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Effects of Mercury, Selenium, and Organochlorine Contaminants on Reproduction of Forster's Terns and Black Skimmers Nesting in a Contaminated Texas Bay

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Abstract. Mean mercury (0.40 μg/g), and geometric mean DDE (1.6 μg/g) and polychlorinated biphenyl (PCB) (2.3 μg/g) concentrations in Forster's tern (*Sterna forsteri*) eggs from Lavaca Bay were higher than those in tern eggs from a reference area in San Antonio Bay, but residues were not correlated with hatching success. Nest success was similar between bays. Selenium levels in Lavaca Bay tern eggs (0.71 μg/g) were also comparable to those in eggs from the reference area (0.68 μg/g).

Clutch size (3.1 to 3.4) of Lavaca Bay black skimmers (*Rynchops niger*) was no different than that (3.4) at a reference colony near Laguna Vista. Nest success was similar among three Lavaca Bay colonies, but success was lower at one Lavaca Bay colony (40%) than at Laguna Vista (65%). Mean mercury (0.46 μg/g) and selenium (0.75 μg/g) concentrations in skimmer eggs from Lavaca Bay were higher than those (0.19, 0.33 μg/g) from Laguna Vista; however, concentrations of neither contaminant were related to hatching success. DDE concentrations in Lavaca Bay skimmer eggs (3.4 μg/g) were similar to those from Laguna Vista (3.2 μg/g) and DDE was negatively correlated with hatching success. PCBs were higher in eggs from Lavaca Bay (1.3 μg/g) than Laguna Vista (0.8 μg/g). Organochlorine and metal contaminants in most eggs were below embryotoxic levels. Eggshell thinning in Forster's terns (7%) and black skimmers (5%) was below that associated with lowered reproduction.

DDE and PCBs were detected in 9 Caspian tern (*S. caspia*) eggs; maximum concentrations were 4.7 and 5.4 μg/g. Caspian tern and least tern (*S. albifrons*) eggs contained low (≤0.9 μg/g) concentrations of mercury and selenium.

High levels of mercury, up to 8.0 μg/g, were reported in finfish, crabs (*Callinectes* sp.) and oysters (*Crassostrea virginica*) collected from Lavaca Bay, Texas (Figures 1 & 2) between 1970–1977 (Texas Dept Health 1982). Highest mercury concentrations were detected in samples collected near an aluminum refining company, but contaminated fish and crabs were taken throughout Lavaca Bay and adjacent Matagorda Bay. Mean mercury residues in 3 of 5 fish species from Lavaca Bay exceeded the U.S. Food and Drug Administration action level of 1.0 μg/g. Mean concentrations in red drum (*Sciaenops ocellata*) fillets were 5.6 μg/g (wet weight); more than 50 times greater than the National Contaminant Biomonitoring Program mean (0.11 μg/g) for mercury in fish collected from 98 North American monitoring stations (May and McKinney 1981). Mercury residues in Lavaca Bay fish were comparable to levels in fish from contaminated lakes in Canada (0.6–3.79 μg/g) (Moore and Sutherland 1980; Speyer 1980). Mallards (*Anas platyrhynchos*) and black ducks (*A. rubripes*) fed diets containing mercury at levels several times lower than those in Lavaca Bay fish laid eggs with thin shells, and experienced lowered clutch size, egg production, hatchability, and nestling survival (Finley and Stendell 1978; Heinz 1980). In related studies, abnormal behavior and brain lesions were noted in chicks hatched from mercury contaminated eggs (Heinz 1975; Heinz and Locke 1976).

At least 14 species of fish-eating birds have nested on islands in Lavaca Bay (Texas Colonial Waterbird Society 1982). In 1983, several waterbird species established nesting colonies in the most polluted portion of the bay on islands adjacent to the aluminum refinery. Little information is available on the reproductive success of birds nesting there. The objectives of this study were to determine the effects of mercury and other contaminants on reproduction of Forster's terns (*Sterna forsteri*) and black skimmers (*Rynchops niger*) nesting on islands in Lavaca Bay and to measure concentrations of contaminants in eggs of Caspian (*S. caspia*) and least (*S. albifrons*) terns nesting there. Since DDE is known to affect the reproductive success of black skimmers (Custer and Mitchell 1987), and there has been increasing concern about the potential harmful effects of selenium on birds (Ohlendorf *et al.* 1986), concentrations of these elements were also determined.

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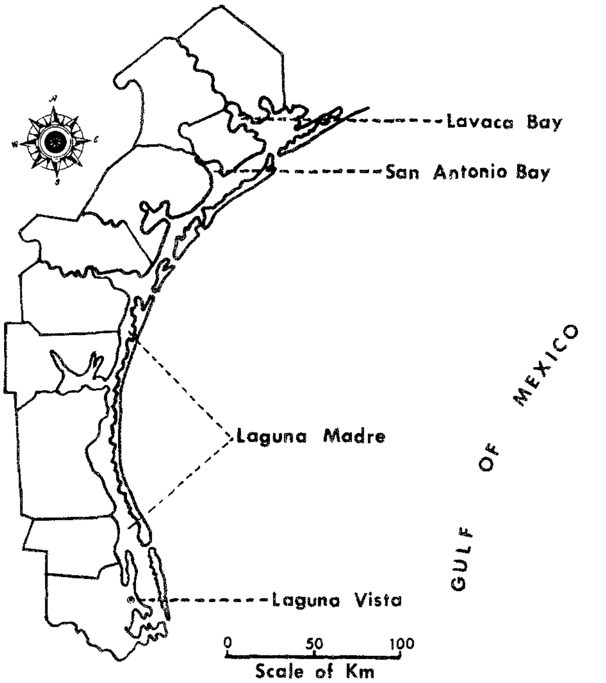

Fig. 1. Location of Forster's tern and black skimmer study sites in Texas

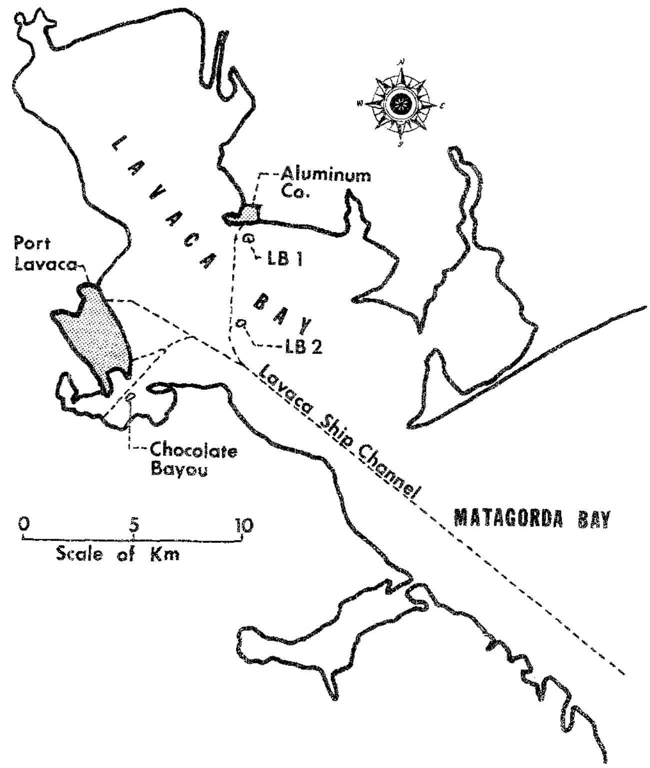

Fig. 2. Location of Forster's tern and black skimmer nesting colonies in Lavaca Bay, Texas

Methods

Field studies were conducted from 11 April through 26 July 1984. The Forster's tern and the black skimmer were selected for reproductive studies based on abundance. The Lavaca Bay study area included two dredged material islands adjacent to the Lavaca Bay Ship Channel and an island at the mouth of Chocolate Bayou near the town of Port Lavaca (Figure 2). A colony of Forster's terns nesting on a single dredged material island in San Antonio Bay about 38 km SW from Lavaca Bay served as the reference area (Figure 1). The reference colony for black skimmers was described by Custer and Mitchell (1987) and is located on a dredged material island in the lower Laguna Madre near the town of Laguna Vista about 300 km south of Lavaca Bay (Figure 1). Both the San Antonio Bay and Laguna Vista areas are relatively uncontaminated by metals (Windom 1972; Sims and Presley 1976).

At Lavaca Bay and at the reference areas, tern and skimmer nests were marked and checked every 2–5 days until the eggs hatched and chicks fledged. Nests were marked with numbered wooden stakes driven into the substrate about 25–30 cm from the perimeter of the nest. Eggs in marked nests were identified by nest number using a nontoxic waterproof marking pen. A 70-cm high fence enclosure was constructed around groups of nests of each species to aid in determinations of fledging success. Nest contents were recorded from egg laying through hatching of the last egg. Nestlings were web-tagged shortly after hatching then later banded with standard Fish and Wildlife Service bands. Counts of individually marked young in the fenced enclosures were continued until the young left the enclosure.

For both species, one egg was collected from each marked nest at the Lavaca Bay and reference areas. Of the 47 Forster's tern eggs collected from Lavaca Bay, 33 were selected for chemical tests based on hatching success category and were analyzed for mercury, selenium, and organochlorines. Three additional eggs were analyzed for mercury and selenium only. For comparison, we analyzed 44 of 80 tern eggs collected from San Antonio Bay for mercury and selenium and 38 eggs for organochlorines. Sixty-seven black skimmer eggs were collected from Laguna Bay of which 43 were analyzed for mercury, selenium, and organochlorines. Fifty-three skimmer eggs from Laguna Vista were analyzed for organochlorines (Custer and Mitchell 1987); nine additional eggs were analyzed for mercury and selenium. Embryonic development in 74 of 80 Forster's tern eggs analyzed was ≤50%. All but one skimmer egg from Lavaca Bay contained embryos that were ≤50% developed. Least and Caspian tern eggs were analyzed for mercury, and selenium; Caspian tern eggs were also analyzed for organochlorines.

Egg contents were removed and stored frozen in jars previously cleaned with an acid wash and rinsed with acetone and hexane. Whole eggs were cut around the girth, then gently washed and allowed to dry. Thickness (shell + shell membrane) was measured at three points around the girth with a micrometer accurate to 0.01 mm. Shell thicknesses of eggs collected in 1984 were compared with those of museum eggs collected in Texas before the widespread use of DDT (pre-1943) and also with measurements of eggs collected in 1970 (King *et al.* 1978).

Chemical analyses were completed at the Patuxent Wildlife Research Center, Laurel, Maryland. Methods for organochlorine analysis were identical to those described by King and Krynitsky (1986). The lower limit of quantification was 0.1 μg/g for all organochlorine pesticides, polychlorinated styrene (PCS), and polychlorinated diphenyl ether (PCDPE), and 0.5 μg/g for polychlorinated biphenyl (PCB). Residue values were corrected for moisture loss (Stickel *et al.* 1973). For wet weight to dry weight conversions, Forster's tern eggs from Lavaca and San Antonio Bays averaged 73 and 74% moisture; black skimmer eggs from Lavaca Bay and Laguna Vista averaged 77 and 76% moisture.

Methods of selenium and mercury analysis were similar to those reported by Krynitsky (1987). The lower limit of reportable values was 0.05 μg/g wet-weight for selenium and 0.02 μg/g wet-weight for mercury. Selenium and mercury values are reported on a wet-weight basis. Moisture content is presented to facilitate wet-weight to dry-weight conversions.

Tern ($n = 35$) and skimmer ($n = 20$) chicks found dead or dying were salvaged and brains removed for histological studies and chemical analyses. Each brain was bisected and one-half examined for lesions or other anomolies. The remaining one-half was saved for mercury analysis and comparison to brains of 10 normal appearing chicks sacrificed as controls. Whole body remainders of prefledglings found dead and controls were frozen for further analysis if needed.

Nest success was estimated by the Mayfield method (Mayfield 1961, 1975); appropriate variance estimates and comparisons of daily survival rates were determined (Hensler and Nichols 1981). The nesting phase was divided into incubation and prefledgling periods by using the number of days in these periods determined for the median clutch size. The incubation period, 20 days for Forster's terns and 21 days for black skimmers, was defined as the number of days from the date the first egg was laid until the day before the first egg hatched. The prefledgling period was considered as the day the first egg hatched to 24 days for Forster's terns and 21 days for black skimmers. Estimates of daily survival rate and corresponding variance of these estimates were calculated for both periods of the nesting cycle. An estimate of the overall survival rate for the entire nesting cycle was calculated from the daily rates and comparisons of these estimates were made as described earlier (Custer *et al.* 1983).

DDE and PCB residue values were transformed to logarithms for statistical comparisons. Geometric means are presented in the tables. Contaminant means were only calculated and compared when at least 50% of the samples had detectable concentrations. A value of one-half the limit of detection (*i.e.*, 0.05 μg/g for organochlorines and 0.25 μg/g for PCBs) was substituted for the "not-detected" values to facilitate transformation to logarithms.

The Bonferroni multiple comparison method (Neter and Wasserman 1974) was used to test for mean separation when ANOVA showed significant differences. Regression analysis was used to compare residue levels with eggshell thickness. Unless otherwise stated, a statistical significance level of 0.05 was used.

Results

Reproductive Success

Forster's Tern: At least 200 pairs of Forster's terns nested on the Lavaca Bay island study site in 1984. Egg laying and incubation were well underway on our first visit to the colony 11 April. The median date for clutch initiation based on calculations assuming a 20 day incubation period was 11 April (range = 1 April to 22 April, N = 47). About 120 pairs of Forster's terns nested on the San Antonio Bay reference island. At San Antonio Bay there were two distinct nesting attempts. The median date for clutch initiation during the first nesting attempt was 13 April (range = 5 April to 21 April, N = 50). The median date for clutch initiation during the second nesting attempt was 22 May (range = 9 May to 3 June, N = 30).

Forty-seven Forster's tern nests were marked at Lavaca Bay and 80 nests were monitored in San Antonio Bay through hatching. Mean clutch size was 3.0 eggs per clutch at Lavaca Bay (141/47) and San Antonio Bay (240/80). Of the 254 eggs monitored to hatching, 102 (40.2%) hatched; 90 (35.4%) remained intact through the incubation period, but did not hatch; 37 (14.6%) were missing; and 15 (6.9%) were lost to flooding. Other, less frequent, losses included eggs that were depredated or abandoned. Of 102 nestlings followed from hatching, 50 (49.0%) survived to 24 days-of-age, 45 (44.1%) disappeared and 7 (6.9%) were found dead.

Nest success of Forster's terns (A × B, Table 1) was similar between Lavaca Bay and San Antonio Bay early nests ($Z = 2.165$, $0.05 < P < 0.10$), Lavaca Bay and San Antonio Bay late nests ($Z = 0.231$, $P > 0.05$) or San Antonio Bay early and San Antonio Bay late ($Z = 1.57$, $P > 0.05$) (Table 1). The probability of at least one egg hatching in successful nests (Table 1, C) and the probability that at least one young attaining 24 days-of-age (D) was not significantly different among colonies (egg Chi-square = 1.172, df = 2, P = 0.556; chick Chi-square = 0.071, df = 2, P = 0.965). The number of young that survived to 24 days (E) was 0.69, 0.30, and 0.51 for Lavaca Bay, San Antonio Bay early, and San Antonio Bay late, respectively.

Black Skimmer: From 16 to 60 pairs of black skimmers were counted on three islands in Lavaca Bay. Skimmers have an extended nesting season and egg laying occurred from late-April to early June (median = 25 May). Nestling skimmers fledged well into the last week of July. Clutch size at Lavaca Bay (3.3, 344/105; was similar to that recorded at Laguna Vista (3.4, 323/94; Custer and Mitchell 1987).

Of 253 Lavaca Bay skimmer eggs monitored to hatching, 151 (59.7%) hatched, 50 (19.8%) were intact but did not hatch, 34 (13.4%) were lost to flooding, and 13 (5.1%) disappeared. Other less frequent losses included eggs that were abandoned, depredated, or cracked. Of 151 skimmer young followed from hatching, 70 (46.4%) survived to 21 days, 57 (37.3%) disappeared and 24 (15.9%) were found dead.

Nest success among the three Lavaca Bay colonies (A × B, Table 2) was similar ($P > 0.05$). Nest success was significantly higher at Laguna Vista than Lavaca Bay 2 ($Z = 2.67$, $P < 0.05$), but not Chocolate Bayou ($Z = 2.26$, $P > 0.05$) or Lavaca Bay 1 ($Z = 2.50$, $0.05 < P < 0.1$). The probability that eggs in successful nests would hatch (C, Table 2) and that chicks in successful nests would survive to 21 days (D) was not significantly different among colonies (egg Chi-square = 2.625, df = 3, P = 0.435; chick Chi-square = 6.868, df = 3, P = 0.076). The number of young per nest that survived to 21 days (E) was 1.09 at Laguna Vista and ≤0.75 at the three Lavaca Bay colonies.

Histopathology

Histopathological examination of Lavaca Bay Forster's tern (35) and black skimmer (20) brains revealed that the brain of one tern nestling contained a minimal perivascular lymphoid cell infiltrate. No other changes were apparent. Brains from all remaining birds showed no abnormal histological development. Because the incidence of brain anomalies was so low, brain tissues were not submitted for mercury residue analyses.

Contaminant Residues

Forster's Tern: Mercury was detected in all Forster's tern eggs from Lavaca Bay and in all but one egg from San An-

Table 1. Nest success, egg success, and number of Forster's tern young raised to 24 days-of-age

Colony location	Number of nests	Nest success[a] Incubation period A	Prefledging period B	Nest success (A × B)	C[b]	D[c]	Egg success (A × B × C × D)	Mean clutch size E	Number young to 24 days (A × B × C × D × E)
Lavaca	47	0.77	0.53	0.40 A[d]	0.73 A[e]	0.76 A[e]	0.23	3.0	0.69
San Antonio (early)	50	0.29	0.71	0.20 A	0.63 A	0.80 A	0.10	3.0	0.30
San Antonio (late)	30	0.66	0.57	0.38 A	0.60 A	0.77 A	0.17	3.0	0.51

[a] The probability that at least one egg or young per nest survives for a given period (based on days of nest exposure, see Hensler and Nichols 1981)
[b] The probability of an egg hatching given that the nest is successful
[c] The probability of young living to 24 d given that the nest is successful
[d] Success and probability values that share a common letter were not significantly different (Bonferroni Multiple Comparison method overall $\alpha = 0.05$) from one another
[e] Frequencies among colonies were not significantly different (Chi-square, $P < 0.05$) from one another and share a common letter

Table 2. Nest success, egg success, and numbe of black skimmer young raised to 21 days-of-age

Colony location	Number of nests	Nest success[a] Incubation period A	Prefledging period B	Nest success (A × B)	C[b]	D[c]	Egg success (A × B × C × D)	Mean clutch size E	Number young to 21 days (A × B × C × D × E)
Chocolate Bayou	16	0.37	0.83	0.31 AB[c]	0.65 A[d]	0.80 A[e]	0.16	3.2	0.51
Lavaca Bay 1	49	0.85	0.51	0.43 AB	0.75 A	0.69 A	0.22	3.4	0.75
Lavaca Bay 2	40	0.73	0.55	0.40 A	0.71 A	0.73 A	0.21	3.1	0.65
Laguna Vista[f]	94	—	—	0.65 B	0.77 A	0.64 A	0.32	3.4	1.09

[a] The probability that at least one egg or young per nest survives for a given period (based on days of nest exposure, see Hensler and Nichols 1981)
[b] The probability of a egg hatching given that the nest is successful
[c] The probability of young living to 21 days given that the nest is successful
[d] Nest success values significantly different (Bonferroni multiple comparison method, overall $\alpha = 0.05$) from one another do not share a common letter
[e] Frequencies among colonies were not significantly different (Chi-square, $P < 0.05$) from one another
[f] Data from Custer and Mitchell (1987)

tonio Bay (Table 3). All concentrations were less than 1.0 μg/g and 6 eggs from Lavaca Bay and 23 eggs from San Antonio Bay contained ≤0.25 μg/g. Mean mercury concentrations were similar among hatching success groups, but the mean level in eggs from Lavaca Bay (0.40 μg/g) was significantly ($P < 0.01$, $F = 16.98$, df = 1,74, 2-way ANOVA) higher than that in eggs from San Antonio Bay (0.22 μg/g). Mercury levels were not correlated with selenium when Lavaca Bay and San Antonio Bay data were analyzed individually, but when the data were combined, there was a significant positive correlation ($r = 0.2711$, $P < 0.05$) of mercury with selenium residues.

Mean selenium concentrations were different among hatching success groups (2-way ANOVA, $P < 0.01$, $F = 12.11$, df = 5,74) and between bays ($P < 0.01$, $F = 16.30$, df = 1,74,) however, there was also a significant ($P < 0.01$, $F = 5.91$, df = 5,74) interaction between variables. The "no eggs hatched" group from Lavaca Bay contained higher selenium levels than the "some" and "all eggs hatched" groups (1-way ANOVA, $P < 0.01$, $F = 10.65$, df = 2,23). There was no difference in selenium levels among hatching success groups at San Antonio Bay (1-way ANOVA, $P > 0.05$, $F = 2.07$, df = 2,41). When the "no eggs hatched" group was deleted, no significant differences occurred between hatching success groups ($P = 0.11$, $F = 2.64$, df = 1,53) or between bays ($P = 0.07$, $F = 3.26$, df = 1,53) and there was no significant interaction ($P = 0.20$, $F = 1.65$).

DDE was recovered in all eggs and residues ranged from 0.1 to 9.0 μg/g (Table 3). PCBs were present in 67 of 71 eggs at up to 8.7 μg/g. Two eggs from Lavaca Bay contained toxaphene (0.4 and 0.5 μg/g) and nine eggs contained chlordane (mean = 0.16 μg/g, range = 0.1–0.5 μg/g). Toxaphene was not detected in eggs from San Antonio Bay, but chlordane was present in 2 samples at 0.2 and 0.9 μg/g. No other organochlorine compounds were detected at either colony.

There was no difference in geometric mean levels of either DDE or PCB among Forster's tern hatching success groups at either bay (Table 3), but there were differences between bays (2-way ANOVA). DDE concentrations in tern eggs from Lavaca Bay (1.6 μg/g) were significantly higher than those from San Antonio Bay, (0.8 μg/g, $P < 0.03$, $F = 4.95$, df = 1,65). Geometric mean PCB levels were also significantly ($P < 0.01$, $F = 9.02$, df = 1,65) higher in Lavaca Bay eggs (2.3 μg/g) than in San Antonio Bay eggs (1.2 μg/g).

Table 3. Mercury, selenium, DDE, and PCB concentrations, μg/g wet weight, in Forster's tern eggs from Lavaca Bay and San Antonio Bay, Texas 1984: a comparison by hatching success and by area

	Mean ± SD/(range)							Geometric mean/range		
			Selenium							
Comparison	No.[a]	mercury[b]	No.	Lavaca	No.	San Antonio		No.	DDE	PCB[c]
Nest success										
No eggs hatched	23	0.44 ± 0.18 A[d] (0.18–0.75)	6	1.00 ± 0.26 A[e] (0.72–1.30)	17	0.72 ± 0.13 A[e] (0.53–0.94)		19	0.9 A[d] (0.2–3.5)	1.5 A[d] (ND[f]–5.0)
Some eggs hatched	35	0.37 ± 0.11 A (0.25–0.62)	15	0.72 ± 0.08 B (0.55–0.84)	20	0.70 ± 0.10 A (0.60–0.87)		34	1.1 A (0.1–9.0)	1.9 A (ND–7.7)
All eggs hatched	22	0.40 ± 0.20 A (ND–0.91)	15	0.71 ± 0.12 B (0.57–1.02)	7	0.61 ± 0.16 A (0.42–0.85)		18	1.4 A (0.6–6.9)	1.9 A (0.6–8.7)
Colony										
Lavaca Bay	36	0.40 ± 0.16 A (0.05–0.91)			30	0.71 ± 0.10 A[g] (0.55–1.30)		33	1.6 A (0.7–9.0)	2.3 A (0.8–7.7)
San Antonio	44	0.22 ± 0.17 B (ND–0.84)			27	0.68 ± 0.12 A (0.42–0.87)		38	0.8 B (0.1–5.9)	1.2 B (ND–8.7)

[a] No. = number of samples analyzed
[b] Mercury was detected in all but one egg
[c] PCB was detected in all but one of the "no eggs hatched" group and in all but three of the "some eggs hatched" group
[d] Among success or between colony means sharing the same letter are not significantly different from one another (2-way ANOVA, colony × success category, Bonferroni multiple comparison method, α = 0.05)
[e] Among success means sharing the same letter are not significantly different from one another (1-way ANOVA, colony × success category, Bonferroni multiple comparison method, α = 0.05)
[f] ND = no residue detected
[g] Between colony means sharing the same letter are not significantly different from one another (2-way ANOVA, colony × success, P > 0.05; no eggs hatched group excluded)

Black Skimmer: Mercury and selenium concentrations did not differ among hatching success groups at Lavaca Bay (Table 4, mercury $F = 1.66$, $df = 2,30$, $P > 0.05$; selenium $F = 0.72$, $df = 2,38$, $P > 0.05$). Only nine eggs from Laguna Vista were analyzed for mercury and selenium, therefore no comparisons of metal concentrations and hatching success were attempted. Both mercury and selenium were higher in black skimmer eggs from Lavaca Bay than in eggs from Laguna Vista (1-way ANOVA). Mercury concentrations were not correlated with selenium in black skimmer eggs from Lavaca Bay, but there was a significant positive mercury-selenium correlation in eggs from Laguna Vista ($r = 0.7289$, $P < 0.05$). When Laguna Vista and Lavaca Bay data were combined, the mercury-selenium relationship was significant ($r = 0.5483$, $P < 0.01$).

DDE was detected in all but one skimmer egg from Lavaca Bay and levels ranged to 36 μg/g (Table 4). At Laguna Vista, DDE was detected in 45 of 53 eggs and concentrations ranged to 28 μg/g. The only other organochlorine contaminant detected was toxaphene which was present at 0.5, 0.6, and 2.4 μg/g in three eggs from Lavaca Bay.

DDE concentrations differed among success groups, but not between colonies (2-way ANOVA); the mean of the "no eggs hatched" group was significantly higher than "some" or "all eggs hatched" groups (Bonferroni multiple comparison method). PCBs were detected in 41 of 43 Lavaca Bay eggs (maximum = 2.9 μg/g) and in 34 of 53 Laguna Vista eggs (maximum = 9.1 μg/g). PCB concentrations did not vary among hatching success groups, but were significantly (2-way ANOVA, $P < 0.01$, $f = 8.50$, $df = 1,90$) higher in Lavaca Bay (1.3 μg/g) than Laguna Vista eggs (0.8 μg/g).

Caspian and Least Terns: Low levels of mercury, (≤0.50 μg/g) and selenium (≤0.42 μg/g) were detected in Caspian tern eggs. Because of their limited biomass, least tern eggs were analyzed for mercury and selenium only. Mercury was recovered in 9 of 10 least tern eggs at ≤0.82 μg/g and selenium was detected in all 10 eggs from 0.54 to 0.87 μg/g. There was no mercury-selenium correlation in Caspian ($r = -0.01$, $P > 0.05$) or least tern ($r = -0.47$, $P > 0.05$) eggs. DDE was detected in all Caspian tern eggs and concentrations varied from 0.7 to 4.7 μg/g (geometric mean = 2.2 μg/g, Table 5). PCBs were also present in all samples at 1.0 to 5.4 μg/g (geometric mean = 2.6 μg/g). Three Caspian tern eggs contained chlordane (0.1 – 0.2 μg/g) and one egg contained a trace (<0.1 μg/g) of dibromo diphenyl ether.

Eggshell Thickness

Mean shell thickness of Forster's tern eggs from Lavaca Bay was similar to the mean of San Antonio Bay eggs but each was different than the mean thickness of eggs collected in 1970 and before 1943 ($P < 0.05$, $F = 13.42$, $df = 3,197$). Black skimmer eggshell thickness averaged 0.24 mm in 1984 which was statistically similar to measurements of eggs collected in 1970 (0.24 mm), but both 1984 and 1970 thickness means were less than the pre-1943 mean of 0.25 mm ($P < 0.01$, $f = 7.75$, $df = 2,139$). Shell thickness of Caspian ($P > 0.05$, $F = 0.15$, $df = 2,53$) and least tern eggs ($P > 0.05$, $F = 0.18$, $df = 2,44$) did not vary between 1943, 1970, and 1984. Correlations between Forster's tern shell thickness and log DDE ($n = 73$, $r = -0.05$), log PCB ($n = 71$, $r = 0.02$),

Table 4. Mercury, selenium, DDE, and PCB concentrations, μg/g wet weight, in black skimmer eggs collected from Lavaca Bay and Laguna Vista, Texas, 1984: a comparison by hatching success and by colony

Comparison	No. eggs anal.	Mean + SD/range		No. eggs anal.	Geom mean/range	
		mercury	selenium		DDE	PCB
Nest success						
No eggs hatched	3	0.47 + 0.24 A[a]	0.78 + 0.08 A[a]	16	7.0 A[b]	1.1 A[b]
		0.19 – 0.65	0.71 – 0.87		2.3–32	ND[c]–9.1
Some eggs hatched	20	0.40 + 0.13 A	0.73 + 0.11 A	40	3.2 B	0.9 A
		0.24 – 0.74	0.54 – 0.94		ND–36	ND–6.1
All eggs hatched	20[d]	0.50 + 0.14 A	0.76 + 0.08 A	40	2.4 B	0.9 A
		0.23 – 0.78	0.62 – 0.89		ND–14	ND–2.8
Colony						
Lavaca Bay	43	0.46 + 0.16 A[e]	0.75 + 0.09 A[e]	43	3.4 A	1.3 A
		0.19 – 0.78	0.54 – 0.94		ND–36.0	ND–2.9
Laguna Vista	9	0.19 + 0.10 B	0.33 + 0.05 B	53[f]	3.2 A	0.8 B
		0.05 – 0.31	0.25 – 0.39		ND–28.0	ND–9.1

[a] Among success means sharing the same letter are not significantly different from one another (1-way ANOVA, $\alpha = 0.05$); Laguna Vista data not included
[b] Among success or between colony means sharing the same letter are not significantly different from one another (2-way ANOVA, colony × success category, Bonferroni multiple comparison method, $\alpha = 0.05$)
[c] ND = no residue detected
[d] Only nineteen eggs in the "all eggs hatched" group were analyzed for selenium due to insufficient sample material for both mercury and selenium analyses.
[e] Between colony means sharing the same letter are not significantly different from one another (1-way ANOVA, $\alpha = 0.05$)
[f] Data from Custer and Mitchell (1987)

Table 5. Organochlorine, mercury, and selenium concentrations in Caspian tern and least tern eggs collected from Lavaca Bay, Texas 1984

Contaminant	Mean residue ± SD, μg/g wet weight (n)[a]	
	Caspian tern	Least tern
DDE	2.2 (9)	NA
	(0.7–4.7)	
PCB	2.6 (9)	NA
	(1.0–5.4)	
Mercury	0.20 ± 0.157 (8)	0.34 ± 0.281 (9)
	(ND–0.50)	(ND–0.82)
Selenium	0.31 ± 0.072 (9)	0.73 ± 0.134 (10)
	(0.22–0.42)	(0.54–0.87)

[a] Sample size = Caspian tern 9, least tern 10. (n) = number of samples with detectable residues. NA = not analyzed. ND = no residue detected. Geometric means are given for DDE and PCB concentrations and arithmetic means are listed for mercury and selenium. Mean moisture content of Caspian and least tern eggs was 75 and 72%

mercury ($n = 79$, $r = 0.07$), and selenium ($n = 79$, $r = -0.19$) were not significant. Correlations between black skimmer shell thickness and log DDE ($n = 41$, $r = 0.05$), log PCB ($n = 41$, $r = 0.11$), mercury ($n = 41$, $r = 0.17$), and selenium ($n = 40$, $r = 0.05$) also were not significant.

Discussion

Population Status and Reproductive Success

Forster's Tern: Oberholser (1974) reported that the Forster's tern population in Texas has declined slowly since World War II. Recent census data indicated that there have been no discernable trends in tern populations since 1970 (Texas Colonial Waterbird Society 1982 and unpub. data). Between 1973 and 1984, populations ranged from 1,210 pairs in 1974 to 4,035 pairs in 1984. During most years, more than 80% of the Forster's tern population in Texas nested on islands along the northeastern one-third of the coastline.

We were unable to locate specific Forster's tern clutch size data to compare with our sample. Bent (1921) reported that Forster's tern clutch size varied from 2 to 6 eggs with sets of 3 being the most common. Nine clutches from Texas collected before 1947 for museums averaged 2.9 eggs per nest, but museum sets seldom represent random collections.

Overall recruitment was low at both colonies; 0.69 young per nest at Lavaca Bay and from 0.30 to 0.51 at San Antonio Bay. Human disturbance may have been an important factor in nest and egg losses as the island colonies were popular areas for wade fishermen. Flooding accounted for the loss of almost 20% of the nests at San Antonio Bay. Fire ants (*Solenopsis* spp.) occurred on most islands, and they were observed swarming on recently pipped tern eggs and, in one instance, on a living young. At least one tern nest at Lavaca Bay and two at San Antonio Bay were lost to fire ants.

Black Skimmer: Population estimates of black skimmers that nested on the Texas coast between 1973 and 1984 varied from 6,340 to 11,540 pairs (Texas Colonial Waterbird Society 1982, Texas Colonial Waterbird Society, unpub data). There may have been a decline in the population between 1973 (10,380 pairs) and 1978 (6,340 pairs), but the long-term trend suggests that the skimmer population in Texas is stable. The estimate of breeding pairs in 1973 was similar to that (10,587) in 1984. Numbers of skimmers nesting in Lavaca Bay also were highly variable during the same period with a low of

125 pairs recorded in 1977 and a high of >600 pairs recorded in 1973, 1975, and 1980.

Mean skimmer clutch size in our study, 3.4, was consistent with that reported earlier for the Texas coast (3.3, White *et al.* 1984; 3.1–3.4, DePue 1974; 2.7–3.5; King and Krynitsky 1986; and 3.4, Custer and Mitchell 1987). Our estimate of young produced per nest (0.51–0.75) at Lavaca Bay was lower than that for skimmers nesting in Galveston Bay (0.9–1.5, King and Krynitsky 1986), Port Mansfield (1.0–1.5, White *et al.* 1984), and Laguna Vista (1.1, Custer and Mitchell 1987). Our estimate of young produced at Lavaca Bay was within the range found in Baffin Bay (0.40–1.04, DePue 1974), Laguna Vista (0.6–2.0, White *et al.* 1984), and Corpus Christi (0.0–1.3, White *et al.* 1984).

Contaminant Residues

Mercury concentrations ≤1 μg/g in tern and black skimmer eggs were considerably lower than levels found in fish-eating waterbirds from mercury contaminated areas in United States and Canada (Fimreite *et al.* 1971; Vermeer 1971; Faber and Hickey 1973; Vermeer 1973). Mercury residues lower than 0.25 μg/g in the eggs of some species may represent background levels (Faber and Hickey 1973). Six of 36 Forster's tern eggs (17%) from Lavaca Bay, 64% (23/36) of the tern eggs from San Antonio Bay, 14% (6/24) of the skimmer eggs from Lavaca Bay and 56% (5/9) of the eggs from Laguna Vista contained <0.25 μg/g mercury.

The highest concentration of mercury in Forster's tern and black skimmer eggs (0.91 and 0.78 μg/g, respectively), was within the range of residues associated with reproductive failure in mallards (*Anas platyrhynchos*), and pheasants, (*Phasianus colchicus*) but was below the level associated with impaired reproduction in the more closely related common tern (*S. hirundo*) and herring gull (*Larus argentatus*). Mercury residues as low as 0.5 to 1.5 μg/g (Fimreite 1971) and 0.9 to 3.1 μg/g (Spann *et al.* 1972) in the eggs of ring-necked pheasants were associated with reproductive failure. Mean levels of mercury in eggs that ranged from 0.79 to 0.86 μg/g had no reproductive effects on first- and third-generation mallards but these residues were associated with lowered reproductive success of second generation hens. In contrast, reproduction of common terns was unaffected when mercury residues in eggs were 1.0 μg/g or less but egg concentrations of 3.6 μg/g were associated with lowered reproductive success (Fimreite 1974, Connors *et al.* 1975). Also, mercury residues from 2 to 16 μg/g in eggs of herring gulls did not affect hatching or fledging success (Vermeer *et al.* 1973).

Selenium concentrations were generally low and may represent background levels. Selenium in eggs of aquatic birds that feed primarily in estuarine habitats varied from 0.21 to 1.06 μg/g wet weight (Blus *et al.* 1977, White *et al.* 1980, King *et al.* 1983, King *et al.* 1985). In our study, selenium concentrations in all black skimmer, Caspian, and least tern eggs and in all but three Forster's tern eggs was ≤1.0 μg/g.

Levels of selenium associated with embryotoxicity of waterbirds in California were several times higher than those detected in our tern and skimmer eggs (Ohlendorf *et al.* 1986). American coot (*Fulica americana*) embryos had an estimated 20% probability of embryo death or deformity when selenium concentrations in eggs were about 3.2 μg/g (converted to wet-weight). For black-necked stilts (*Himantopus mexicanus*), the 20% mortality/deformity level was about 1.5 μg/g (converted to wet-weight).

The addition of the Lavaca Bay DDE residue data to the Laguna Vista data set (Custer and Mitchell 1987) strengthened earlier findings. DDE was significantly higher in black skimmer clutches where no eggs hatched than in clutches in which some or all remaining eggs hatched; PCB levels did not differ among hatching success groups.

The geometric mean DDE concentration in Forster's tern eggs from Lavaca Bay (1.6 μg/g) was similar to that (1.9 μg/g) reported in tern eggs from San Francisco Bay. In contrast, PCB concentrations were almost 2.5 times higher (2.3 vs. 5.6 μg/g) in Forster's tern eggs from San Francisco Bay (Ohlendorf *et al.* 1988). Forster's terns nesting in a PCB contaminated area of Lake Michigan experienced reproductive failure associated with egg PCB concentrations that ranged from 6.2 to 25.9 μg/g (median 22.2 μg/g) (Kubiak *et al.* 1989). Reproductive problems were possibly caused by aryl hydrocarbon hydroxylase inducing components of PCBs. In our study, only two tern eggs from Lavaca Bay and one egg from San Antonio Bay contained PCBs within the range that affected reproduction in the Green Bay population. Overall, PCB residues in eggs of both Forster's terns and black skimmers were generally below levels associated with reproductive problems in most species of birds (Stickel 1973; Custer and Heinz 1980; Blus 1982).

DDE concentrations in Forster's tern and black skimmer eggs have remained at almost the same level or have declined since 1970. DDE in tern eggs collected from Lavaca Bay in 1984 averaged 1.6 μg/g, about the same level (1.7 μg/g) as in eggs collected from the upper and central Texas coast in 1970 (King *et al.* 1978). DDE in skimmer eggs collected in 1970 from the upper and central coast averaged 9.7 μg/g (King *et al.* 1978) and mean residues declined nearly 3-fold by 1984. Current levels of DDT contamination do not seem to be a major influence on skimmer numbers as the decline before 1980 did not occur along the lower Texas coast, the area considered to be most heavily contaminated with DDT (White *et al.* 1984; Custer and Mitchell 1987). The downward trend of PCB residues since 1970 was more sharply defined than DDE. In Forster's tern eggs, PCBs declined from 12.5 μg/g to 1.2–2.3 μg/g from 1970 to 1984. PCBs in skimmer eggs declined almost as dramatically from 5.4 μg/g to 0.8–1.3 μg/g during the same period.

Eggshell Thickness

Shell thinning in many species of birds has been associated primarily with residues of DDE (Stickel 1973; Blus *et al.* 1974; Blus 1982); however, DDE was not correlated with shell thickness of Forster's tern or black skimmer eggs from Lavaca Bay. Although shell thinning of both Forster's tern and black skimmer eggs was greater in 1984 than in 1970 and 1943, we found no evidence that shell thinning of either tern (7%) or skimmer (5%) eggs adversely affected reproduction in 1984. While 5 to 7% shell thinning is statistically significant, it is probably not biologically significant. Numerous field studies have shown that average eggshell thinning of less than 10% is seldom associated with egg breakage and population decline (Anderson *et al.* 1969; Blus 1970, 1982; King *et al.* 1980). Our findings that DDE was not correlated with black skimmer shell thickness is consistent with results of other studies where no relationship was established between DDE and black skimmer eggshell thickness (White *et al.* 1984; King and Krynitsky 1986; Custer and Mitchell 1987).

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References

Anderson DW, Hickey JJ, Risebrough RW, Hughes DF, Christensen RE (1969) Significance of chlorinated hydrocarbon residues to breeding pelicans and cormornats. Can Field-Nat 83:91–112

Bent AC (1921) Life Histories of North American Gulls and Terns. US Nat Museum Bull 113. Washington DC, 345 pp

Blus LJ (1970) Measurements of brown pelican eggshells from Florida and South Carolina. BioScience 20:867–869

——— (1982) Further interpretation of the relation of organochlorine residues in brown pelican eggs to reproductive success. Environ Pollut 28:15–23

Blus LJ, Neely BS, Lamont TG, Mulhern B (1977) Residues of organochlorines and heavy metals in tissues and eggs of brown pelicans, 1969–73. Pestic Monit J 11:40–53

Blus LJ, Neely Jr BS, Belisle AA, Prouty RM (1974) Organochlorine residues in brown pelican eggs: relation to reproductive success. Environ Pollut 7:81–91

Connors PG, Anderlini VC, Risebrough RW, Gilbertson M, Hays H (1975) Investigations of heavy metals in common tern populations. Can Field-Nat 89:157–162

Custer TW, Heinz GH (1980) Reproductive success and nest attentiveness of mallard ducks fed Aroclor 1254®. Environ Pollut 21:313–318

Custer TW, Hensler GL, Kaiser TE (1983) Clutch size, reproductive success, and organochlorine contaminants in Atlantic Coast black-crowned night-herons. Auk 100:699–710

Custer TW, Mitchell CA (1987) Organochlorine contaminants and reproductive success of black skimmers in south Texas, 1984. J Field Ornithol 58:480–489

DePue J (1974) Nesting and reproduction in the black skimmer (*Rynchops niger*) on four spoil islands in the Laguna Madre, Texas. MS Thesis, Texas A&I Univ, Kingsville

Faber RA, Hickey JJ (1973) Eggshell thinning, chlorinated hydrocarbons, and mercury in inland aquatic bird eggs, 1969 and 1970. Pestic Monit J 7:27–36

Fimreite N (1971) Effects of dietary methylmercury on ring-necked pheasants. Occas Pap Can Wildl Serv 9:1–37

——— (1974) Mercury contamination of aquatic birds in northwestern Ontario. J Wildl Manage 38:120–131

Fimreite N, Holsworth WM, Keith JA, Pearch PA, Gruchy IM (1971) Mercury in fish and fish-eating birds near sites of industrial contamination in Canada. Can Field-Nat 84:211–220

Finley MT, Stendell RC (1978) Survival and reproductive success of black ducks fed mercury. Environ Pollut 16:51–64

Heinz G (1975) Effects of methylmercury on approach and avoidance behavior of mallard ducklings. Bull Environ Contam Toxicol 13:554–564

——— (1980) Eggshell thickness in birds fed methylmercury. Bull Environ Contam Toxicol 25:498–502

Heinz G, Locke LN (1976) Brain lesions in mallard ducklings from parents fed methylmercury. Avian Dis 20:9–17

Hensler G, Nichols JD (1981) The Mayfield method for estimating nesting success: A model, estimators and simulation results. Wilson Bull 93:42–53

King KA, Blankinship DR, Payne E, Krynitsky AJ, Hensler GL (1985) Brown pelican populations and pollutants in Texas 1975–1981. Wilson Bull 97:201–214

King KA, Flickinger EL, Hildebrand HH (1978) Shell thinning and pesticide residues in Texas aquatic bird eggs. Pestic Monit J 12:16–21

King KA, Krynitsky AJ (1986) Population trends, reproductive success, and organochlorine chemical contaminants in waterbirds nesting in Galveston Bay, Texas. Arch Environ Contam Toxicol 15:367–376

King KA, LaFever CA, Mulhern BM (1983) Organochlorine and metal residues in royal terns nesting on the central Texas coast. J Field Ornithol 54:295–303

King KA, Meeker DL, Swineford DM (1980) White-faced Ibis populations and pollutants in Texas, 1969–1976. Southwest Nat 25:225–240

Krynitsky A, (1987) Preparation of biological tissue for determination of arsenic and selenium by graphite furnace atomic absorption spectrometry. Anal Chem 59:1884–1886

Kubiak TJ, Harris HJ, Smith LM, Schwartz TR, Stalling DL, Trick JA, Sileo L, Docherty DE, Erdman TC (1989) Microcontaminants and reproductive impairment of the Forster's tern on Green Bay, Lake Michigan-1983. Arch Environ Contam Toxicol 18:706–727

May TW, McKinney GL (1981) Cadmium, lead, mercury, arsenic, and selenium concentrations in freshwater fish 1976–77-National Pesticide Monitoring Program. Pestic Monit J 15:14–38

Mayfield HF (1961) Nesting success calculated from exposure. Wilson Bull 73:255–261

——— (1975) Suggestions for calculating nest success. Wilson Bull 87:456–466

Moore JW, Sutherland DJ (1980) Mercury concentrations in fish inhabiting two polluted lakes in Northern Canada. Water Res 14:903–907

Neter J, Wasserman W (1974) Applied linear models. Richard D Irwin Inc, Homewood IL

Oberholser HC (1974) The birdlife of Texas. Vol. 1. Univ Texas Press, Austin TX

Ohlendorf HM, Custer TW, Lowe RW, Rigney M, Cromartie E (1988) Organochlorines and mercury in eggs of coastal terns and herons in California, USA. Colonial Waterbirds 11:85–94

Ohlendorf HM, Hothem RL, Bunck CM, Aldrich TW, Moore JF (1986) Relationships between selenium concentrations and avian reproduction. In: Trans 51st N Amer Wildl & Nat Res Conf 51:330–342

Sims RR Jr, Presley BJ (1976) Heavy metal concentrations in organisms from an actively dredged Texas bay. Bull Environ Contam Toxicol 16:520–527

Spann JW, Heath RG, Kreitzer JF, Locke LN (1972) Ethyl mercury *p*-toluenesulfonanilide: Lethal and reproductive effects on pheasants. Science 175:328–331

Speyer MR (1980) Mercury and selenium concentrations in fish, sediments, and water of two northwestern Quebec lakes. Bull Environ Contam Toxicol 24:427–432

Stickel LF (1973) Pesticide residues in birds and mammals. In: Edwards CA (ed) Environmental pollution by pesticides. Plenum Press, New York, pp 254–312

Stickel LF, Wiemeyer SN, Blus LJ (1973) Pesticide residues in eggs of wild birds: adjustments for loss of moisture and lipid. Bull Environ Contam Toxicol 9:193–196

Texas Colonial Waterbird Society (1982) An atlas and census of Texas waterbird colonies. Caesar Kleberg Wildlife Research Institute, Kingsville, TX

Texas Department of Health, Division of Shellfish Sanitation and Control (1982) Mercury concentrations in marine organisms of Lavaca Bay. Unpub rept 112 pp

Vermeer K (1971) A survey of mercury residues in aquatic bird eggs in the Canadian prairie provinces. Trans N Am Wildl Nat Resour Conf 36:138–152

——— (1973) Comparison of food habits and mercury residues of Caspian and common terns. Canadian-Field Nat. 87:305

Vermeer K, Armstrong FAJ, Hatch DRM (1973) Mercury in aquatic birds at Clay Lake, Western Ontario. J Wildl Manage 37:58–61

White DH, King KA, Prouty RM (1980) Significance of organochlorine and heavy metal residues in wintering shorebirds at Corpus Christi, Texas, 1976–77. Pestic Monit J 14:58–63

White DH, Mitchell CA, Swineford DM (1984) Reproductive success of black skimmers in Texas relative to environmental pollutants. J Field Ornithol 55:18–30

Windom HL (1972) Arsenic, cadmium, copper, lead, mercury, and zinc in marine biota-North Atlantic Ocean. In: Baseline studies of pollutants in the marine environment, (I.D.O.E.) Nat Sci Found. Upton, Long Island, NY, pp 121–148

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