DDE, SELENIUM, MERCURY, AND WHITE-FACED IBIS REPRODUCTION AT CARSON LAKE, NEVADA

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Abstract: We studied organochlorine, mercury (Hg), and selenium (Se) contamination in white-faced ibis (*Plegadis chihi*) nesting at Carson Lake, Nevada, in 1985 and 1986. Dichloro diphenyl dichloroethylene (DDE) was related to fewer young produced/nesting attempt ($P = 0.0001$), fewer young produced/successful nest ($P = 0.0075$), and eggshell thinning ($P = 0.0001$). As DDE in eggs increased to >4 ppm (wet wt), and especially >8 ppm, productivity decreased significantly ($P \leq 0.05$) and the incidence of cracked eggs increased. Assuming that 4 ppm DDE is the critical residue level, 40% of the nesting population in 1985 and 1986 was adversely impacted by DDE, with a net loss of 20% of the population's expected production (to about 10 days old). Most eggs containing exceptionally high DDE levels (8–29 ppm) also had substantial amounts of dichloro diphenyl trichloroethane (DDT), which implies recently-used DDT as the source. No evidence of breeding ground DDE-DDT contamination was found. The white-faced ibis winter in Mexico, and mostly in the interior agricultural region. Concentrations of DDE-DDT in ibis eggs, unlike most other wading bird species from the Great Basin, did not decline during the last decade. Other organochlorine contaminants were generally low and detected in ≤33% of the eggs. Selenium and Hg were accumulated by ibis on the Nevada breeding grounds, but concentrations in eggs did not reach levels sufficient to impact the production of 7–10 day old young. Potential Se and especially Hg accumulation during the remainder of the summer was high, but actual effects on growing young and adults remain unknown.

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The U.S. Fish and Wildlife Service (USFWS) (1987) listed the white-faced ibis as a migratory nongame bird of management concern, to stimulate research and management efforts. The species restricted and vulnerable nesting habitat were of primary concern in addition to pesticides and other contaminants. Pesticide studies were conducted at several locations (Capen 1978, King et al. 1980) including earlier work at Carson Lake, a state Wildlife Management Area (WMA) (Henny et al. 1985). The white-faced ibis was the only wading bird in the Great Basin that failed to show a downward trend in DDE residues from 1979 to 1983 (Henny et al. 1985). Furthermore, DDE residues were about the same in ibis from Utah several years earlier (Capen 1978). The earlier work (Henny et al. 1985) was based on 15 or 16 nests (1 egg taken from each) each year from early May nesters, and most nests were not revisited at the proper time to determine the number of young produced. Therefore, the relation between residues in the sample egg collected (i.e., the "sample egg technique" [Blus 1984]) and productivity was not fully understood.

We knew from the initial Great Basin wading bird study (Henny et al. 1985) that white-faced ibis at Carson Lake were having contaminant-related problems; DDE was causing severe shell thinning that resulted in cracked and/or dented eggs in the nests and DDE residues in eggs were not declining over time. Questions remained concerning the residue burden in eggs required to reduce reproductive success (i.e., the critical DDE residue level), the magnitude of the reproductive problem, and the adequacy of sampling based on eggs from 1 nesting segment (in early May), when the Carson Lake population included ≥3 segments (each highly synchronized) nesting on slightly different schedules. We expanded the ibis study at Carson Lake in 1985 and 1986 to include several nesting segments each year. Also, weekly checks of the nests were made including a final check when young were 7–10 days old.

At about the time this study began, embryo deformities were reported in waterbirds at Kesterson National Wildlife Refuge (NWR) in California (Ohlendorf et al. 1986). The problems were related to elevated concentrations of Se in waste irrigation drainwater. Carson Lake is located in Churchill County, in the lower Carson River basin, about 90 km east of Reno, Nevada. Prior to the Newlands Irrigation Project (authorized in 1903) (Townley 1977), northwest Nevada contained extensive highly productive wetlands that received undiverted flows of water from the Truckee and Carson rivers. Following

the agricultural development of the Carson River and the Newlands Project, most water flows were changed from freshwater to the return flows from irrigated fields. Now the principal source of irrigation water to the area is released from Lahontan Reservoir fed by the Carson and the Truckee rivers via the Truckee Canal. Agricultural return flows eventually empty into the lower-elevation areas (e.g., Carson Lake and Stillwater WMA). Outflows from the WMA, if any, discharge to the Carson Sink. The water in these closed basins is lost by evapotranspiration. Because of the Newlands Project, Se became an additional concern at Carson Lake. Elevated concentrations of Hg also were reported in fish from the Carson River system; the Hg was introduced into the river during the Comstock gold and silver mining era (1865–95) (Cooper 1983). During the 30-year peak of the Comstock, an estimated 6.75×10^6 kg of Hg was lost in the milling process (Bailey and Phoenix 1944). Nearly all of the processing was carried out along the Carson River (because of water power availability), and Carson Lake is located near the terminus of the old bed of the Carson River.

The objectives of our study were to determine if significant differences in egg residue concentrations occurred among the highly synchronized nesting segments within the large ibis colony, evaluate organochlorine trends in eggs over time, determine if DDE or other organochlorines adversely impacted reproduction, further evaluate eggshell thinning, and provide an initial evaluation of the relation between Hg and Se concentrations in eggs and reproduction.

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METHODS

We collected a sample egg (Blus 1984) at random from 140 white-faced ibis nests at Carson Lake. The nests, which were all over water and located in bulrush (*Scirpus* spp.), were marked and checked at weekly intervals. The Carson Lake colony consisted of several nesting segments, each in a physically distinct nesting area, but sometimes immediately adjacent to another, and with different mean nesting times. Twenty nests were marked at 7 nesting segments (3 in 1985 and 4 in 1986) to determine if contaminants varied within the colony. Embryo development of the sample egg was recorded when eggs were processed for chemical analyses. The first and second segments in 1985 were the same, although the second egg collection was made 2 weeks later. With the above exception, eggs were freshly laid at the time nests were initially located and marked. The second segment in 1985 was not located and marked at the proper time, thus, production data was not used, but 118 of the remaining 120 nests (2 not relocated) were revisited weekly, including a final visit when young were 7–10 days old. After young reach 7–10 days, they move from their nests when approached and counts become inaccurate (Capen 1978). The loss of young during the next several weeks before flight could not be assessed in the large colony.

Success of each nest was evaluated in relation to residues encountered in the sample egg from that nest. The initial analysis of 1980–83 data for shell thickness, clutch size, and incidence of cracked eggs contained DDE subdivisions at $\leq$1.0, 1.01–4, 4.01–8, 8.01–16, and >16 ppm (Henny et al. 1985). We adhered to those predetermined subdivisions in this analysis of the 1985 and 1986 data, although we recognized that the subdivisions were artificial. Most of the earlier data (61 of 90 nests) were collected at Carson Lake and were compared to the recent information.

The collection of a random egg from each nest for chemical analyses potentially biases the observed productivity values. Other nests were marked without collecting an egg to evaluate the effect of collecting 1 egg on nest success and brood size.

Shell thickness (including membranes) was measured at 3 sites on the egg equator with a micrometer graduated in units of 0.01 mm; the mean of the 3 measurements was used to represent the thickness of the shell. Measurements of historic white-faced ibis eggs were obtained from Capen (1977).

On 27 June 1985, we collected (with steel shot) 18 adult white-faced ibis between the agricultural fields and the colony nesting site at Carson Lake. The stomach contents of the 18 ibis (9 M and 9 F) were placed in 3 containers (each representing 6 birds) and analyzed for organochlorine pesticides, Hg, and Se.

Egg contents were placed in chemicallycleaned glass bottles and frozen. Analyses of 140 eggs for organochlorine pesticides, their metabolites, and polychlorinated biphenyls (PCB's) were conducted at the Environmental Chemistry Section of Patuxent Wildlife Research Center (PWRC), Laurel, Maryland. A 10-gram portion of the homogenized egg was mixed with anhydrous sodium sulfate and extracted with hexane for 7 hours in a soxhlet apparatus. After removing the lipids for Florisil column chromatography, the extracts were separated into 3 fractions by SilicAR or silica gel column chromatography following procedures of Cromartie et al. (1975) and Kaiser et al. (1980). Stomach contents were handled in the same manner. Pesticides and PCB's in the fractions were quantified with a gas-liquid chromatograph equipped with an electron capture detector and a 1.5% OV-17/1.95% QF-1 column. Typically, recoveries of pesticides and PCB's from spiked chicken eggs ranged from 92 to 110%. Residue data were not corrected for rates of recovery. The lower limit of residue quantification was 0.1 ppm for pesticides and 0.5 ppm for PCB's. Residues in about 10% of the samples were confirmed with a gas chromatograph–mass spectrometer (Kaiser et al. 1980). We converted contents of eggs to an approximately fresh wet weight using egg volume (Stickel et al. 1973); all organochlorines in eggs were expressed on a fresh wet weight basis.

The analyses of 120 of 140 eggs (excluding the second 20 eggs in 1985 because they were part of the first nesting segment) for Hg and Se were conducted at the Environmental Chemistry Section of PWRC. The lower limit of quantification was 0.10 ppm (dry wt) for Hg and 0.25 ppm for Se. The ibis stomach contents were analyzed for Hg and Se at the PWRC Analytical Control Facility. Samples were homogenized and subsamples taken for analysis. Mercury samples were digested as described by Monk (1961) and analyzed on a Perkin Elmer 460 Atomic Absorption spectrometer (Hatch and Ott 1968). Selenium analyses were performed on nitric acid digests using a Perkin Elmer Zeeman 3030 graphite furnace atomic absorption spectrometer (Ohlendorf et al. 1986), with a lower limit of quantification of 0.15 ppm (dry wt) for Hg and Se. Livers of 18 adult ibis were analyzed for Hg (detection limit 0.15 ppm dry wt), Se (0.15 ppm), arsenic (0.15 ppm), boron (2.3 ppm), lead (0.15 ppm), and cadmium (0.03 ppm) at the Environmental Trace Substances Research Center, Columbia, Missouri, by inductively coupled plasma (ICP Scan) emission spectroscopy using a Jarrell-Ash 1100 Mark III with a DEC 11/23+ computer (Thermo Jarrell Ash, Inc., Franklin, Mass.), after perchloric-nitric acid digestion. Concentrations were reported on a wet weight basis, but we converted them to dry weight for this study.

The lower quantification limit was halved for samples in which a contaminant was not detected. This value was used to calculate geometric means when $\geq$50% of the samples contained detectable residues. If a 1-factor analysis of variance (ANOVA) was significant ($P \leq 0.05$), Tukey's pairwise comparison was used to separate means. A 2-sample t-test was used when comparing 2 means, or a Chi-square test for comparing frequency of occurrence. The frequency of occurrence was presented for most organochlorines detected in <50% of the eggs.

To answer the question of how to pool across the different nesting segments, we used the General Linear Models Procedure (SAS 1985) and fit the full analysis of covariance (ANCOVA) model for each of the dependent variables separately (no. young/nest, no. young/successful nest, clutch size, and egg shell thickness). This requires fitting a different multiple regression equation (independent variables: ln DDE, ln Hg, and ln Se) for each combination of year and sequence. We performed an F-test to determine whether to stop with the "full model" or go to a reduced model. This test compared slopes (a test of parallelism) for the residues in each of the 6 nesting segments. The P-values from this test for each dependent variable were not statistically significant. Therefore, we accepted the null hypothesis of common slopes for each contaminant, but separate intercepts for each nesting segment. With the sample size of 120, the power of the test presumably was sufficiently high to detect differences among slopes.

We also conducted correlation analyses among the 3 important contaminants measured in the egg samples (DDE, Se, Hg). There were no strong correlations, thus, the data would not have collinearity problems. For the ANOVAs and ANCOVAs, all residues were log transformed to stabilize variances and achieve a linear relationship. All statements of statistical significance, unless otherwise stated, were with $P \leq 0.05$.

During investigations at Carson Lake between 1982–87, we banded 1,073 nestlings and

Table 1. Timing of clutch completion and the clutch size of white-faced ibis nesting segments sampled at Carson Lake, Nevada, 1985–86.

Yr	Nesting segment	Clutch completion		Clutch size	
		$\bar{x}$ date	Range	$\bar{x}$	SD
1985	First and second[a]	23 Apr	19–25 Apr	3.13	0.61
1985	Third	21 May	20–23 May	2.90	0.45
1986	First	19 Apr	15–21 Apr	3.40	0.50
1986	Second	1 May	30 Apr–5 May	3.55	0.51
1986	Third	15 May	30 Apr–21 May	3.25	0.55
1986	Fourth	21 May	16–26 May	3.15	0.67

[a] Clutch size data combined because first and second segments were part of the same nesting segment with identical clutch completion dates.

evaluated winter band recoveries. Counts of nesting white-faced ibis were made from the ground between 1972–85. We usually reached the colony by airboat; we estimated the nesting population by determining the general area occupied (by flushing the ibis) and relative nest density. Although estimates may not be precise, we believe the trends are realistic because of consistency in observers. GBH conducted the counts from 1976 to 1985, and CJH participated from 1980 to 1985. Since 1986 a helicopter survey involved an air count adjusted by a visibility rate obtained from air : ground comparisons at Malheur NWR in eastern Oregon. The fall surface area of water (late Aug or Sep) was routinely recorded by Stillwater WMA personnel (S. P. Thompson, refuge files, Stillwater WMA, Nevada, unpubl. reps.).

RESULTS

Egg Contaminants among Nesting Segments and Years

Nesting within each segment was synchronized and ≥1 week out of synchrony with the next segment (Table 1). These segments may represent age classes or population components wintering in different localities.

Organochlorine Concentrations.—Concentrations of DDE and the occurrence of DDT and other organochlorine pesticides from 1980–83 (Henny et al. 1985) and for 1985 and 1986 are presented in a sequence from early to late nesters (Table 2). No significant difference in DDE concentrations was detected among 1985 and 1986 nesting segments, but a higher incidence of eggs with >4 ppm DDE occurred in the earliest nesting segment each year. This condition seemed associated with the higher incidence of DDT. In general, eggs with elevated DDE also contained DDT (e.g., the 19 eggs in 1986 with ≥8 ppm DDE all contained DDT). Ratios of DDE:DDT varied from 6:1 to 86:1 in the series with the highest DDT concentrations being 2.5 and 2.0 ppm.

Concentrations of DDE in white-faced ibis at Carson Lake showed no significant change from 1980 to 1986, although they were significantly lower in 1982 than in several 1985 and 1986 nesting segments (Table 2). With the exception of 1982, DDE was consistently found above 4 ppm in about 30–50-% of the eggs. We detected DDT in 33% of 201 eggs collected between 1980 and 1986. Dieldrin was also found in 33% of the eggs while hexachlorobenzene was found in 26%. Endrin occurred in 16% and heptachlor epoxide in 11% of the eggs. Chlordanes, whose origin was probably not heptachlor (i.e., those with no heptachlor epoxide detected), were found in 5% of the eggs. Toxaphene occurred in 10% of the eggs and PCB's in 2 eggs (1%). Organochlorine pesticides (Table 2) had as high or higher occurrence rates in 1986 (80 eggs) than during all years combined (1980–86, 201 eggs).

Mercury and Selenium Concentrations.—Eggs were collected at 3 time intervals in 1985 but the second series (Table 1) was not analyzed for Hg and Se because it was actually part of the first nesting segment. Mercury and Se concentrations were significantly higher in eggs of the late nesting segment than those laid by the early nesting segment in 1985 (Table 3). Mercury concentrations showed the same significant pattern in 1986. In addition, Hg concentrations increased significantly in the early nesting segment from 1985 to 1986. The last nesting segment in 1986 also contained higher Hg concentrations than in 1985, but the difference was not significant. Selenium concentrations in 1986 did not reach levels recorded in 1985 and, contrary to the early–late significant increase in 1985, no change was apparent between eggs of early and late nesters in 1986.

Table 2. Eggshell thickness and organochlorine pollutants (ppm, wet wt) in eggs (geometric [Geo] $\bar{x}$ or frequency of occurrence) of white-faced ibis from Carson Lake, Nevada, 1980–86.

					Occurrence							
Yr	*N*	Shell thickness (mm)	Geo $\bar{x}$ DDE[a] ppm	High DDE ppm	DDE >4 ppm	DDT	Dieldrin	HE	Chlordanes[b]	Toxaphene	HCB	Endrin
1980	15	0.295 BC[c]	1.62 AB[c]	15	4	8	6	3	1	2	1	3
1981	15	0.288 ABC	2.23 AB	19	5	9	5	4	0	1	5	2
1982	16	0.310 C	0.54 A	3	0	2	2	0	0	1	na	1
1983	15	0.285 ABC	1.71 AB	20	5 (23%)[d]	3 (36%)	2 (25%)	2 (15%)	1 (3%)	2 (10%)	1 (16%)	1 (11%)
1985	20	0.261 A	3.39 B	18	13	7	13	0	0	1	na	3
1985	20	0.273 AB	3.47 B	21	12	0	12	0	0	0	na	3
1985	20	0.276 AB	1.87 AB	9	6 (52%)[e]	4 (18%)	4 (48%)	1 (2%)	0	0 (2%)	na	4 (17%)
1986	20	0.264 A	3.23 B	28	11	11	7	0	4	9	3	4
1986	20	0.282 ABC	1.70 AB	29	7	8	4	4	3	4	10	6
1986	20	0.287 ABC	2.10 AB	19	6	7	7	4	0	1	7	3
1986	20	0.287 ABC	1.53 AB	14	4 (35%)[f]	7 (41%)	4 (37%)	4 (15%)	2 (11%)	0 (18%)	6 (33%)	3 (20%)

[a] DDE = dichloro diphenyl dichloroethylene, DDT = dichloro diphenyl trichloroethane, HE = heptachlor epoxide, HCB = hexachlorobenzene, and na = not analyzed. Only 1 egg contained dichloro diphenyl dichloroethane (DDD) in 1980, 2 eggs in 1985, and 3 eggs in 1986. Polychlorinated biphenyls were detected in 2 eggs in 1980 (0.61 and 0.63 ppm).
[b] Includes oxychlordane, or *trans*-nonachlor, but not heptachlor epoxide.
[c] Means within each of these columns sharing a letter are not significantly different, $P > 0.05$.
[d] % occurrence 1980–83.
[e] % occurrence 1985.
[f] % occurrence 1986.

Table 3. Mercury (Hg) and selenium (Se) concentrations (ppm, dry wt) in white-faced ibis eggs from Carson Lake, Nevada, 1985–86.

		Geometric $\bar{x}$		Occurrence (%)	
Yr	*N*	Hg	Se	Hg >1 ppm	Se >4 ppm
1985	20	0.22 A[a]	3.29 B[a]	1 (5%)	3 (15%)
1985	20	0.77 BC	5.40 C	6 (30%)	17 (85%)
1986	20	0.47 B	2.95 B	1 (5%)	
1986	20	0.43 AB	1.91 A	1 (5%)	
1986	20	0.70 BC	2.75 B	3 (15%)	2 (10%)
1986	20	1.09 C	2.77 B	11 (55%)	2 (10%)

[a] Means within each of these columns sharing a letter are not significantly different, $P > 0.05$.

Reproduction and Egg Contaminants

Selenium, Hg, and DDE concentrations were not significantly correlated with each other and made the data set ideal for multiple regression procedures.The ANCOVA was used to separate the effects of DDE, Se, and Hg concentrations in eggs on white-faced ibis reproduction. We found DDE strongly and negatively related to young produced/nesting attempt ($P = 0.0001$), young produced/successful nest (i.e., brood size) ($P = 0.0075$), and eggshell thickness ($P = 0.0001$) although clutch size was not affected (Table 4). Selenium and Hg did not show a significant relationship to the reproductive parameters of interest although Hg may be having an effect on young produced/nesting attempt ($P = 0.0942$). The nearly significant ($P = 0.0559$) relationship between Hg and eggshell thickness was positive and perhaps an artifact of the trend toward lower DDE concentrations from later nesting segments each year, and the opposite Hg trend (significantly higher concentrations) from later nesting segments.

Reproduction and DDE.—The ANCOVA approach could be used to estimate the slope to describe the significant DDE relationship; however, we decided to use the pre-determined DDE groups (Henny et al. 1985) and compare reproductive responses among these groups with a 1-factor ANOVA or the Chi-square test. This approach with the pooled data presents a graphic representation of the data.

Two patterns became clear when further evaluating the pooled productivity data in relation to DDE concentrations: the percentage of successful nests decreased above 4 ppm ($P < 0.001$), and the brood size at successful nests decreased significantly above 8 ppm. The net effect was fewer young produced/nesting attempt as DDE increased >4 ppm because of reduced nest success and brood size. Although some 4-egg clutches were found in the 2 higher DDE categories (Table 5), no nests contained 3 young (Table 6); 12 of the 17 successful nests contained only 1 young.

Eggshell Thinning and DDE.—Eggshell thickness was negatively correlated with DDE in an earlier series of eggs that included 61 collected at Carson Lake between 1980 and 1983 (Henny et al. 1985); the relation was similar to previous reports (Capen 1978, King et al. 1980, Steele 1984). Eggs collected in 1985 and 1986 also showed a negative correlation between eggshell thickness and DDE (Fig. 1); the relationship was nearly identical to that during 1980–83 ($\hat{Y} = 0.298 - 0.029 \log_{10}X$, $r = -0.628$, $N = 96$, $P < 0.001$).

Table 4. Summary of significance levels from the analysis of covariance for several white-faced ibis response variables in relation to dichloro diphenyl dichloroethylene (DDE), selenium (Se) and mercury (Hg) concentrations in eggs.

Response variable	Nesting segment	Ln DDE (ppm wet wt)	Ln Hg (ppm dry wt)	Ln Se (ppm dry wt)
Young/nesting attempt	0.7547	0.0001*	0.0942	0.4319
Young/successful nesting attempt	0.0186*	0.0075*	0.2644	0.9077
Clutch size	0.0668	0.1460	0.5098	0.8687
Eggshell thickness	0.2526	0.0001*	0.0559	0.1178

* $P \leq 0.05$.

Table 5. Concentrations of dichloro diphenyl dichloroethylene (DDE) (ppm wet wt) in white-faced ibis eggs at Carson Lake, Nevada, 1985–86, in relation to clutch size, the incidence of cracked eggs, and eggshell thickness (mm).

DDE (ppm)	Clutch size					Clutches with cracked eggs				Shell thickness[b]		
	$\bar{x}$	N	2	3	4	This study[a]		Henny et al. (1985)		$\bar{x}$	N	SD
≤1.0	3.31 A[c]	42	3	23	16	0		1/37	2.7%	0.301 A[c]	64	0.023
1.01–4.0	3.33 A	39	1	24	14	2	5.1%	2/38	5.3%	0.290 A	64	0.020
4.01–8.0	3.00 A	20	3	14	3	1	5.0%	2/8	25.0%	0.274 B	26	0.018
8.01–16.0	3.11 A	28	4	17	7	11	39.3%	2/4	50.0%	0.252 C	32	0.021
>16.0	3.09 A	11	1	8	2	6	54.5%	3/4	75.0%	0.239 C	15	0.013
Totals	3.21	140	12	86	42	20	14.3%	10/91	11.0%	0.282	201	0.029

[a] Chi-square test 21.92 (≤4 ppm *vs.* >4 ppm) ($P < 0.001$).
[b] Includes 1980–83 data from Carson Lake (Henny et al. 1985). The mean pre-DDT era eggshell thickness for 374 eggs in Ut. and Calif. was 0.327 ± 0.001 (SE), mm (Capen 1977).
[c] Means within each of these columns sharing a letter are not significantly different, $P > 0.05$.

Twenty marked nests (14.3%) contained cracked eggs at Carson Lake in 1985 and 1986 (Table 5), and the incidence of cracking increased at higher DDE concentrations ($P < 0.001$). Few clutches with ≤4 ppm DDE contained cracked eggs, and cracked eggs occurred at similar frequencies for given levels of DDE during this and the earlier study (Henny et al. 1985). Because the 2 regression equations for the DDE–eggshell thickness relationship were nearly identical, all Carson Lake eggshell thickness data were combined (Table 5). The greater occurrence of cracking in the 8–16 ppm and >16 ppm DDE categories was associated with 23 and 27% shell thinning, respectively. Although most nests were found during egg laying or early incubation, the slightly smaller clutches at higher DDE concentrations may have resulted from earlier undetected egg breakage.

Reproduction and Other Organochlorines.—Other organochlorines in eggs were generally at low levels and frequencies of occurrence (Table 2). To our knowledge, no adverse reproductive effects have been reported at levels <0.50 ppm. Therefore, we reviewed reproductive success of nests with eggs containing ≥0.50 ppm of other organochlorines to provide an assessment of potential impact on productivity. Recall the data set includes 140 nests (eggs) with organochlorine residue data and 118 with reproductive data. Only 3 eggs contained ≥0.50 ppm dieldrin, with the highest 0.80 ppm. Two of those nests were successful (1 and 2 young) including those with the highest residues. Heptachlor epoxide at ≥0.50 ppm was found in 2 eggs (0.56 and 0.60 ppm) and each nest produced 2 young. No chlordane isomers were found at ≥0.50 ppm. Endrin was not found at ≥0.50 ppm; only 3 eggs contained ≥0.25 ppm and all produced young (2, 2, and 1). Hexachlorobenzene was evaluated in 1986 and 12 eggs contained ≥0.50 ppm. Ten of the 12 nests were successful and produced 19 young. One of the failed nests also contained 23 ppm DDE (1 of the highest DDE residues recorded during the study). Eleven eggs contained ≥0.50 ppm toxaphene, with 1 egg >1 ppm (2.2 ppm); all of these eggs also contained >10 ppm DDE. Only

Table 6. Concentrations of dichloro diphenyl dichloroethylene (DDE) (ppm wet wt) in white-faced ibis eggs at Carson Lake, Nevada, 1985–86, in relation to productivity.

DDE (ppm)	Young				Total nests	Nests successful[a]		Young/ successful nest	Young/ nesting attempt
	0	1	2	3		n	%		
≤1.0	3	8	20	6	37	34	92	1.94 A[b]	1.78 A[b]
1.01–4.0	3	4	24	3	34	31	91	1.97 A	1.79 A
4.01–8.0	6	2	6	2	16	10	63	2.00 A	1.25 AB
8.01–16.0	9	9	4	0	22	13	59	1.31 B	0.77 B
>16.0	5	3	1	0	9	4	44	1.25 AB[c]	0.56 B
Totals	26	26	55	11	118	92	78	1.84	1.43[d]

[a] Chi-square test 19.15 (≤4 ppm *vs.* >4 ppm) ($P < 0.001$).
[b] Means within each of these columns sharing a letter are not significantly different, $P > 0.05$.
[c] Only 4 successful nests were in the category.
[d] Estimated adjustment to compensate for egg collection increases this value to 2.05.

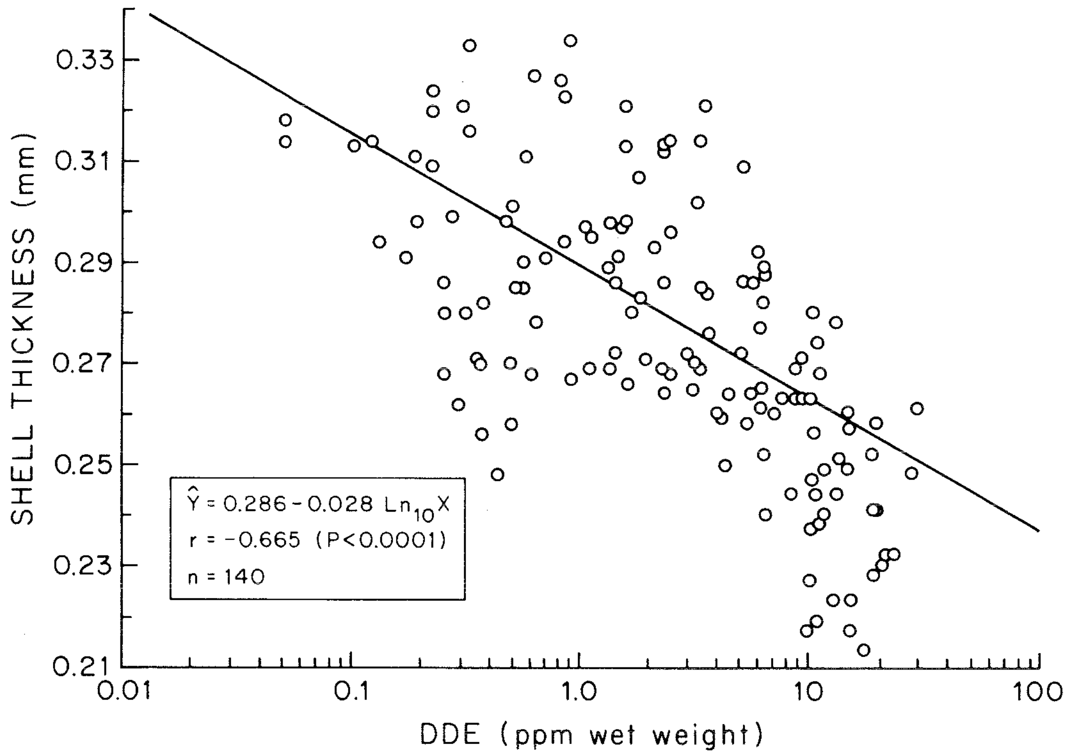

Fig. 1. The relationship between dichloro diphenyl dichloroethylene (DDE) (wet wt) and eggshell thickness (mm) for white-faced ibis from Carson Lake, Nevada, 1985–86.

5 of the nests were successful with 7 young produced.

Reproduction and Mercury.—The ANCOVA provided a hint ($P = 0.0942$) that Hg may be affecting young produced/nesting attempt (Table 4). We reviewed the subset of data with <4 ppm DDE to further evaluate for possible effects of Hg on reproduction. Mercury concentrations were stratified into 2 groups from this subset (≤1 and >1 ppm Hg). The number of young produced/successful nest was 1.96 for ≤1 ppm Hg and a nearly identical 1.94 for >1 ppm Hg. For young produced/nesting attempt with Hg ≤1 and >1 ppm, 1.75 and 1.94 young were produced, respectively. Two eggs contained >2 ppm Hg; a nest with 7.1 ppm produced 2 young, and 1 with 6.4 ppm failed but also contained 9.3 ppm DDE. The population included 22 of 118 (18.6%) with Hg concentrations in their eggs >1 ppm.

Eggs for the last nesting segment investigated in 1986 contained the highest Hg concentrations recorded during the study and 55% contained >1 ppm Hg (Table 3). One nest initially contained a clutch of 4 eggs in May and 1 was collected. Two chicks and an unhatched egg were in the nest during the final check on 19 June. The 2 chicks were banded and the unhatched egg was saved. Upon opening the unhatched egg, there was no right eye, only a small slit for the left eye, and the lower bill was longer than the upper bill. The sample egg collected earlier from that nest contained no organochlorines (1 of the few eggs with none). Mercury and Se were found at 1.7 and 2.3 ppm, respectively. The Hg concentration was the second highest recorded in 1986 (out of 80 eggs) and the third highest recorded in 1985–86 (out of 120 eggs), whereas the Se concentration was below the 1985–86 mean.

Reproduction and Selenium.—The ANCOVA provided no indication that Se was having an effect on reproduction (Table 4). To further evaluate for possible effects of Se on reproduction, the subset of data with ≤4 ppm DDE was reviewed. Selenium concentrations were stratified into 2 groups from this subset (≤4 and >4 ppm Se), and nests with the highest Se concentrations were evaluated individually. The number of young produced/successful nest

Table 7. The influence of 1 egg collected on white-faced ibis brood size at about 7–10 days in successful nests, 1985.

Brood size	24 May		30 May	7–12 Jun	
	Egg collected	Not collected	Not collected	Egg collected	Not collected
1	7	0	7	4	9
2	5	9	13	13	20
3	0	3	37	0	47
4	0	0	4	0	1
Mean	1.42	2.25	2.62	1.76	2.52
Difference	0.83			0.76	

was 1.98 and 1.87 for Se ≤4 and >4 ppm, respectively. Similar results were obtained for young/nesting attempt (1.80 and 1.75, respectively). Only 22 of 118 nests (18.6%) contained >4 ppm Se. Six of 22 nests with elevated Se (>4 ppm) had elevated Hg (>1 ppm). These 6 nests were all successful (1.67 young/nesting attempt).

Eight of 118 nests (6.8%) contained eggs with >6 ppm Se; 6.2 (2 young), 6.3 (1 young, but 1.1 ppm Hg), 6.4 (no young), 6.9 (1 young), 7.3 (2 young), 8.3 (no young, but 5.4 ppm DDE), 8.8 (2 young), and 8.8 (2 young). The 7 nests with >6 ppm Se, excluding the 1 with DDE, produced 10 young (1.67/successful nest or 1.43/nesting attempt).

Adjustments for Sample Egg

The unadjusted production rates we report are not directly comparable to data in the literature because a sample egg was collected. Additional nests (with no eggs collected) were studied in 1985 to evaluate the impact of collecting an egg. The removal of a sample egg had a negative effect on the brood size in successful nests; reductions ranged from 0.76 to 0.83 young in the 2 groups where direct comparisons could be made (Table 7).

Nest success (% nests successful) comparisons were based on a more limited set of data because some unmarked nests were used to evaluate brood size at 7–10 days (only successful nests were required) at nests without eggs collected. A comparison between nests marked early in incubation with final checks on 30 May (42 nests with no eggs collected) and 7 June (20 nests with 1 egg collected) showed 83% and a nearly identical 85% successful ($P > 0.80$). Henny et al. (1984) reported similar findings for black-crowned night-herons (*Nycticorax nycticorax*), including the collection of 1 sample egg having no effect on the percentage of successful nests.

To adjust the young/successful nest for the loss of the egg collected, 0.80 young can be added. To adjust young/nesting attempt for the egg collected, the percentage of nests successful can be multiplied by 0.80 and added. This adjustment would elevate the overall production rate in Table 6 from 1.43 to 2.05 young/nesting attempt. Adjusted data may be used to compare our results with other studies (no eggs collected), but the unadjusted data (less complex and with percent nests successful not affected by taking an egg) are best used to evaluate the potential impact of environmental contaminants on production rates.

Mercury and Selenium in Livers

Among the adult ibis, Hg and Se concentrations in livers tended to be higher in males than in females (Table 8), although the difference was not significant. Arsenic, boron, cadmium, and lead concentrations were generally low.

Organochlorine Pesticides, Mercury, and Selenium in Prey

The esophagi of 16 of 18 white-faced ibis collected in June held prey items previously identified (Bray and Klebenow 1988). Earthworms had the highest volume (68%) and dry weight (68%) with insect larvae (Libellulidae, Tabanidae, Lepidoptera) forming the bulk of the remainder (29 and 28%, respectively). Three pools (each pool from 6 ibis) of stomach contents from adult ibis averaged 5.9 ppm dry weight Hg (range = 3.1–9.7 ppm) and 1.5 ppm Se (range = 0.99–1.9 ppm), but no organochlorine pesticides were detected. Therefore, Hg and Se were accumulated locally on the breeding grounds in Nevada, while the organochlorine pesticides (DDE and DDT being of most concern) were obtained elsewhere.

White-faced Ibis Wintering Grounds

The Carson Lake banding program yielded 5 winter recoveries: in Aquascalientes, Michoa-

Table 8. Concentrations (geometric $\bar{x}$) of mercury, selenium, arsenic, boron, and cadmium (ppm dry wt) in livers[a] of 9 M and 9 F adult white-faced ibis collected 27 June 1985 at Carson Lake, Nevada.

Sex	Statistic	Mercury	Selenium	Arsenic	Boron	Cadmium
M	$\bar{x}$	27.0	10.7	0.28	1.8	2.6
	Range	7.8–87	5.0–27	nd[b]–0.58	nd–6	1.7–4.2
F	$\bar{x}$	19.8	8.6	0.47	3.1	2.4
	Range	8.6–36	5.7–12	0.30–1.0	nd–11	0.80–4.3
Samples with elements detected		18	18	17	11	18

[a] Only 10 of 18 livers contained measurable lead and only 2 (M 3.9 and F 4.5) contained concentrations >0.65 ppm.
[b] nd = none detected.

can, Vera Cruz, Sinaloa, and Baja California (Mexicali). The Carson Lake ibis wintered in Mexico.

Population Numbers at Carson Lake and Vicinity

The apparent ibis response to local water conditions makes it impossible to assess the nesting population's long-term status based on population counts in only a portion of their range (e.g., Carson Lake and vicinity). The nesting at Stillwater WMA, and the adjacent Canvasback Club during 6 of the last 17 years (Table 9), further illustrates local movements when habitat requirements are met or not met. Water availability at Carson Lake is somewhat in synchrony with Stillwater WMA, but not subject to the severe flooding that can occur at Stillwater (e.g., 1983–86). The maximum fall surface area is about 6,000 ha at Carson Lake. The high water years throughout the Great Basin (including Great Salt Lake) in the mid-1980's resulted in Carson Lake being 1 of the few suitable nesting locations in the region, although population increases were also noted at Malheur NWR in eastern Oregon (Ivey et al. 1988).

DISCUSSION AND MANAGEMENT IMPLICATIONS

Organochlorine Pesticides and Their Effects

Concentrations of DDE in eggs among the population segments sampled in 1985 and 1986 were not significantly different and we believe the early and late samples in 1985 and the early and late, plus 2 intermediate samples, in 1986 provide a representative sample of the contaminant burdens in the Carson Lake ibis population. The 1980–83 samples were from the first half of the nesting season and, based on the 1985 and 1986 findings, can be used to represent the organochlorine burden during those years.

The obvious DDE concentration declines reported for black-crowned night-heron eggs in the Great Basin during the 1980's (Henny et al. 1985) have not occurred for the white-faced ibis at Carson Lake. Furthermore, the continued occurrence of DDT (sometimes at especially low DDE:DDT ratios) suggests exposure to recently used DDT (Henny et al. 1982). The presence of DDT in all 1986 eggs with >8 ppm DDE implies that the highest DDE concentrations in the population resulted from recent DDT use in a portion of the white-faced ibis range. We found DDE significantly correlated with eggshell thinning and productivity decreased as DDE residues increased >4 ppm. The 4 ppm should not

Table 9. A summary of water levels and white-faced ibis nesting at Carson Lake and Stillwater WMA, Nevada, 1972–88.

Yr	Pairs nesting[a]	Fall water (surface ha, 1,000's): Stillwater WMA	Fall water (surface ha, 1,000's): Carson Lake
1972	1,300	6.5	5.7
1973	3,300	5.3	5.6
1974	0[b]	4.5	4.3
1975	1,700	6.1	5.3
1976	500	3.4	2.8
1977	0[b]	1.4	0.8
1978	400	5.1	NA[c]
1979	1,200	5.1	NA
1980	1,800	7.7	NA
1981	2,500[d]	3.4	NA
1982	2,900[d]	16.2	NA
1983	3,600[d]	81.7	NA
1984	4,000[d]	100.0+	NA
1985	5,000	100.0+	NA
1986[e]	1,400	100.0+	5.1
1987[e]	4,200[f]	3.7	2.3
1988[e]	3,400[f]	1.8	1.7

[a] Nesting at Carson Lake unless otherwise indicated (Nev. Dep. Wildl. and USFWS files).
[b] Fifty adults present in 1974 but not nesting; 300–400 adults present in 1977 but not nesting.
[c] NA = Not available.
[d] Includes 400 or 500 pairs nesting at Stillwater WMA.
[e] Nesting population estimated by helicopter survey, in prior years estimated by ground counts.
[f] Includes about 1,500 pairs nesting at Canvasback Club, adjacent to Stillwater WMA.

be construed as rigid or fixed except for descriptive purposes. The exact placement is judgmental and other investigators may place the cutoff point slightly higher or lower. The critical level of 4 ppm DDE makes white-faced ibis second in sensitivity to the 3 ppm (Blus 1982) determined for brown pelicans (*Pelecanus occidentalis*).

The magnitude of the DDE impact on production can be evaluated in 2 ways: percentage of the population adversely impacted, and overall loss of young produced when compared to "expected production." Although 4 ppm DDE is not a rigidly fixed point, it appears that major decreases in production occur above that DDE level, which is in close agreement with the 3 ppm mentioned by Steele (1984). Assuming that 4 ppm is a good "threshold," productivity in 40% (47 of 118) of the nesting population in 1985 and 1986 was adversely impacted by DDE. The 118 nests studied produced 169 young, but an estimated 211 young would have been produced if production rates in the higher DDE categories (>4.00 ppm) had equalled production rates at ≤4.00 ppm, a net loss of 20% of the population's expected production.

Other organochlorine contaminants in eggs were found less frequently or at levels below those causing reproductive effects with the possible exception of toxaphene. We believe toxaphene can be discounted because reproductive success declined in nests containing >4 ppm DDE, and all nests with toxaphene contained >10 ppm DDE, and egg shell thinning and cracked eggs were common in these failed nests. However, toxaphene does not cause eggshell thinning (Haseltine et al. 1980). Haseltine et al.'s (1980) laboratory study of black ducks (*Anas rubripes*) fed toxaphene showed egg production, fertility, hatchability, growth, and survival of young unaffected. We have no evidence for organochlorines, other than DDE, adversely influencing ibis reproduction.

Mercury and Selenium and Their Effects

Mercury and Se were accumulated locally on the breeding grounds. Bray and Klebenow (1988) reported that ibis fed primarily in flood-irrigated alfalfa fields (≥86% of obs), with the majority observed within 3–6 km of the Carson Lake nesting colony, although some used fields ≤ 18 km away.

Mercury increased significantly in eggs from early to late nesting population segments in 1985 and 1986. However, by sampling various nesting segments throughout the season, a representative sample of the ibis population was obtained. No significant relationship was found between productivity and Hg concentrations, although a 1-eyed embryo causes us concern because it contained the third highest Hg concentration (1.7 ppm) recorded during the study. Eggs collected in Texas in 1976 provide the only other white-faced ibis Hg and Se data (King et al. 1980). Mercury concentrations in 20 eggs averaged 0.63 ppm (arithmetic $\bar{x}$, dry wt based on Nev. egg moisture content to convert from wet to dry wt), which was within the range we reported (e.g., the early and late 1985 Nev. geometric $\bar{x}$ convert to arithmetic $\bar{x}$ 0.23 and 0.82 ppm dry wt).

Newton and Haas (1988) reported that merlin (*Falco columbarius*) productivity declined in clutches where Hg exceeded 3 ppm (dry wt). Heinz (1979) reported behavioral changes in mallard (*Anas platyrhynchos*) ducklings produced from eggs with about 0.80 ppm Hg (wet wt, which converts to about 3 ppm dry wt). Heinz (1979) also reported more eggs laid outside the nestbox and fewer 1-week old ducklings produced than in the control population. But the 3 ppm was considerably above the mean Hg concentration (<1 ppm) we found.

Avian embryos are also sensitive to the toxic effects of Se. Laboratory studies with mallards (Heinz et al. 1987, Hoffman and Heinz 1988) have shown the primary effect of excessive dietary Se to be reduced hatching success of fertile eggs, including developmental abnormalities. The work with mallards revealed selenomethionine to be teratogenic in a dose-dependent manner with a threshold occurring between 4 and 8 ppm (dry wt) Se in the diet. Eggs from females fed these dosage levels averaged 3.4 and 11.0 ppm (wet wt), respectively, which converts to about 10 and 35 ppm (dry wt). Field studies of Ohlendorf et al. (1986) showed Se concentrations in eggs reflect dietary Se levels, and adverse Se effects on reproduction begin at about 10 ppm (dry wt) in the egg, or perhaps a little lower. Thus, the laboratory and field studies showed similar reproductive effects that began at about 10 ppm in the egg. Hoffman and Heinz (1988) also fed mallards diets of 1 and 2 ppm Se (as selenomethionine) which showed no adverse reproductive effects and resulted in eggs containing 0.8 and 1.6 ppm Se (wet wt), or about 3 and 5 ppm (dry wt). The earthworm-insect larvae diet of white-faced ibis in this study averaged 1.5 ppm Se (halfway between the 2 low diets of Hoffman and Heinz [1988]). Observed Se concentrations in the eggs among the various ibis nesting segments varied from 1.9 to 5.4 ppm (dry wt), which shows agreement with the expected egg concentrations (3–5 ppm) based on the mallard feeding study.

The highest Se concentration encountered was 8.8 ppm in eggs from 2 nests that each produced 2 young. Only 8 eggs (6.8%) contained >6 ppm Se in 1985 and 1986 and 6 of 7 (without >4 ppm DDE) were successful. Selenium concentrations in 20 white-faced ibis eggs from Texas (King et al. 1980) (using arithmetic $\bar{x}$) were 3.5 ppm compared to 3.4 and 5.7 ppm for early and late Nevada, respectively, in 1985. Therefore, Hg and Se concentrations in Nevada eggs were similar to those in Texas, and with no significant effect on productivity to the age of 7–10 days.

Mercury and Se are excreted via birds' eggs (Heinz 1979, Magat and Sell 1979) and were found in ibis eggs during this study, which probably accounts for the slightly higher concentrations found in livers of males. Adult ibis were collected about 1–2 months after the egg laying period. Twenty livers from non-migratory (Telfair and Swepston 1987) adult ibis collected in Texas in 1971 (King et al. 1980) averaged 5.2 ppm Hg (arithmetic $\bar{x}$, dry wt converted by Nev. liver moisture content), which was considerably below the 28 ppm (arithmetic $\bar{x}$, dry wt) for 18 adult ibis collected in late June 1985 at Carson Lake. The exceptionally high Hg in livers at Carson Lake probably reflects continued increases with time on the Nevada breeding grounds. Additional evidence for breeding grounds accumulation includes the significant Hg increase in eggs from early to late layers in 1985 and 1986.

Early results from mammals highlighted a relationship ($r = 0.932$) between Hg and Se found in livers of some seals, dolphins, and porpoises (Koeman et al. 1973). Least squares treatment of Koeman et al.'s (1973) data and seal data by Kari and Kauranen (1978) resulted in a correlation coefficient between Hg and Se that averaged 0.98 in the liver of all specimens and a least squares treatment leads to the following equation (Kari and Kauranen 1978): $Hg = 2.95Se - 11.6$. The slope 2.95 is nearly equivalent to a 1:1 molar ratio. Mercury and Se are naturally occurring in a 1:1 molar ratio in many aquatic organisms (especially marine mammals) and has been attributed to Hg plus Se antagonism (Pelletier 1985). A similar relationship was found in the 18 white-faced ibis livers during this study: for males $Hg = 3.45Se - 8.43$ ($r = 0.984$), for females $Hg = 1.47Se + 8.76$ ($r = 0.319$), and for males and females combined $Hg = 3.32Se - 7.14$ ($r = 0.921$). The Hg–Se relationship for 9 females was weaker than for 9 males probably because of the excretion of Hg and Se at different rates in eggs during the 2 months prior to collection (F had 27 and 20% lower Hg and Se concentrations, respectively, than M in their livers). The interaction between Hg and Se appears to be occurring with ibis but, as Pelletier (1985) reports, "interaction between selenium and mercury is real but true antagonism between these two elements has not been clearly shown." Residues were probably too low in this study to detect an antagonistic effect.

Although Se and Hg concentrations in ibis prey and eggs showed no significant effect on production through 7–10 days of age and agreed with observed diet-egg relationships reported for laboratory mallards, we remain concerned about accumulation of Se and especially Hg in adults and young as they remain in the area throughout the remainder of the spring and summer. Unlike the Central Valley of California (e.g., Kesterson NWR) where many nesting birds are resident, the ibis population in the Great Basin is migratory. They arrive shortly before nesting and have a limited time to accumulate local contaminants before egg laying occurs. However, the adults (based on liver residues) appear to be accumulating substantial amounts of Hg during the summer. The young are fed by the adults that feed in flood-irrigated fields away from Carson Lake. These fields were probably less contaminated than Carson Lake. Following this logic, other species that feed in the lake and/or marsh may be more exposed to drainwater contaminants, and additional species are now being studied. Of concern is the accumulation of drainwater contaminants by young and adults that continue feeding directly in the marshes during summer. We have no data on survivorship of young ibis after leaving their nests or the pollutant accumulation before leaving the region to winter elsewhere.

Sources of the Contaminants

Sources of DDE-DDT and sources of Hg and Se were different. First, no DDE-DDT or other organochlorine pesticides were found in the stomach contents of the adult ibis collected on the breeding grounds in 1985, whereas Hg and Se were found. Significant increases in Hg and Se from early to late nesting segments provides additional evidence that breeding grounds in Nevada were a source of Hg and Se. No significant changes in DDE occurred in eggs laid throughout the season.

The major contaminant problem facing the Carson Lake white-faced ibis population is DDE-DDT that is not being accumulated on the breeding grounds in Nevada. Ryder (1967) and Capen (1977) concluded that most ibis migrate from Utah marshes to Mexico in late September and early October with a few stragglers remaining until December. Ibis in Idaho and Nevada also winter in Mexico (Henny et al. 1985). Published data on winter band recoveries (Ryder 1967, Henny et al. 1985) showed that the adjacent states of Michoacan, Jalisco, and Colima accounted for many of the Mexican recoveries of ibis banded in Utah 56%, Nevada 50%, and Idaho 38%. White-faced ibis breeding on our study area and adjacent areas winter in Mexico with about 40–50% of the winter band recoveries coming from the adjacent states of Michoacan, Jalisco, and Colima. Michoacan and Jalisco, and perhaps adjacent Aquascalientes represent inland Mexico agricultural states, and Blake (1977) reported ibis wintering chiefly in freshwater habitats. There is agreement in published banding data that Great Basin ibis winter in Mexico. We know nothing about DDE-DDT residues in interior Mexico, where most ibis winter, except by inference.

In contrast, black-crowned night-herons and several other wading bird species from the Great Basin, which showed declining DDE-DDT egg residues during the early 1980's, winter in coastal Mexico or the southwestern United States. Egrets, stilts, and night-herons from the Great Basin may now be benefiting from the generally low DDE-DDT residues in fish and other food organisms from coastal Mexico, although elevated DDE-DDT levels were found occasionally in fish from coastal zone agricultural areas (Henny et al. 1985). Eggs from non-migratory white-faced ibis in Texas were of special interest; they contained exceptionally low DDE residues (0.14 and 0.27 ppm, geometric $\bar{x}$ wet wt) and no DDT in 1985 (Custer and Mitchell 1989). With the exception of 1 egg, no other organochlorine pesticides were detected in the Texas eggs.

Ibis are nomadic in response to local changes in water conditions on the breeding grounds (Ryder 1967), and Steele (1984) thought some ibis from Carson Lake relocated in northern Utah during the 1977 drought at Carson Lake. The high water condition at the Great Salt Lake was perhaps responsible for ibis' return to Carson Lake in the mid-1980's when the Carson Lake ibis population increased to a peak of 5,000 pairs. The Great Basin ibis might be considered 1 population that nests within several states depending upon local breeding ground conditions. To assess the nesting populations long term status requires coordinated census efforts within the Great Basin and adjacent regions.

We documented the extreme sensitivity of white-faced ibis to DDE. Now, the impact of DDE can be evaluated quite easily by sampling a series (perhaps 20) of random fresh eggs (1/nest) to determine DDE contamination in other populations. Complete nesting studies would not be required; the percentage of eggs containing $\geq$4 ppm has been established as the parameter of interest. In addition to evaluating other nesting populations in the Great Basin to further understand the magnitude of the DDE problem, cooperative investigations with the Mexican authorities on the wintering grounds would be most helpful.

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Addendum: To eliminate any misinterpretation, the references to DDE, DDD, and DDT in this paper refer to p,p'-DDE; p,p'-DDD; and p,p'-DDT, respectively.