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SPATIAL AND TEMPORAL TRENDS OF CONTAMINANTS IN EGGS OF WADING BIRDS FROM SAN FRANCISCO BAY, CALIFORNIA

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Abstract – Between 1989 and 1991, reproduction by black-crowned night-herons (*Nycticorax nycticorax*) and snowy egrets (*Egretta thula*) was studied at sites in San Francisco Bay. Eggs were collected from these and other bay sites and from South Wilbur Flood Area, a reference site in California's San Joaquin Valley. Eggs were analyzed for inorganic trace elements, organochlorine pesticides, and polychlorinated biphenyls (PCBs). Results were compared among sites and years and with results of previous studies. There was some evidence of impaired reproduction, but concentrations of contaminants were generally lower than threshold levels for such effects. Egg hatchability was generally good, with predation being the factor that most limited reproductive success. Mean PCB concentrations were generally higher in eggs from the south end of San Francisco Bay than from the north, but the only temporal change, an increase, was observed at Alcatraz Island. There were spatial differences for *p,p'*-DDE in night-heron eggs in 1990, but the highest mean concentration of DDE was in night-heron eggs from South Wilbur in 1991. Temporal declines in maximum concentrations of DDE in eggs were observed in the bay, but means did not change significantly over time. At Bair Island in the southern end of the bay, mean concentrations of mercury decreased while selenium increased in night-heron eggs over time, but there were no clear bay-wide spatial or temporal trends for either element.

Keywords – Wading birds Eggs San Francisco Bay Contaminants Organochlorines

INTRODUCTION

Environmental contaminants of major concern in the San Francisco Bay Estuary include cadmium, copper, mercury, nickel, selenium, silver, tin, chlordane and its metabolites, DDT and its metabolites, polychlorinated biphenyls (PCBs), toxaphene, and polycyclic aromatic hydrocarbons (PAHs) [1]. In recent studies, concentrations of PCBs, DDE, and other chlorinated hydrocarbons were found to be elevated in sediments and biota from San Francisco Bay [2]. In addition, elevated concentrations of selenium, mercury, silver, copper, and cadmium were detected in bivalves [3] and wintering ducks [4,5] from the bay. Some of these contaminants, including selenium, cadmium, mercury, PCBs, and DDE, have been detected at concentrations in birds or their foods that are associated with adverse effects in field or laboratory studies [6].

Colonially nesting waterbirds can be useful biological monitors of the health of estuarine ecosystems because they are high in the food web and may reflect contamination in many different ecosystem components [7]. In addition, residues of contaminants that are bioaccumulated are frequently detected at elevated concentrations in their eggs [8,9]. Certain species that nest colonially are convenient monitors because of their wide geographic distribution, nest site fidelity, and synchronous nesting within a given region [10]. Colonies can be surveyed repeatedly, and eggs can be readily collected [11].

Previous studies suggested that organochlorines adversely affected reproduction by black-crowned night-herons (*Nycticorax nycticorax*) nesting in San Francisco Bay. In 1982, 11% of the night-heron eggs collected at Bair Island in the South Bay contained >8 μg/g DDE [12], the level associated with reproductive impairment [13]. A second study at Bair Island in 1983 found a negative correlation between embryonic weight and PCB residues in night-herons [14].

The objectives of our study were to evaluate the reproductive success of night-herons and snowy egrets (*Egretta thula*) nesting in San Francisco Bay and to determine if there were among-site differences or temporal trends in mean contaminant concentrations in eggs compared with the early 1980s.

MATERIALS AND METHODS

Study areas

Of the six major sites (>50 nests) used for nesting by night-herons in San Francisco Bay between 1989 and 1991, eggs were collected from all but Red Rock (Fig. 1). Snowy egrets nested at all but Alcatraz Island; eggs were collected from all but Red Rock and Brooks Island. About 50% of the 1,100 night-heron nests and 27% of the 900 snowy-egret nests present at these sites were monitored in 1990, the most intensive year of the study.

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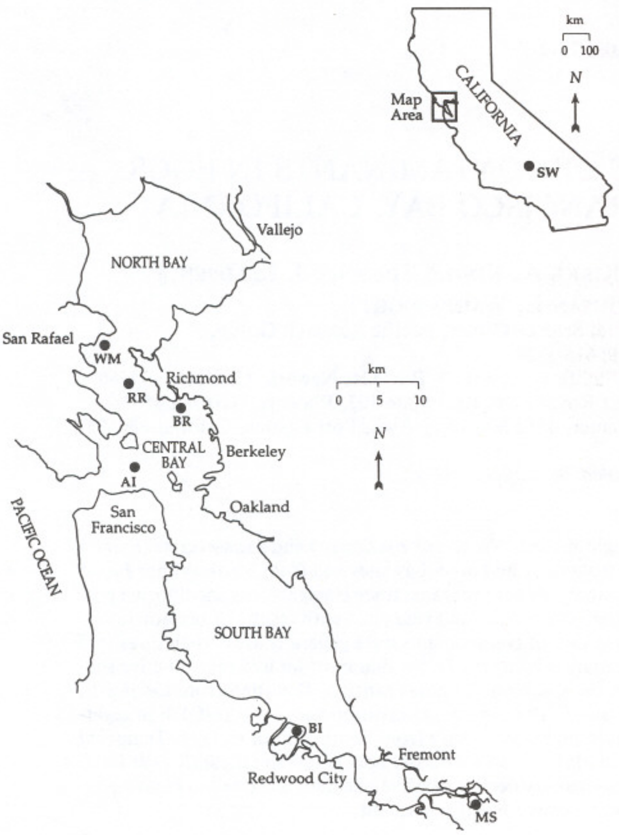

Fig. 1. Locations of primary nesting sites of wading birds during 1989–1991 in San Francisco Bay (AI = Alcatraz Island, BI = Bair Island, BR = Brooks Island, MS = Mallard Slough, RR = Red Rock, and WM = West Marin Island) and the reference site in the San Joaquin Valley (SW = South Wilbur Flood Area).

Randomly selected night-heron and snowy-egret eggs were collected from the Mallard Slough colony (Santa Clara County) during one visit in May 1989 and one in June 1990 (Fig. 1). Eggs were collected from this site at the southern end of the bay (South Bay) to compare contaminant concentrations with eggs collected there in 1982 and 1983 [15]. Reproduction was not monitored at this site because the nesting substrate, giant bulrush (*Scirpus acutus*), made access impossible without significantly disturbing the colony.

Night-heron and egret nests were monitored and eggs were collected in 1989 and 1990 at Bair Island (Fig. 1), a site in the South Bay located near Redwood City (San Mateo County). This site had been studied in 1982 and 1983 [12,14]. Wading birds did not nest at this site in 1991, presumably because newly arrived red foxes (*Vulpes fulva*) caused abandonment of the colony.

Night-heron nests were monitored and eggs were collected from 11 separate locations on Alcatraz Island (Fig. 1) in 1990 and 1991. This 9.1-ha island is located in the central portion of San Francisco Bay (Central Bay), about 1.8 km north of the city of San Francisco (San Francisco County).

Night-heron nests were monitored and eggs were collected in 1990 and 1991 on Brooks Island (Fig. 1), a site in the Central Bay near Richmond (Contra Costa County). Nesting of the few snowy egrets on Brooks Island was monitored, but eggs were not collected.

In 1989 and 1990, night-heron and snowy-egret nests were monitored and eggs were collected at West Marin Island, a site in the northern end of the bay (North Bay), near San Rafael (Marin County) (Fig. 1). Eggs were also collected at this 0.8-ha site during one visit in May 1991.

For comparison with San Francisco Bay, we collected night-heron and snowy-egret eggs at random from nests at the South Wilbur Flood Area (Fig. 1) in July 1991. South Wilbur is a freshwater storage area located along with numerous drainwater evaporation ponds in an area of intensive agriculture in California's San Joaquin Valley (Kings County), about 80 km northwest of Bakersfield. Reproductive success was not evaluated at this site.

Field methods

Each colony in which reproduction was to be assessed was observed from a nearby vantage point beginning in late March to determine the nesting status of night-herons and egrets. To minimize disturbance, the initial visit to each colony was delayed until most of the birds were in the laying or early incubation stages [16].

Individual nests were monitored at all parts of Bair, Brooks, and West Marin islands to minimize within-colony bias. At Alcatraz, however, all nests that could be located were monitored in 1990; in 1991, all nests that could be found, except for those in one subcolony, were monitored. Each selected nest was assigned a unique number and marked using plastic flagging to facilitate its relocation. Marked nests were checked once every 3 to 5 d (April 22 to June 19) in 1989, and once every 7 d in 1990 (April 23 to July 26) and 1991 (April 25 to July 26). Eggs in nests found during mid-incubation were floated to estimate their incubation status [17]. Marked nests and their vicinities were closely checked each visit for cracked or crushed shells or other signs of reproductive impairment or depredation.

After clutches were considered complete, one egg was selected randomly from each of at least five nests per species per site for chemical analysis. The collected egg was assumed to be a valid estimate of the concentration of contaminants in the clutch because intra-clutch variability was assumed to be low [18]. In addition, it was assumed that the collection of one egg from a clutch of three or four did not affect nest success [19]. Eggs that failed to hatch were collected, embryos examined, and up to 10 submitted for chemical analysis.

All eggs were kept on wet ice in a cooler and then refrigerated until they could be processed. Eggs were examined to determine fertility, stage of embryo development [20], and condition of the embryo (i.e., viability and normality). Egg contents were placed in chemically clean jars and frozen until analyzed for contaminants.

Procedures for collection and analysis of eggs from Bair Island and Mallard Slough in 1982 and 1983 were similar [12].

Chicks were monitored to estimate fledging success. However, because of difficulties with monitoring chicks once they left the nest, we set arbitrary cutoff dates for successful fledging at 15 d for night-herons and 10 d for egrets.

Chemical analyses

Each year, eggs were analyzed for organochlorines, mercury, selenium, other inorganic elements, or various combinations thereof, depending on the contaminants of particular interest and the funds available. Laboratories under contract to the U.S. Fish and Wildlife Service conducted the analyses. Moisture content was determined for each sample by drying a weighed aliquot and then reweighing the sample.

Analyses for organochlorine pesticides and PCBs

Each egg was individually homogenized, thoroughly mixed with anhydrous sodium sulfate, and Soxhlet-extracted with hexane. The extract was then concentrated to dryness for lipid determination. The weighed lipid sample was dissolved in petroleum ether and extracted four times with acetonitrile saturated with petroleum ether. Residues were partitioned into petroleum ether and fractionated on a Florisil chromatographic column with diethyl and petroleum ethers. A silicic acid chromatographic column was used to separate total PCBs from other organochlorines in one fraction. Fractions were concentrated,and organochlorine pesticides and metabolites and total PCBs were quantified by packed or megabore column, electron-capture gas chromatography.

The lower limit of detection was 0.01 μg/g (wet wt.) for organochlorine pesticides and metabolites and 0.05 μg/g (wet wt.) for toxaphene and total PCBs. In 1982 and 1983, the detection limit for organochlorines was 0.10 μg/g (wet wt.) [12].

Residues in a portion of the samples were confirmed by gas chromatography–mass spectrometry. The precision, as measured by duplicate sample analyses, was acceptable for all analytes. The accuracy, as measured by spike recovery, was acceptable for all analytes, except for hexachlorobenzene (HCB) in 1989 and 1990. Results reported as "not detected" for HCB may have been due to method performance, because recovery of HCB from spiked samples was low, ranging from 52 to 64%. Therefore, results for HCB are not presented here.

Analyses for mercury, selenium, and other inorganics

Homogenized individual eggs were analyzed for mercury using cold vapor atomic absorption spectrophotometry. The lower limit of detection ranged from 0.01 to 0.15 μg/g (dry wt.), depending on the laboratory conducting the analyses.

Homogenized individual eggs were analyzed for selenium using graphite furnace atomic absorption spectrometry in 1989 and 1991; the lower limit of detection ranged from 0.30 to 0.50 μg/g (dry wt.). In 1990, samples were analyzed for selenium using hydride generation with a lower limit of detection of 0.10 μg (dry wt.).

Homogenized individual eggs were analyzed for other inorganics using inductively coupled plasma emission spectrophotometry (ICPES).

The accuracy of the inorganic results, as measured by spike recovery and reference material analysis, was generally acceptable for all analytes. However, recovery of antimony, silver, and tin by ICPES was usually low, and little confidence can be placed in their accuracy. Therefore, the results of these analyses are not presented. Average recovery for spiked sample analyses ranged from 91 to 116%. The precision, as measured by duplicate sample analysis, was acceptable for all analytes, except aluminum. Aluminum data had unusually high variability and are not presented.

Statistical analyses of chemical results

Results for inorganics are expressed on a dry-weight basis to avoid errors in interpretation associated with varying moisture levels in tissues [21] and to make them comparable to other recent field studies in the region [4,15]. Results for organochlorines are on a fresh wet-weight basis [22]. Concentrations were transformed to common logarithms to improve homogeneity of variances, and geometric means were calculated when a contaminant was detected in at least 50% of the samples. Where means were calculated, a value equal to one-half the detection limit was assigned to any not-detected values prior to logarithmic transformation.

Analysis of variance and Tukey's multiple comparison test were used to compare geometric means between species and among sites and years.

Estimation of reproductive success

The Mayfield method was used to estimate nesting success [23,24]. After exposure days were calculated [25], rates of nesting success, fledging success, and cause-specific nesting failure (and associated 95% C.I.) were calculated using program MICROMORT [26,27].

In 1989, all pipped eggs collected from Bair and West Marin islands for a second study [28] were alive and normal. If at least one other egg hatched from the same nest as the pipped egg, then it was assumed that the pipped egg would also have hatched. Hatchability was calculated for both egrets and night-herons by dividing the total eggs that hatched by the total hatched plus those that failed (including infertile, but not including those that disappeared or were otherwise destroyed).

Program CONTRAST [29] was used to conduct two-tailed standard-normal tests (z tests) for among-year and among-location comparisons of nesting success and cause-specific nesting failure rates [30,31]. The probability level used to determine statistical significance for these comparisons was $p \leq 0.05$.

RESULTS

Contaminants

Organochlorines. The most frequently detected of all the organochlorines included in the analyses was p,p'-DDE, which was detected in every egg analyzed in this study. Other organochlorines detected in randomly collected eggs at one or more sites in San Francisco Bay between 1989 and 1991 (and percentage of eggs with detectable amounts) were: total PCBs (99%), *trans*-nonachlor (98%), oxychlordane (96%), heptachlor epoxide (82%), dieldrin (80%), p,p'-DDD (52%), p,p'-DDT (52%), *cis*-nonachlor (51%), and β-benzenehexachloride (BHC) (29%). Other organochlorines included in the analyses that were either not detected or detected infrequently at very low concentrations were: α-BHC, γ-BHC, δ-BHC, α-chlordane, γ-chlordane, *o,p′*-DDE, *o,p′*-DDD, *o,p′*-DDT, toxaphene, endrin, and mirex.

Although there were not significant interspecific differences in concentrations of organochlorines at any site during 1989 to 1991, for clarity, night-heron and egret results are reported separately (Tables 1 and 2).

At Bair Island, there were no significant interyear differences for night-herons or egrets for mean concentrations of DDE or PCBs, although DDE seemed to decline with time, especially in night-heron eggs (Table 1). At Mallard Slough, the mean DDE concentration in night-heron eggs in 1989 was lower than that found in 1983, but the 1990 mean was not different from either year. The maximum observed concentration of DDE decreased from 1983 (16 μg/g) to 1990 (2.5 μg/g). Mean concentrations of PCBs were similar all 3 years at Mallard Slough (Table 1).

Mean concentrations of DDE and PCBs in eggs of both species were similar all 3 years (1989–1991) at West Marin. At Alcatraz Island, the mean PCB concentration in night-heron eggs increased significantly from 1990 to 1991, while concentrations of DDE remained low both years. At Brooks Island, the mean concentration of DDE in night-heron eggs was lower in 1991 than 1990; mean concentrations of PCBs did not change (Table 1).

Although the mean concentration of PCBs in night-heron eggs was higher at Bair Island than at West Marin in 1989, DDE concentrations were similar (Table 3). In 1989, there were no among-site differences for egrets for either contaminant. In 1990, the mean PCB concentration in egret eggs was significantly higher at Bair Island than at West Marin (Table 3). Although the mean PCB concentration in night-heron eggs in 1990 ranged from 0.690 μg/g at West Marin to 3.95 μg/g at Bair Island, no differences existed among sites that year. DDE was higher in night-heron eggs at Bair and Brooks than at Alcatraz, but there were no differences for egrets.

In 1991, mean PCB concentrations in night-heron eggs were not different among the bay sites. The mean at Alcatraz Island, however, was significantly higher than that at South Wilbur. As with night-heron eggs, the mean concentration of PCBs in South Wilbur egret eggs was lower than that found in the bay (West Marin Island) (Table 3). The mean DDE concentration in night-heron eggs from South Wilbur in 1991, however, was significantly higher than the three bay sites. Mean DDE concentrations in snowy-egret eggs from South Wilbur and West Marin Island were similar.

During this study, only four randomly collected eggs exceeded 8 μg/g DDE, the level identified with reproductive

Table 1. Concentrations[a] of PCBs and *p,p′*-DDE in random eggs of black-crowned night-herons and snowy egrets from San Francisco Bay, California

Species and location	Year	*N*	Total PCBs	*p,p′*-DDE
Black-crowned night-heron				
Mallard Slough	1983[b]	12	1.58 (ND–7.7) A	3.11 (1.1–16) A
Mallard Slough	1989	10	2.00 (0.44–7.8) A	1.15 (0.66–3.3) B
Mallard Slough	1990	5	2.47 (0.37–8.7) A	1.36 (0.78–2.5) AB
Bair Island	1982[b]	24	3.03 (0.50–18) A	2.86 (0.59–16) A
Bair Island	1983[b]	12	4.13 (0.76–52) A	1.73 (0.57–5.6) A
Bair Island	1989	10	2.74 (0.52–7.8) A	1.69 (0.35–6.5) A
Bair Island	1990	5	3.95 (2.7–7.3) A	1.78 (0.67–8.9) A
Alcatraz Island	1990	10	0.991 (0.22–10) B	0.520 (0.26–1.2) A
Alcatraz Island	1991	10	6.08 (1.6–46) A	0.812 (0.27–2.6) A
Brooks Island	1990	10	2.72 (0.48–31) A	1.36 (0.50–2.8) A
Brooks Island	1991	10	2.00 (0.36–16) A	0.466 (0.16–0.91) B
W. Marin Island	1989	16	0.603 (ND–5.1) A	0.787 (0.20–7.0) A
W. Marin Island	1990	5	0.690 (0.34–1.9) A	0.961 (0.29–2.9) A
W. Marin Island	1991	5	1.77 (0.46–4.7) A	0.485 (0.22–0.77) A
S. Wilbur Flood Area[d]	1991	5	1.22 (0.44–2.2)	5.97 (4.3–9.4)
Snowy egret				
Mallard Slough	1990	5	2.49 (1.1–7.2)	0.925 (0.51–2.8)
Bair Island	1982[c]	10	3.32 (0.84–13) A	2.04 (0.58–14) A
Bair Island	1989	5	1.23 (0.38–2.6) A	1.71 (0.49–3.0) A
Bair Island	1990	5	5.38 (2.7–19) A	1.88 (0.76–4.3) A
W. Marin Island	1989	5	2.19 (0.78–18) A	1.86 (0.30–3.8) A
W. Marin Island	1990	5	0.792 (0.45–2.5) A	0.824 (0.26–1.8) A
W. Marin Island	1991	5	1.55 (0.74–3.3) A	1.17 (0.42–4.0) A
S. Wilbur Flood Area	1991	5	0.185 (ND–1.1)	3.01 (0.50–12)

[a]Geometric mean (and extremes) in μg/g (fresh wet wt.). ND = not detected. Within site, species, and contaminant, concentrations sharing a capital letter are not significantly different by Tukey's multiple comparison test ($p \le 0.05$).
[b]Data from a previous study [15]. Minor discrepancies with reference data related to rounding errors.
[c]Data from a previous study [12]. Minor discrepancies with reference data related to rounding errors.
[d]South Wilbur Flood Area is a reference site in California's San Joaquin Valley (Fig. 1).

Table 2. Geometric mean concentrations of organochlorines (μg/g, fresh wet wt.) in eggs of black-crowned night-herons and snowy egrets from San Francisco Bay, California

Species and site-year[b]	N	Contaminant[a] BHC	OXYCHLOR	HEP	TNONA	CNON	DIEL	DDD	DDT
Black-crowned night-heron									
MS-83[c]	12	NA[d]	NC[e]	ND[f]	0.0926	NC	NC	NC	NC
MS-89	10	ND	0.0300	0.0179	0.0589	NC	0.0156	ND	NC
MS-90	5	NC	0.0267	0.0130	0.0476	0.0240	0.0198	0.0150	0.0172
BI-82[d]	24	NA	0.133	NC	0.198	NC	NC	NC	NC
BI-83[d]	12	NA	NC	ND	0.134	NC	NC	NC	ND
BI-89	10	NC	0.0448	0.0147	0.0632	0.0272	0.0363	0.0163	0.0188
BI-90	5	NC	0.0898	0.0228	0.104	0.0569	0.0304	0.0251	0.0266
AI-90	10	ND	0.0175	NC	0.0364	NA	NC	NC	ND
AI-91	10	0.0062	0.0432	0.0203	0.0843	0.0211	0.0286	NC	ND
BR-90	10	0.0118	0.0459	0.0240	0.0633	0.0177	0.0282	0.0157	0.0243
BR-91	10	NC	0.0310	0.0169	0.0446	NC	0.0101	NC	ND
WM-89	16	NC	0.0200	0.0108	0.0256	0.0183	0.0111	0.0091	0.0118
WM-90	5	ND	0.0159	NC	0.0246	NC	0.0276	0.0100	0.0117
WM-91	5	NC	0.0194	0.0165	0.0242	NC	0.00663	ND	ND
SW-91	5	0.0113	0.0208	0.0277	0.0274	ND	0.0268	0.0144	0.0186
Snowy egret									
MS-90	5	0.0092	0.0355	0.0160	0.0744	0.0233	0.0258	0.0222	0.0122
BI-82[g]	10	NA	0.109	ND	0.151	0.103	0.0926	0.246	NC
BI-89	5	0.0168	0.0153	0.0170	0.0290	ND	0.0270	0.0180	0.0282
BI-90	5	0.0342	0.0549	0.0242	0.166	0.114	0.0661	0.0473	0.0506
WM-89	5	ND	0.0241	0.0151	0.0657	NC	0.0308	0.0168	0.0185
WM-90	5	ND	0.0306	0.0132	0.0677	NC	0.0240	0.0098	0.0236
WM-91	5	0.0264	0.0204	0.0146	0.0352	ND	0.00887	NC	NC
SW-91	5	0.0120	0.0167	0.0110	0.0366	ND	0.0275	0.0683	0.0572

[a]Contaminants detected in eggs: BHC = β-Benzenehexachloride (BHC); OXYCHLOR = oxychlordane; HEP = heptachlor epoxide; TNONA = *trans*-nonachlor; DIEL = dieldrin; CNON = *cis*-nonachlor; DDD = *p,p'*-DDD; DDT = *p,p'*-DDT. Mean concentrations of total PCBs and *p,p'*-DDE are presented in Table 1. Hexachlorobenzene results are not presented because accuracy was unacceptable in 1989 and 1990. Included in chemical analyses, but either not detected or detected infrequently at very low concentrations, were: α-BHC, γ-BHC, δ-BHC, α-chlordane, γ-chlordane, *o,p'*-DDE, *o,p'*-DDD, endrin, *o,p'*-DDT, mirex, and toxaphene. Percent moisture content ranged from 79.2 to 83.6% (mean = 81.5%). Percent lipids ranged from 4.39 to 7.31 (mean = 6.13%).

[b]Collection sites: AI = Alcatraz Island; BI = Bair Island; BR = Brooks Island; MS = Mallard Slough; SW = South Wilbur Flood Area (a reference site in California's San Joaquin Valley); WM = West Marin Island.

[c]Data from a previous study [15]. Minor discrepancies with reference data related to rounding errors.

[d]NA = eggs not analyzed for this compound.

[e]NC = not calculated; contaminant detected in <50% of the samples.

[f]ND = not detected; below the limit of detection.

[g]Data from a previous study [12]. Minor discrepancies with reference data related to rounding errors.

impairment [13]. The only one from San Francisco Bay was a night-heron egg collected at Bair Island in 1990 that contained 8.9 μg/g DDE. The other three were from South Wilbur: one egret egg (12 μg/g DDE) and two night-heron eggs (9.0 and 9.4 μg/g DDE). Three of 25 nonrandom eggs, collected in 1989 because they failed to hatch or were otherwise defective (i.e., crushed or dented), also contained elevated concentrations of DDE. A night-heron egg from Bair Island and two egret eggs, one from West Marin Island and another from Bair Island, contained 9.7, 12, and 16 μg/g DDE, respectively.

Inorganics. Inorganic contaminants detected in randomly collected eggs at one or more sites in San Francisco Bay between 1989 and 1991 (and percentage of eggs with detectable amounts) were: copper (100%), iron (100%), mercury (100%), magnesium (100%), manganese (100%), selenium (100%), zinc (100%), strontium (97%), chromium (67%), molybdenum (62%), boron (57%), and barium (40%) (Tables 4 and 5). Beryllium, cadmium, cobalt, lead, and vanadium were not detected in any eggs. Nickel was detected in ≥50% of the samples only in night-heron eggs from Brooks Island in 1990, and the geometric mean for five random eggs was 0.251 μg/g.

In 1982, the mean concentration of mercury in egret eggs from Bair Island was significantly lower than that in night-heron eggs [12]. However, in this study, no significant differences existed between species for inorganics at any of the sites. Mean mercury concentrations were lower in night-heron eggs at Bair Island in both 1989 and 1990 than in 1982. The mean concentrations of selenium, however, were significantly higher in 1989 and 1990 compared with 1983 (Table 5). Neither mercury nor selenium concentrations in egret eggs

Table 3. Among-site comparisons of concentrations of PCBs and p,p'-DDE in random eggs of black-crowned night-herons and snowy egrets from San Francisco Bay, California[a]

Year and location	Black-crowned night-heron			Snowy egret		
	N	Total PCBs	p,p'-DDE	N	Total PCBs	p,p'-DDE
1989						
Mallard Slough	10	2.00 AB	1.15 A	0	–	–
Bair Island	10	2.74 A	1.69 A	5	1.23 A	1.71 A
W. Marin Island	16	0.603 B	0.787 A	5	2.19 A	1.86 A
1990						
Mallard Slough	5	2.47 A	1.36 AB	5	2.49 AB	0.925 A
Bair Island	5	3.95 A	1.78 A	5	5.38 A	1.88 A
Alcatraz Island	10	0.991 A	0.520 B	0	–	–
Brooks Island	10	2.72 A	1.36 A	0	–	–
W. Marin Island	5	0.690 A	0.961 AB	5	0.792 B	0.824 A
1991						
Alcatraz Island	10	6.08 A	0.812 B	0	–	–
Brooks Island	10	2.00 AB	0.466 B	0	–	–
W. Marin Island	5	1.77 AB	0.485 B	5	1.55 A	1.17 A
S. Wilbur Flood Area[b]	5	1.22 B	5.97 A	5	0.185 B	3.01 A

[a]Geometric means in μg/g (fresh wet wt.). Within year, species, and contaminant, concentrations sharing a capital letter are not significantly different by Tukey's multiple comparison test ($p \leq 0.05$).
[b]South Wilbur Flood Area is a reference site in California's San Joaquin Valley (Fig. 1).

differed temporally at Bair Island. At West Marin Island, however, the mean concentration of selenium in egret eggs was higher in 1991 than in either of the previous 2 years. Mean mercury and selenium concentrations in night-heron eggs did not change significantly over time at either West Marin Island or Mallard Slough. Between 1990 and 1991, mean selenium in night-heron eggs at both Alcatraz and Brooks islands decreased. The mean mercury concentration declined at Alcatraz in 1991, but it increased at Brooks Island (Table 5).

In 1989, there were no significant differences among locations for mercury or selenium (Table 6). However, in 1990, night-heron eggs from Bair Island had a significantly lower

Table 4. Geometric mean concentrations of inorganic elements (μg/g, dry wt.) in eggs of black-crowned night-herons and snowy egrets

Species and site-year[b]	N	Element[a]									
		B	Ba	Cr	Cu	Fe	Mg	Mn	Mo	Sr	Zn
Black-crowned night-heron											
MS-89	10	0.712	0.313	1.01	6.17	94.6	583	4.76	0.534	2.64	48.8
BI-89	5	0.677	0.835	0.903	6.40	110.0	548	2.90	NC[c]	6.10	53.9
AI-90	10	ND[d]	NC	ND	6.13	87.4	452	2.82	ND	5.74	49.5
AI-91	10	0.942	NC	0.821	6.00	101.0	695	2.78	0.532	5.38	44.4
BR-90	5	NA[e]	NA	0.189	5.52	100.0	NA	2.91	NA	NA	42.2
BR-91	10	0.487	ND	NC	5.69	100.0	485	2.46	0.561	4.74	40.6
WM-89	5	ND	NC	0.708	6.25	93.5	561	3.98	NC	3.81	50.6
WM-91	5	NC	NC	ND	5.00	103.0	421	2.82	0.822	5.27	44.0
SW-91	5	1.16	1.90	NC	5.36	94.8	423	2.32	0.915	5.72	43.0
Snowy egret											
BI-89	5	0.408	0.259	0.849	7.16	119.0	549	2.43	0.778	5.01	53.6
WM-89	5	0.395	0.351	0.813	7.10	121.0	623	3.07	0.884	6.65	57.8
WM-91	5	0.859	NC	NC	7.12	135.0	597	4.54	0.617	6.02	51.5
SW-91	5	1.29	0.823	NC	6.21	141.0	643	2.43	0.616	5.71	52.3

[a]Elements included in chemical analyses: B = boron; Ba = barium; Cr = chromium; Cu = copper; Fe = iron; Mg = magnesium; Mn = manganese; Mo = molybdenum; Sr = strontium; and Zn = zinc. Mean concentrations of selenium and mercury are presented in Table 5. Beryllium, cadmium, cobalt, lead, and vanadium concentrations were below the limits of detection. Nickel was detected in ≥50% of samples only at Brooks Island in 1990 (mean of random eggs = 0.251 μg/g). Percent moisture content range from 79.2 to 83.6% (mean = 81.5%).
[b]Collection sites: AI = Alcatraz Island; BI = Bair Island; BR = Brooks Island; MS = Mallard Slough; SW = South Wilbur Flood Area (a reference site in California's San Joaquin Valley); WM = West Marin Island.
[c]NC = not calculated; element detected in <50% of the samples.
[d]ND = not detected; below the limit of detection.
[e]NA = eggs not analyzed for this element.

Table 5. Concentrations[a] of mercury and selenium in random eggs of black-crowned night-herons and snowy egrets from San Francisco Bay, California

Species and location	Year	N	Mercury	Selenium
Black-crowned night-heron				
Mallard Slough	1983[b]	12	NA[c]	2.93 (2.3–3.6) A
Mallard Slough	1989	10	0.909 (0.32–3.0) A	3.21 (2.1–5.3) A
Mallard Slough	1990	5	1.39 (0.77–2.1) A	3.33 (2.7–3.8) A
Bair Island	1982[d]	24	2.15 (1.0–5.9) A	NA
Bair Island	1983[b]	6	NA	2.83 (2.3–3.7) B
Bair Island	1989	5	0.662 (0.49–0.84) B	3.58 (3.0–4.2) A
Bair Island	1990	5	0.502 (0.27–0.72) B	4.08 (3.5–4.8) A
Alcatraz Island	1990	10	1.17 (0.59–2.3) A	5.68 (4.3–9.7) A
Alcatraz Island	1991	10	0.56 (0.28–1.0) B	4.33 (3.7–5.4) B
Brooks Island	1990	10	0.763 (0.51–1.2) B	4.78 (3.7–6.4) A
Brooks Island	1991	10	1.41 (0.44–3.0) A	3.58 (2.6–4.9) B
W. Marin Island	1989	5	0.711 (0.48–1.4) A	3.61 (2.8–4.4) A
W. Marin Island	1990	5	1.33 (0.61–4.2) A	3.06 (2.1–3.9) A
W. Marin Island	1991	5	1.29 (0.45–4.5) A	4.12 (3.1–5.7) A
S. Wilbur Flood Area[e]	1991	5	0.591 (0.36–1.1)	4.87 (3.1–6.5)
Snowy egret				
Mallard Slough	1990	5	1.48 (0.61–2.8)	3.89 (3.2–4.7)
Bair Island	1982[d]	10	1.17 (0.79–3.0) A	NA
Bair Island	1989	5	0.965 (0.70–1.8) A	3.29 (2.3–3.8) A
Bair Island	1990	5	1.50 (0.52–4.0) A	3.81 (3.3–4.2) A
W. Marin Island	1989	5	1.07 (0.37–2.1) A	3.46 (3.0–4.0) A
W. Marin Island	1990	5	1.49 (0.79–2.2) A	3.02 (2.7–3.5) A
W. Marin Island	1991	5	1.16 (0.54–3.1) A	4.33 (3.3–5.3) B
S. Wilbur Flood Area	1991	5	1.04 (ND[f]–6.4)	5.26 (1.8–9.6)

[a]Geometric mean (and extremes) in μg/g (dry wt.). Moisture levels ranged from 77.6% for egrets (West Marin 1991) to 83.9% for night-herons (Bair Island 1989). Within site, species, and contaminant, concentrations sharing a capital letter are not significantly different by Tukey's multiple comparison test ($p \leq 0.05$).
[b]Selenium data from a previous study [15]. Mean concentration converted from wet weight basis to dry weight using reported moisture level.
[c]NA = none analyzed.
[d]Mercury data from a previous study [12]. Mean concentration converted from wet weight basis to dry weight using reported moisture level.
[e]South Wilbur Flood Area is a reference site in California's San Joaquin Valley (Fig. 1).
[f]ND = not detected; below the limit of detection.

Table 6. Among-site comparison of concentrations of mercury and selenium in random eggs of black-crowned night-herons and snowy egrets from San Francisco Bay, California[a]

Year and location	Black-crowned night-heron			Snowy egret		
	N	Mercury	Selenium	N	Mercury	Selenium
1989						
Mallard Slough	10	0.909 A	3.21 A	0	–	–
Bair Island	5	0.662 A	3.58 A	5	0.965 A	3.29 A
W. Marin Island	5	0.711 A	3.61 A	5	1.07 A	3.46 A
1990						
Mallard Slough	5	1.39 A	3.33 BC	5	1.48 A	3.89 A
Bair Island	5	0.502 B	4.08 BC	5	1.50 A	3.81 A
Alcatraz Island	10	1.17 A	5.68 A	0	–	–
Brooks Island	5	0.763 AB	4.78 AB	0	–	–
W. Marin Island	5	1.33 A	3.06 C	5	1.49 A	3.02 B
1991						
Alcatraz Island	10	0.564 B	4.33 AB	0	–	–
Brooks Island	10	1.41 A	3.58 B	0	–	–
W. Marin Island	5	1.29 AB	4.12 AB	5	1.16 A	4.33 A
S. Wilbur Flood Area[b]	5	0.591 AB	4.87 A	5	1.04 A	5.26 A

[a]Geometric mean in μg/g (dry wt.). Within year, species, and contaminant, concentrations sharing a capital letter are not significantly different by Tukey's multiple comparison test ($p \leq 0.05$).
[b]South Wilbur Flood Area is a reference site in California's San Joaquin Valley (Fig. 1).

mean mercury concentration than all but those from Brooks Island. Mercury concentrations in egret eggs from bay sites were not different. The highest mean selenium concentration in night-heron eggs in 1990 was from Alcatraz, and the lowest was from West Marin Island (Table 6). For egret eggs, mean selenium concentrations at Bair Island and Mallard Slough were similar; both were higher than West Marin.

In 1991, the mean mercury concentration was higher in night-heron eggs from Brooks Island than in those from Alcatraz; mean concentrations in night-heron eggs from West Marin Island and South Wilbur were intermediate and not significantly different from one another or the other two sites. Mercury concentrations in egret eggs from South Wilbur and West Marin Island were similar. The mean selenium concentration in night-heron eggs from South Wilbur was higher than Brooks Island but not Alcatraz or West Marin islands. Although the mean selenium concentration in egret eggs was high at South Wilbur, it was not different from West Marin (Table 6).

Reproductive success

Predation was a major factor limiting nesting success in San Francisco Bay. In 1990, predators destroyed 42.5% of the eggs and 46.4% of the chicks in egret nests at Bair Island, which was significantly greater than in 1989 when 24.3% of the eggs and 33.9% of the chicks were depredated. Nest and fledging success were likewise significantly lower in 1990, due primarily to high rates of predation. Nest success was also lower for egrets at West Marin in 1990 than in 1989, primarily because predation was higher in 1990 (25.5% of eggs destroyed) than in 1989 (9.5% destroyed). Rates of predation on egret chicks and fledging success at West Marin, however, did not differ between years.

Predation rates, nest success, and fledging success did not differ for night-herons at Bair Island between 1989 and 1990 or for Alcatraz or Brooks islands between 1990 and 1991 (Table 7). At West Marin Island, however, nest survival was significantly lower in 1990 than in 1989, primarily because predators destroyed 19.1% of the night-heron eggs in 1990, compared with only 4.8% in 1990. Neither the rate of chick predation nor fledging success differed between the 2 years at West Marin.

In 1990, the only year that reproduction was studied at all four San Francisco Bay sites, night-heron nest survival at Alcatraz and Bair islands was significantly better than at West Marin, whereas nest survival at Brooks was intermediate (Table 8). Fledging success was better at Alcatraz than at Bair and West Marin (Table 8), despite interspecific competition from about 500 pairs of nesting western gulls (*Larus occidentalis*).

Relatively few eggs failed to hatch during this study, and night-heron egg hatchability ranged from 89.5% at West Marin in 1989 to 97.8% at Brooks Island in 1991 (Table 7). Hatchability was especially uniform in 1990 when it ranged from 94.0 to 94.8% (Table 8).

There were signs of reproductive impairment, however, at all monitored nesting sites in San Francisco Bay except Brooks Island in 1991. These included 16 egret and 21 night-

Table 7. Nest and fledging success of black-crowned night-herons and snowy egrets in San Francisco Bay, 1989–1991[a]

Species, site, and year	Hatchability[b] (%)	Nest success		Fledging success	
		Total nests[c]	Survival estimate	Total nests[c]	Survival estimate
Black-crowned night-heron					
Bair Island					
1989	92.3	106/33	0.531 A	74/29	0.600 A
1990	94.4	191/41	0.670 A	152/45	0.704 A
Alcatraz Island					
1990	94.1	140/26	0.701 A	127/12	0.896 A
1991	95.5	81/22	0.637 A	61/10	0.824 A
Brooks Island					
1990	94.8	52/14	0.557 A	44/10	0.766 A
1991	97.8	55/27	0.385 A	33/10	0.681 A
W. Marin Island					
1989	89.5	106/16	0.733 A[d]	88/36	0.573 A
1990	94.0	102/28	0.475 B	72/20	0.691 A
Snowy egret					
Bair Island					
1989	95.3	80/21	0.634 A[d]	58/26	0.553 A[d]
1990	92.7	96/53	0.379 B	63/37	0.335 B
W. Marin Island					
1989	92.0	110/20	0.711 A[d]	88/33	0.626 A
1990	93.0	116/32	0.598 A	88/31	0.587 A

[a]Within sites, survival estimates sharing a capital letter are not significantly different by Tukey's multiple comparison test ($p \leq 0.05$).
[b]Hatchability was calculated by dividing the total eggs that hatched by the total hatched plus those that failed (including infertile, but not including those that disappeared or were otherwise destroyed).
[c]Total nests included in analysis/total unsuccessful nests.
[d]Predation was significantly greater in 1990 than in 1989 at these sites.

Table 8. Black-crowned night-heron reproductive success, San Francisco Bay, 1990

Location	Hatchability[a]	Nest success		Fledging success	
		Nests[b]	Survival estimate	Nests[b]	Survival estimate
Bair Island	94.4%	191/41	0.670 A[c]	152/45	0.704 B
Alcatraz Island	94.1%	140/26	0.701 A	127/12	0.896 A
Brooks Island	94.8%	52/14	0.557 AB	44/10	0.766 AB
W. Marin Island	94.0%	102/28	0.475 B	72/20	0.691 B

[a]Hatchability was calculated by dividing the total eggs that hatched by the total hatched plus those that failed (including infertile, but not including those that disappeared or were otherwise destroyed).
[b]Total nests included in analysis/total unsuccessful nests.
[c]Within reproductive categories, survival estimates sharing a capital letter are not significantly different by Tukey's multiple comparison test ($p \leq 0.05$).

heron eggs than had crushed, cracked, dented, or brittle shells. In addition, teratogenesis was observed in two of the 18 night-heron eggs that failed and were collected at Alcatraz in 1990. One of the embryos had no upper mandible, there was bilateral anophthalmia, and the joints were swollen. In the other embryo, the upper mandible had lateral malformations, the lower mandible was poorly developed, there were no eyes, the neck was shortened, and there was encephalocoele of the forebrain. Two deformed chicks were also observed at San Francisco Bay sites. One, a snowy egret from West Marin in 1989, had a shortened and severely deflected upper mandible. The other was a night-heron chick found in 1990 at Alcatraz with a similar deformity.

The average number of night-heron chicks that survived to 15 d per successful nest ranged from 1.45 at West Marin in 1989 to 2.04 at Alcatraz in 1990. The average number of egret chicks that survived to 10 d per successful nest ranged from 1.90 at West Marin in 1990 to 2.72 at Bair Island in 1990.

DISCUSSION

Organochlorines

Chemical analyses of randomly collected eggs from five sites in San Francisco Bay indicated that, despite the ubiquitous presence of many organochlorines throughout the Bay ecosystem [1,32], certain spatial and temporal variations occurred. This study focused on *p,p′*-DDE and PCBs because both are regularly found at elevated concentrations in San Francisco Bay and because they have been linked to impaired avian reproduction in the bay and elsewhere.

PCBs. PCBs are generally slow to degrade, and they continue to persist in aquatic environments even though their manufacture and use were prohibited in the United States in 1979 [33]. Although PCB concentrations in night-heron eggs from certain sites seemed to increase over time, the only site where this increase was significant was Alcatraz.

Mean concentrations of PCBs in San Francisco Bay sediments were up to 100 times higher than coastal reference sites (Bodega Bay and Tomales Bay), and concentrations were higher in resident mussels (*Mytilus edulis, M. californianus*) from the southern than from the northern parts of the bay [32]. Mean concentrations of PCBs in night-heron eggs in 1989 and egret eggs in 1990 were lower at West Marin in the North Bay than at Bair Island in the South Bay. These findings were confirmed by a cytochrome P450 study of night-herons in 1989 [28]. The highest mean PCB concentration (6.08 μg/g) detected in this study, however, was in 1991 in night-heron eggs from Alcatraz Island, a site in the Central Bay. The mean and range (1.6–46 μg/g) at Alcatraz were similar to those of night-heron eggs from an earlier study at Bair Island in 1983 ($\bar{X} = 4.13$ μg/g, range = 0.76–52 μg/g), where embryonic growth was negatively correlated with PCBs [14].

The concentrations of total PCBs in the two deformed embryos from Alcatraz Island (6.6 and 8.2 μg/g, respectively) were generally lower than those associated with malformations in fish-eating birds in the Great Lakes [34]. However, they were within the range recorded for deformed common terns (*Sterna hirundo*) from the Great Lakes in 1985 [35]. Although no chicks were analyzed for contaminants, deformities observed in the chicks from West Marin and Alcatraz islands resembled those attributed to PCBs in double-crested cormorant (*Phalacrocorax auritus*) chicks from the Great Lakes [36].

As expected, the mean PCB concentrations in eggs from South Wilbur, a site located in an agricultural area, were low compared to those from the highly urbanized San Francisco Bay. However, PCBs were detected in 80% of the eggs analyzed from South Wilbur, which is more than reported from three sites in the northern San Joaquin Valley: Kesterson Reservoir (9%), Volta Wildlife Management Area (0%), and Mendota Wildlife Management Area (44%) [15]. Although the detection limit for PCBs in this study was 0.05 μg/g, compared with 0.5 μg/g for the other three sites, the percentage of South Wilbur eggs with detectable concentrations would only be reduced to 70% if the detection limit were increased to 0.5 μg/g. Means could not be compared among these sites because they were not calculated at Kesterson, Volta, or Mendota where PCBs were detected in <50% of the eggs. However, low maximum concentrations at these agricultural sites (≤2.0 μg/g) were more similar to those observed at South Wilbur than to those of San Francisco Bay.

DDT. Although it was banned in California in 1970 and the rest of the United States in 1971, DDT and its metabolites are well mixed and distributed throughout San Francisco Bay [32]. DDE was detected in every egg analyzed from San

Francisco Bay, and both DDT and DDD were detected in 51.6% of the analyzed eggs.

During this study, less than 1% of the randomly collected eggs from San Francisco Bay had >8 μg/g DDE. Of the eggs that were collected because they failed to hatch or were defective (i.e., crushed or dented), only 12% contained >8 μg/g DDE. Concentrations of DDE similar to these have been related to shell defects in eggs of black-crowned night-herons [37] and white-faced ibises (*Plegadis chihi*) [38].

At Bair Island and Mallard Slough, mean DDE in night-heron eggs appeared to decline with time, but the differences were not significant. Maximum observed concentrations, however, for night-heron and egret eggs at Bair Island and night-heron eggs at Mallard Slough were about 10 μg/g lower in 1989 and 1990 than in 1983. Mean organochlorine concentrations in eggs of California clapper rails (*Rallus longirostris obsoletus*) from San Francisco Bay were found to have declined significantly from 1975 to 1986 [39]. Similar declines have been noted elsewhere in North America and Western Europe, with a concomitant improvement in reproductive success [40].

Fish, mussels, and sediments from the Lauritzen Canal, located only about 3 km from Brooks Island, still contain concentrations of DDT, DDT metabolites, and other chlorinated pesticides that exceed most other bay sites, more than 20 years after the closure of the nearby pesticide packaging plant [32]. Based on the close proximity of the Brooks Island night-heron colony to the canal, it was hypothesized that DDT and its metabolites would likely be elevated in night-heron eggs from that site. In 1990, however, the mean concentration of DDE in night-heron eggs from Brooks was only higher than Alcatraz and was not different from the other three sites. In 1991, the mean DDE concentration in night-heron eggs from Brooks Island was significantly lower than that observed in 1990 and was not different from the other bay sites. The highest observed concentration of DDE at Brooks Island was 4.5 μg/g in a night-heron egg that failed to hatch, well below the level associated with reproductive impairment [13].

Although the Lauritzen Canal was within the normal foraging range of night-herons nesting on Brooks Island [7], many other less-contaminated feeding sites were also within that range. It is likely that unsuccessful night-herons followed successful ones and foraged at sites with more abundant prey that were less contaminated with organochlorines.

Mean DDE concentrations in snowy-egret eggs from South Wilbur were not significantly higher than those from West Marin Island in 1991. However, the mean DDE concentration in night-heron eggs from South Wilbur was significantly higher than the three bay sites (by a factor of 10). This difference was not unexpected, based on the likely history of pesticide use in this agricultural area and the persistence of DDT and its metabolites.

Inorganics. Although numerous inorganics were detected in a high percentage of eggs analyzed from San Francisco Bay, selenium and mercury are the two elements that have been most often implicated in cases of impairment of avian reproduction [41,42]. Selenium was detected in every egg analyzed during this study, and mercury was detected in every egg except one from South Wilbur.

Mercury. Game-farm mallards (*Anas platyrhynchos*) fed 0.5 μg/g methylmercury displayed abnormal egg-laying behavior, impaired reproduction, and slowed duckling growth [43]. The mean concentration in eggs from that study was 0.86 μg/g (wet wt.), or, assuming a moisture content of 80%, about 4.3 μg/g (dry wt.). Although none of the means from this study or from the one conducted at Bair Island in 1982 was more than one-half the mean from the laboratory study, the maximum concentrations in night-heron eggs from West Marin Island were 4.2 μg/g mercury in 1990 and 4.5 μg/g in 1991. If night-herons are affected by mercury similar to mallards, then some night-herons at West Marin may have experienced reproductive impairment.

There was a long-term (8-year) trend of increasing mean mercury concentrations in night-heron eggs at Bair Island, the only site that had 1982 data for comparison. However, no similar trend was observed for mercury in snowy-egret eggs from the same site. No differences existed for either species when means from 1989 were compared with 1990. When 1990 and 1991 were compared, a decrease in mean mercury concentration in night-heron eggs was observed at Alcatraz, there was an increase in night-heron eggs at Brooks, and there was no change for either species at West Marin. The variable short-term (1- to 2-year) trends in mercury concentrations in eggs were probably related to factors such as annual variation in contaminant inputs, rainfall amounts and timing, and bird feeding behavior.

Inter-site differences in mercury contamination of eggs were not consistent among years. Concentrations of mercury in night-heron eggs at Alcatraz and Brooks islands were not different in 1990, but the mean at Alcatraz declined significantly in 1991 while the mean at Brooks was significantly increasing. The result was that the mean mercury concentration at Brooks was significantly higher than Alcatraz in 1991.

Spatial differences within regions of the bay were also unclear. For example, the site with the highest mean mercury concentration in night-heron eggs in 1990 was Mallard Slough, in the South Bay. Bair Island, the site with the lowest mean mercury concentration, was also located in the South Bay. Inter-colony movements by birds could make the interpretation of spatial differences in levels of persistent chemicals difficult.

A major historical source of mercury in San Francisco Bay was upstream mining in the 1800s [44]. Current sources are poorly defined, but high concentrations in small streams may indicate that urban runoff is an important source [1]. Multiple sources of mercury could explain some of the difficulty in determining spatial and temporal trends in eggs from the bay.

Selenium. In a laboratory study, selenium as selenomethionine was fed to nesting female mallards. The threshold for reproductive impairment, including embryo mortality and teratogenesis, was >17 μg/g (dry wt., assuming 80% moisture) selenium in the egg [45].

Night-heron embryos appear to be less sensitive than mallards to selenium in the diet. Eggs of night-herons fed a diet containing 10 μg/g selenium contained a mean of 16.5 μg/g (dry wt.) selenium; these birds exhibited no reproductive impairment [46]. Although both the means and upper limits of the ranges for all the sites sampled in 1989 through 1991 were above normal background concentrations (3 μg/g) [47], all were well below the 16.5-μg/g no-effect level.

The two grossly deformed embryos collected at Alcatraz Island in 1990 had malformations similar to those associated with selenium toxicosis [48,49]. However, the concentrations in these eggs, 6.1 and 7.6 μg/g selenium, respectively, while above background, were probably not sufficient to have caused the observed teratogenesis.

As with mercury, there was some evidence of a long-term trend (6 to 7 years) of increasing mean selenium concentrations in eggs in the South Bay. Two sites had data from 1983 for comparison: The mean in night-heron eggs was significantly higher in 1990 at Bair Island, but the means were not different at Mallard Slough. Short-term trends in selenium concentrations in eggs were not clear. Mean selenium concentrations in night-heron eggs from three sites and in egret eggs from two sites from 1989 were compared with 1990, but there were no differences. When selenium concentrations in 1990 and 1991 were compared, night-heron eggs decreased at Alcatraz and Brooks but did not change at West Marin. Selenium increase in egret eggs at West Marin, however.

Although there are multiple sources of selenium in the Bay, West Marin was the site closest to significant sources in the North Bay, namely the six petroleum refineries and the riverine outlet from the agricultural Central Valley [50,51]. Despite its close proximity to these major sources, however, eggs from West Marin did not contain higher selenium concentrations than other bay sites. In fact, the mean selenium concentrations at West Marin in 1990 were lower for both species than some other bay sites. In 1989 and 1991, no significant spatial differences existed within the bay.

Although not contaminated by selenium from petroleum refineries like the bay, South Wilbur is located in an area with large numbers of selenium-contaminated drainwater ponds [47], so it is not surprising that eggs from this area contained elevated concentrations of selenium.

Reproductive success

At sites in San Francisco Bay where reproduction was monitored, predation was the most common cause of nest failure. In previous studies, predation has been a major limiting factor for both nesting night-herons [13,52,53] and snowy egrets [54–56]. Predation on eggs was heaviest in 1990, especially for egrets at Bair Island and night-herons at West Marin Island.

Predation on chicks was more difficult to determine, but there was conclusive evidence, especially at Bair Island, that chicks of both species were preyed upon by northern harriers (*Circus cyaneus*). These birds nested near and sometimes within the colony at Bair Island, and harrier nests often contained remains of egret and night-heron chicks. Other potential avian predators observed at one or more sites included common ravens (*Corvus corax*), turkey vultures (*Cathartes aura*), western gulls, and other nesting wading birds. Mammalian and other predatory species were not identified as limiting factors in San Francisco Bay during 1989 through 1991, except at Bair Island where foxes apparently caused colony abandonment in 1991.

Between 1989 and 1991, hatchability of night-herons and egrets in San Francisco Bay was similar to that observed in the St. Lawrence Estuary in 1975 and 1976 where infertility, breakage, and embryonic death, combined, comprised only 1 to 10% of the egg loss [52]. Concentrations of toxic chemicals were relatively low in those eggs, and reproduction was considered normal. Hatchability in San Francisco Bay was also similar to Atlantic Coast night-herons (93.3%) [19] but was higher than night-herons from Idaho (87.7%) where DDE-induced losses significantly reduced reproductive success in 1979 [57].

Some evidence of impaired reproduction, including defective eggshells, and deformed embryos and chicks, were observed during this study, but chemical analyses of failed eggs did not confirm the causes of the impairment. Concentrations of DDE, mercury, and selenium in the two deformed embryos from Alcatraz Island were below toxic thresholds; only PCB concentrations were within the range that might cause teratogenic effects [35].

Although the levels of hatchability and overall reproductive success in San Francisco Bay were similar to those from relatively uncontaminated sites, the incidence of reproductive impairment observed could be related to foraging in contaminated "hot spots" in San Francisco Bay or elsewhere. Night-herons nesting in colonies in Oregon, Idaho, and Nevada were found to be migratory, wintering in Mexico or the southwestern United States where they likely acquired substantial loads of pollutants [58]. Night-herons in the San Francisco Bay area, however, are less migratory and are thus more likely to acquire their contaminant loads locally. Band recoveries indicated that night-herons dispersed within the suitable wintering area of San Francisco Bay, unlike snowy egrets, which migrated to southern California or Mexico [59].

Although crushed eggshells, deformed embryos, and deformed chicks were found in San Francisco Bay heronries, mean contaminant concentrations and most maximum concentrations in eggs were lower than those known to impair avian reproduction. Reproductive success was affected more by predation than by toxic effects from contaminants.

Spatial differences were observed for certain contaminants, but the ubiquitous distribution of most contaminants made these differences relatively rare. In addition, seasonal and annual movements of the birds among colony sites probably contributed to the variation in spatial differences. Temporal changes were noted for certain contaminants, but the resistance to degradation by some organochlorines, combined with the continued input into the bay of these and other contaminants, made such changes, especially in the short term, difficult to discern.

South Wilbur was found to be a poor reference site because eggs from that site had significantly higher concentrations of certain contaminants than those from San Francisco Bay. Further study of South Wilbur may be warranted, especially based on the high concentrations of DDE and selenium in eggs of both snowy egrets and black-crowned night-herons.

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