibenzofuran (PCDF), (**D**) polychlorinated biphenyl (PCB) 169, and (**E**) avian-based TEQ values including the dioxin and furan contributions.

the dioxin congener exhibited a positive correlation. Other dioxin and furan congeners were not correlated to RK (Table 2), although a linear relationship between RK and 2,3,7,8-TCDD was suggestive ($p = 0.056$; Figs. 1C and 4).

Planar PCBs also accumulated in all bald eagle eggs. The mono-ortho–substituted PCBs 105 and 118 had the greatest concentrations compared to all other dioxin-like compounds, while PCBs 77 and 126 had the highest concentrations of the non-ortho–substituted PCBs (Table 2). Mean five-year productivity was not correlated to planar PCB concentrations measured during the study, and only PCB 169 was correlated to RK (Table 2, Fig. 4).

Mean five-year productivity was not correlated to TEQs, and only the dioxin and furan fraction of the TEQ calculation was correlated with RK (Table 2, Figs. 1C and 4). Concentrations of M-TEQs in samples collected in this study were similar to the earlier investigation [5], although sample size was insufficient to statistically compare results (Table 3).

The non-*ortho*–substituted PCBs contributed the most dioxin-like toxic potency to the TEQ (Figs. 1C and 5), and PCB 126 was the most important dioxin-like toxicity contributor. For the 1994 samples (which included analysis of the mono-*ortho* PCB congeners), PCBs 77 and 126 contributed 31 and 37% of the dioxin-like activity, respectively, followed by PCB

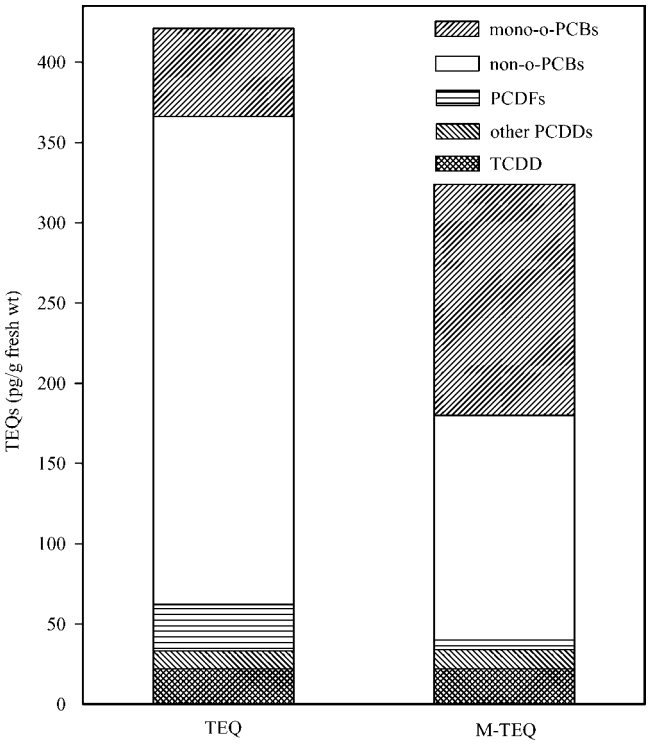


Fig. 5. Geometric means for 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) and toxic equivalents derived from avian- (TEQ) and mammalian (M-TEQ)-based endpoints in 19 bald eagle eggs collected from the lower Columbia River, USA, from 1994 to 1995. The TEQs were calculated based on the contributions of polychlorinated dioxins and furans (PCDDs and PCDFs), non-*ortho*–substituted polychlorinated biphenyls (non-o–PCBs), and mono-*ortho*–substituted PCBs (mono-o–PCBs).

81 > 2,3,7,8-TCDD > 2,3,7,8-TCDF. Although concentrations of PCBs 105 and 118 were higher relative to other dioxin-like compounds, these mono-ortho–substituted congeners did not contribute much to the total TEQ (Figs. 1C and 5). The M-TEQ calculation exhibited a greater contribution from the mono-ortho–substituted congeners than the avian-based TEQ (Fig. 5).

The TCDD-EQs, as derived from the H4IIE bioassay, were detected in all 11 egg samples in 1994. The geometric mean was similar to the additive TEQ calculated with the dioxin and furan fractions, but was much lower than the TEQs that included the planar PCBs (Table 2). The TCDD-EQs were not correlated to mean five-year productivity or to RK (Table 2).

DISCUSSION

Changes in contaminant concentrations and comparisons to effect levels

Anthony et al. [5] associated environmental contaminants, including DDE and total PCBs, with poor reproduction and eggshell thinning in LCR eagles. Compared to egg concentrations in the mid-1980s, mean concentrations of DDE declined by 34% and total PCBs by 49% in eagle eggs from the LCR. Mean total PCB concentrations also declined at six breeding territories sampled during both studies, but mean DDE did not change. Although concentrations declined, mean total PCBs in eggs still exceeded a suggested no-observable-adverse-effect-level of 4.0 μg/g [3] and approached a value of 6 μg/g estimated for healthy productivity for bald eagles ([21], T.J. Kubiak and D.A. Best, U.S. Fish and Wildlife Service, East Lansing, MI, unpublished report). In addition, DDE concentrations were within the range of values (3.6–6.0 μg/g) related to reduced productivity in bald eagles based on addled egg collections [4]. Other OC pesticides were present in eagle eggs but were considered to be below levels associated with poor reproduction [4].

Wiemeyer et al. [4] derived three regression equations relating DDE concentrations in eagle eggs that failed to hatch to mean five-year productivity. The weighted sigmoidal equation fit the best, predicting a mean five-year productivity for LCR eagles of 0.52 young/occupied territory using mean DDE values of 5.63 μg/g. This predicted value is lower than mean five-year productivity (0.82 in 1996) for all LCR eagles, but is very similar to the five-year productivity (0.56 in 1996) observed at 23 older breeding territories. The equation derived by Wiemeyer et al. [4] represented addled bald eagle eggs collected after failure to hatch, and the estimates from the equation may not be as applicable to populations where fresh eggs were collected, as in this study. The equation typically predicts productivity values that are lower by 0.1 to 0.4 young per occupied breeding territory than the total population productivity [4], which may explain in part the higher observed than predicted productivity values from the LCR population.

Concentrations of DDE have been linked to eggshell thinning in raptors and other birds [22,23]. Eggshells from the LCR were thin and shell thickness at older sites had not improved since the mid-1980s. A comparison of eggshell thickness between old and new sites sampled in 1994 to 1995 indicated no differences, although sample size of the new sites was limited and could have influenced results. Similar to findings in other field studies [24,25], eggshell thinning was not correlated to DDE concentrations or productivity. Mean eggshell thinning (−11%) for LCR eagles was less than values (>15–20%) considered severe and associated with population declines, although Wiemeyer et al. [4] reported that mean production increased in eagle populations when shell thinning was less than 10%. Therefore, eggshell thinning may impact some individual pairs of LCR eagles.

Other contaminants, such as heavy metals, can impact bald eagle productivity [4]. Mercury concentrations in eggs collected in 1994 did not change from concentrations found in eagle eggs collected along the river from 1985 to 1987 [5]. The highest concentration of mercury in eggs collected by Anthony et al. [5] and during the present study did not exceed concentrations (>0.5 μg/g) associated with adverse effects on bald eagle production [3].

A variety of responses to 2,3,7,8-TCDD in other avian species has been observed in both laboratory and field studies [26–28]. Mean 2,3,7,8-TCDD concentrations of 22 pg/g in eagle eggs from the LCR exceeded a reference value of 15 pg/g developed from bald eagle eggs collected in British Columbia, Canada [25], and approached or exceeded values associated with effects in other avian species [21,26]. However, 2,3,7,8-TCDD was not correlated to mean five-year productivity of LCR eagles and did not appear to be the sole contaminant limiting eagle reproduction, similar to findings of bald eagle studies in British Columbia [27].

Toxic equivalents in LCR eggs were elevated above reference or threshold values estimated for bald eagles. Based on numerous field and laboratory studies, Giesy et al. [21] estimated a lowest-observable-adverse effect concentration/no-observable-adverse effect concentration for TEQs in bald eagle eggs of 7 pg/g. Elliott et al. [27] estimated a no-observed-

effect level of 100 pg/g and a lowest-observed-effect level of 210 pg/g for TEQs based on bald eagle eggs collected near pulp mill sites and a reference site, and hatched under experimental conditions. The TEQ values in LCR eggs exceeded values found in five reference bald eagle eggs collected off the coast of British Columbia, and exceeded the estimated lowest-observed-effect level concentration of 210 pg/g [27]. Exceedence of reference and lowest-observed-effect level values indicates that LCR bald eagles are accumulating dioxin-like compounds to concentrations where adverse reproductive effects to eagle pairs would be expected.

Planar PCB contributions

The non-*ortho*–substituted PCBs contributed greatly to the total dioxin-like toxic potency of the TEQ value in bald eagle eggs along the Columbia River. Planar PCBs were considered the primary contaminants associated with increased incubation period, reduced hatchability, lower body weight, increased liver-to-body weight ratio, and edema in Forster's terns (*Sterna fosteri*) from Green Bay (WI, USA) [26]. Jarman et al. [29] suspected DDE and non-*ortho* PCBs were the most important compounds adversely affecting reproduction in peregrine falcons (*Falco peregrinus*) in California, USA. The total geometric mean concentration (4,100 pg/g) of three non-*ortho* PCBs (PCBs 77, 126, and 169) in LCR bald eagle eggs was 20% lower than the median total (5,500 pg/g wet wt) of these three congeners found in Forster's terns in Green Bay, USA [26] and nearly double the geometric mean (2,070 pg/g) of these PCBs found in peregrine falcon eggs in California [29]. In contrast, Elliott et al. [25] reported that the concentration of non- and mono-*ortho*–substituted PCBs were less important than PCDDs and PCDFs in bald eagle eggs collected near three bleached kraft pulp mills along the Pacific Coast of Canada, and were more important in samples outside the pulp mill–influenced area.

Numerous studies have documented the importance of planar PCBs, especially PCB 126, in contributing total dioxin-like toxic potency in TEQ calculations [26,30]. In eggs from the LCR, PCBs 126 and 77 contributed the majority of dioxin-like activity toward the TEQ value. Mono-*ortho* PCBs contributed less than 8% toward the TEQ, based on concentrations in the 1994 egg samples. In the Great Lakes region, PCB congeners 126 and 105 accounted for more than 90% of the estimated M-TEQs in eggs of Forster's terns from Green Bay [26]. In California, PCB 126 accounted for 83% of the total M-TEQs in peregrine falcon eggs, although mono-*ortho* PCBs were not included in the analysis [29]. Similar to eggs collected from bald eagles and other avian species in other areas, TEQ values in LCR eagle eggs were influenced highly by the contribution of the non-*ortho* PCBs, primarily PCB 126.

H4IIE bioassay

The mean TCDD-EQ derived from the H4IIE bioassay conducted on LCR eagle eggs was more representative of the TEQ calculated with the dioxin and furan contributions than of the total TEQ value; TCDD-EQs were much lower than total TEQs (Table 2). Similarly, Thomas and Anthony [31] reported that total calculated TEQs were up to 24 times greater than H4IIE bioassay-derived TCDD-EQs in great blue heron eggs from the LCR. Mean TCDD-EQs from LCR eggs were well below the geometric mean (162.4 pg/g) for TCDD-EQs measured in eggs of bald eagles with poor productivity in Maine, USA [6], and were comparable to the less-contaminated sites in the Great Lakes, USA [32]. The H4IIE bioassay accounts for interactions of multiple planar halogenated hydrocarbons in egg extracts [32], and antagonism among hydrocarbons could explain the lowered total dioxin-like toxic potency of Columbia River eggs as measured by the bioassay. Additional information is needed to discern this relationship in bald eagles before an adequate risk evaluation can be made using H4IIE bioassay results.

Productivity changes and relations to contaminants

Productivity of the bald eagle population nesting along the LCR has increased as a result of greater reproductive success of new nesting pairs. Between 1990 and 1996, 26 pairs established breeding territories along the river, and average productivity has improved due to the higher breeding success of eagle pairs at the new sites. In contrast, eagles at 23 older breeding territories produced about half the number of young as the eagles at newer sites, and reproductive success of eagles at the older territories has not improved in over 10 years (Fig. 2). Average productivity of LCR eagles, especially at the older sites, remains well below eagle productivity in other areas of Oregon and below values (one young per occupied nest) indicative of a healthy population [33]. Additional data are needed on the age-related productivity and recruitment aspects of eagles along the LCR to better understand reasons for the improved productivity of new eagle pairs.

Mean five-year productivity for LCR bald eagles was not correlated inversely to OC pesticides, total PCBs, PCDDs, PCDFs, or TEQs in eggs. Productivity was correlated positively with dieldrin and 1,2,3,7,8,9-hexaCDD, but concentrations were low and generally below values considered to affect the species. Other investigations on bald eagles experiencing poor productivity and elevated egg contaminants in Oregon, Maine, and along the Pacific Coast of Canada have found no correlations of these individual compounds in eggs to productivity [6,24,25]. Investigations in the Great Lakes reported that productivity was related inversely to various contaminants in bald eagle plasma and eggs [7], although productivity was compared on a regional basis rather than from individual territories. Elliott et al. [27] found stronger correlations between biochemical and physiological endpoints and 2,3,7,8-TCDD or 2,3,7,8-TCDF concentrations, as opposed to the TEQ values, and suggested that use of the toxic equivalency factors may overestimate contribution of PCBs to dioxin-like toxic potency. Although no relationship between individual contaminant concentrations and productivity was demonstrated, many OC contaminants exceeded threshold-effect level estimates and multiple chemicals could interact to contribute to the poor reproductive success observed in LCR bald eagles at older breeding territories.

Numerous factors influence bald eagle productivity and population numbers. In the Great Lakes region, bald eagle productivity was affected by habitat availability, degree of human disturbance to nesting pairs, and environmental contaminants [7]. These same factors, along with weather conditions and competition, could impact eagle productivity along the LCR. Earlier studies along the LCR reported that limited prey, weather conditions, and competition were not obvious influences on eagle productivity [34], although human disturbance may influence foraging success of some eagle pairs [35]. The recent increase in successful new eagle breeding territories located throughout the lower estuary suggests that competition, habitat, and food availability are not limiting. Environmental contaminants, possibly combined with human disturbance, are

the most prominent factors influencing productivity for the LCR eagles.

Concentrations of DDE appear to have the greatest impact on reproductive success at older territories, based on the similarities between the predictive weighted sigmoidal equation [4] and observed productivity. Dioxins, furans, and PCBs exceeded estimated threshold effect levels and may be interacting to further impact reproductive success at older breeding territories. Without the increased reproduction observed at new territories from immigrating eagles, the low productivity at older breeding territories (0.50–0.60 young per occupied nest site) likely would prevent the population from doubling as fast as was observed.

Contaminant availability and sediment deposition

Bald eagles nesting along the river are resident year-round [1,34] and are exposed to DDE, PCBs, dioxins, and furans by consuming contaminated prey. Because these eagles are nonmigratory, their contaminant burdens primarily originate from prey obtained from the Columbia River. Bald eagles forage predominantly on large scale sucker (*Catostomus macrocheilus*), American shad (*Alosa sapidissima*), and carp (*Cyprinus carpio*), which accounted for 71% of prey remains found at nest sites and 90% of direct foraging observations [34]. Birds (mallards [*Anas platyrhynchos*], western grebes [*Aechmophorus occidentalis*], cormorants [*Phalacrocorax* spp.], and gulls [*Larus* spp.]) comprised 26% of nest remains and 7% of direct observations [34]. Accumulation of OC compounds has been documented throughout the Columbia River food web in fish, eggs of fish-eating birds, and mammals [5,31,36]. Home ranges of LCR bald eagles can be as large as 22 km^2, but most eagle activity occurs within 0.5 to 1 km of the nest site [1] where contaminated prey is captured and consumed or delivered to nestlings [5].

Heptachlor epoxide, beta-BHC, 2,3,7,8-TCDF, 2,3,4,7,8-pentachlorinated dibenzofuran, PCB 169, and the TEQs, excluding planar PCBs, were correlated to nest location, with higher values observed in eggs from breeding territories near the mouth of the river. This indicates that exposure to dioxin-like compounds or contaminant availability is less in new pairs located upriver from the older breeding territories. Also, new pairs may not have accumulated contaminants to the extent that older pairs have along the LCR, and some pairs nesting in upriver locations (above RK 97) may be foraging on prey with minimal contamination.

Dioxin-like compounds may be deposited and become more bioavailable in the lower reaches of the river near RK 40 (Fig. 1), although sources of dioxins such as pulp mills are located only upstream of these reaches. McCarthy and Gale [37] deployed semi-permeable membrane devices in the Columbia River and found that some dioxin-like compounds, DDE, total PCBs, and other contaminants were transferred down the river in the dissolved phase and in association with particulate matter. Fine materials and particulate organic matter deposit primarily in protected peripheral bays such as Baker Bay, Youngs Bay, Cathlamet Bay, and Mott Basin, and in channel bottoms in the mid- to upper estuary of the Columbia River (below RK 40; Fig. 1) [38]. Clay, silt, very fine sand, and organic matter also are trapped in the estuarine turbidity maximum and can be deposited in this region [38]. Any hydrophobic OC contaminants associated with these materials also would be transported to these depositional zones. In depositional zones or near the estuarine turbidity maximum, aquatic organisms could mobilize and accumulate contaminants adhered to the particulate matter, exposing predators of the organisms to greater concentrations along the food chain [39]. In addition, Watson et al. [34] determined that eagles along the LCR with territories associated with the shallow bays and tidal flats consumed more waterfowl and fish-eating birds than other eagles, and fish-eating birds usually are a greater source of OC compounds in eagle diets than fish [24]. Colonies of fish-eating birds (gulls, terns, and cormorants) predominately are located in these lower reaches near older breeding territories, whereas shallow bays and fish-eating birds may be much less available to the new eagle pairs nesting in the upper reaches. Concentrations of some OC compounds were highest in eggs from nests in the lower estuary below RK 97, where predominantly older breeding territories occur (Figs. 1 and 4). Moreover, total productivity was lowest (0.42 young/occupied site) between RKs 21 and 50. Contaminant concentrations appeared higher in eggs from older breeding territories than from newly established breeding territories, but insufficient samples were obtained from newer breeding territories to make statistical comparisons.

Contaminant sources

Sources of OC pesticides and PCB contaminants in the Columbia River Basin are considered to result primarily from nonpoint source runoff or chemical spills and releases. The use of large quantities of DDT in orchard crops in the Columbia Basin before 1974 [40] and use of PCBs in electrical transformers, along roads as dust suppressants, or from spills at dam sites could have contributed to the DDE and PCB burdens found in Columbia River biota. Tributaries of the Columbia, such as the Willamette River, also contribute greatly to the contaminant loading [37]. In addition, Thomas and Anthony [31] found the highest concentrations of OC contaminants in great blue heron eggs at a site along the Willamette River. Streambed sediment in the Willamette River contains DDT, PCBs, dioxins, and furans [41], and DDT and its transformation products have been found in water in the Yakima River, which drains into the LCR [42].

Dioxin and furan contamination results from permitted discharges or nonpoint runoff from pulp and paper mills using chlorine for bleaching, wood treatment plants, municipal wastewater treatment facilities, industrial sites, agricultural areas, and urban areas near the Columbia River (U.S. Environmental Protection Agency, Seattle, WA, unpublished report). In Canada, elevated concentrations of 2,3,7,8-TCDD, 1,2,3,7,8-pentaCDD, 1,2,3,6,7,8-hexaCDD, and 2,3,7,8-TCDF in bald eagle plasma and eggs were attributed to pulp mill sources, and elevated 1,2,3,4,6,7,8-heptaCDD, octaCDD, and higher chlorinated PCDFs reflected sources from pulp mills using chlorophenol-treated wood chips for feedstock, and possibly from local combustion sources [25]. Similarly, the most elevated PCDDs and PCDFs in LCR eagle eggs were the 2,3,7,8-tetra and pentachlorinated dioxin and furan congeners, and one hexachlorinated dioxin. The dioxin and furan pattern in the LCR eggs were similar to the pattern in eggs from Canada indicative of pulp and paper mill sources. Reduction of PCDDs and PCDFs in effluent by a pulp mill in Canada led to a corresponding decrease in the contaminant burden in eggs of great blue herons and improved embryo condition [43]. Recently, pulp mills along the Columbia River have changed from using elemental chlorine in the bleaching process to chlorine dioxide. Bald eagle eggs have not been collected since

the change in the bleaching process occurred, and it remains to be seen whether or not Columbia River biota will exhibit corresponding decreases in PCDD and PCDF burdens as a result of the change in bleaching process.

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