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Eggshell Thinning and Organochlorine Residues in Rocky Mountain Peregrines, *Falco peregrinus,* and Their Prey

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Eggshell thinning, and organochlorine residues in egg contents and in prey, were determined for Peregrine Falcons (*Falco peregrinus*) in Colorado and northern New Mexico. Eggshells from 141 eggs from 16 territories in 1973-79 averaged 16% thinner than eggs collected prior to 1947, 13% thinner than eggs laid by captives from the region in 1978. Similar amounts of thinning have been found in declining peregrine populations in Alaska, California and Britain. DDE averaged (geometric mean) about 20 ppm (wet weight) in the contents of 47 eggs, an amount predicted to correlate with about 18% thinning. PCBs averaged (geometric mean) about 2 ppm (wet weight) in egg contents, an amount below that producing no adverse effect on reproduction in captive Screech Owls (*Otus asio*). Among birds eaten by peregrines or available to them, 19 of 29 species had at least one pooled sample with 0.5 ppm DDE or more (whole body, wet weight), and 11 of these species had 1.0 ppm or more. Previous studies suggested that a diet containing 1.0 ppm DDE or more could be expected to produce the eggshell thinning we found. Migratory insectivorous prey species contained 5.8 ppm DDE (S.E. – 2.98), several times more than any permanent resident species. Because prey species with high DDE levels were found at all peregrine eyries examined in the region, reproductive performance of both wild-produced and captive-released falcons is not expected to improve there until a downward trend in prey contamination occurs.

Key Words: Peregrine Falcon, *Falco peregrinus*, DDT, PCB, eggshell thinning.

Early studies on organochlorine pollutants in Peregrine Falcon eggs in Alaska and north-western Canada revealed DDT and its metabolities in concentrations 15 to 30 times greater than the whole-body levels found in small samples of prey (Cade et al. 1968; Enderson and Berger 1968). Subsequent eyrie surveys indicated vacancy as high as 75% in those regions (Fyfe et al. 1976). Reduction in eggshell thickness dating back to 1947 was first described for North American Peregrines by Hickey and Anderson (1968), and an inverse correlation between DDE residues in egg contents and shell thickness was soon discovered in Alaskan peregrines (Cade et al. 1971), suggesting a mechanism for reproductive failure. In an innovative study, Peakall (1974) was able to show that levels of DDE extracted from the interiors of peregrine eggshell specimens from California had been adequate to cause thinning as early as 1948.

In 1964 a widespread reduction of nesting peregrines was found in the central Rocky Mountains (Enderson 1965). Evidence that these falcons are at least weakly migratory include: 1) the only three recoveries of banded peregrines were in central New Mexico and northern Mexico, 2) a check of several eyries in mid-winter revealed no falcons, and 3) the winter weather at most mountain eyries is extremely severe. By 1973 the species had suffered an estimated nesting decline of at least 50% in the region. High DDE levels were found in a sample of 4 eggs, and 9 eggshells averaged 20% thinner than normal (Enderson and Craig 1974).

In the spring of 1974, two captive-bred downy young were placed in a Colorado eyrie containing one addled egg and one cracked egg, and in 1976 two pairs received captive-bred young (Burnham et al. 1978). This effort was expanded to seven states in the region and in 1980 nearly 60 young were successfully placed in the wild. The information presented here bears directly on the reproduction that can be expected from released and wild-produced peregrines and may be useful in management planning.

In this paper we report on pesticide residues, prim-

arily DDE, in the contents of peregrine eggs, the levels of these materials in a wide variety of principal prey species, and on eggshell condition, as these variables relate to the goal of increasing this drastically reduced population by the release of captively produced young.

Methods

Eggshell thickness measurements were made on 141 eggs from 48 first clutches and 12 second clutches laid in 16 territories in Colorado and northern New Mexico in 1973-79. In the years 1973-76 the collection of eggs was not systematic and we obtained only eggs that were addled, broken, or abandoned. In 1977-79 we routinely collected and incubated all eggs from eyries that were accessible. Often dummy eggs were substituted to maintain incubation behavior until captive-bred young could be placed in the eyrie, or no dummies were used and second clutches were laid and later replaced by dummies or young.

Thickness was measured optically from fresh chips taken at three places on the equators of the rinsed and desiccated shells and included shell plus shell membranes. In 14 instances where membranes were absent the average membrane thickness of 0.073 mm for 127 eggshells was added to the shell thickness. Optical measurement, accurate to ± 0.004 mm, was made with a 60X compound microscope using an ocular scale calibrated from a Bausch and Lomb 0.01 mm stage micrometer. Reproducibility of measurement on each chip, and for chips from the same egg, was greater than that which we obtained with mechanical micrometers, probably because surface irregularities were discounted. We did not calculate clutch mean thickness in instances where more than one egg from a clutch was available because within-clutch variation was often great. We obtained 36 eggs from second clutches and these were grouped with eggs from first clutches because shell thickness and residue values showed no trends between clutches.

Intact addled peregrine eggs for organochlorine analysis were either emptied into acetone-washed vials with foil-lined stoppers and frozen or frozen intact prior to analysis. Eggs collected in 1973-75 were analyzed by the Denver Wildlife Research Center, Fish and Wildlife Service, using methods described by Peterson et al. (1976). Eggs collected in 1976-79 were analyzed by the Patuxent Wildlife Research Center, Fish and Wildlife Service, using methods described by Cromartie et al. (1975). In 1973-74 egg contents were analyzed for DDE, dieldrin and polychlorinated biphenyls (PCBs), the latter quantified as Arochlor 1254. The efficiency of recovery was 84-100%. In 1975 only DDE and PCBs (Arochlor 1260) were measured. Eggs collected in 1976-79 were analyzed for p,p'-DDE, p,p'-DDD, p,p'-DDT, dieldrin, heptachlor epoxide, oxychlordane, *cis*-chlordane, *trans*-nonachlor, *cis*-nonachlor, hexachlorobenzene, mirex, β-BHC, and PCBs (Arochlor 1260) and the range of recovery was 83-104%. The lower limit of sensitivity was 0.10 ppm and the reported residue levels are accurate to two significant figures. Identification of residues was confirmed on a combined gas chromatograph mass spectrometer for 8 of the 43 samples collected in 1976-79. Percent moisture was determined from 10g aliquots and residue levels were corrected to approximate fresh egg weight assuming a moisture content of 85%, the highest reported for a nearly fresh egg in our sample collected early in incubation when desiccation was probably slight.

Prey remains were collected at peregrine eyries and identified by comparison with museum skins. In 1977-79 we collected adult birds identified as important or potential peregrine prey. Seven to 10 adults of each species were shot in May or early June within 9 km of active or recent eyries. Some species were collected near more than one eyrie. Freshly shot individuals were wrapped in acetone-washed foil and frozen. Samples were prepared for analysis by removing the feet, beak, feathers, and large intestine of each bird and finely homogenizing the remainder. The individuals of each species from a locality were homogenized separately. Equal weights, usually 10 g, of the 7-10 individual homogenates were then pooled and the mixture wrapped thoroughly in acetone-washed foil and sent frozen to Wisconsin Alumni Research Foundation Institute (later became Raltech Scientific Services) for analysis. A 10 g aliquot of each pool was mixed with sodium sulfate, allowed to dry and subjected to Soxhlet extraction with 50:50 ethyl ether: petroleum ether for 8 hours. The sample was then evaporated just to dryness and brought to 25 ml with 25% toluene in ethyl acetate. A 5 ml aliquot was transferred to a gel permeation apparatus. The eluate was then evaporated just to dryness and brought to 10 ml in hexane for injection on a 1.5% OV-17 plus 1.95% QF-1 on 80/100 G.C.O. gas chromatograph column. The lower limit of detection for chlorinated pesticides was 0.01 ppm and for PCBs (Arochlor 1254) 0.10 ppm, and the range of recovery was 80-90%. Arithmetic means are used throughout unless stated otherwise.

Results

Eggshell Thickness and Chemical Residues

Of the eggs collected, 77 contained large embryos or nearly full-term chicks, 57 showed little or no development, and development could not be determined for 7. We found no difference in the average thickness of shells from eggs showing little development compared to those with large embryos or hatched eggs.

Figure 1 shows the eggshell thickness of eggs col-

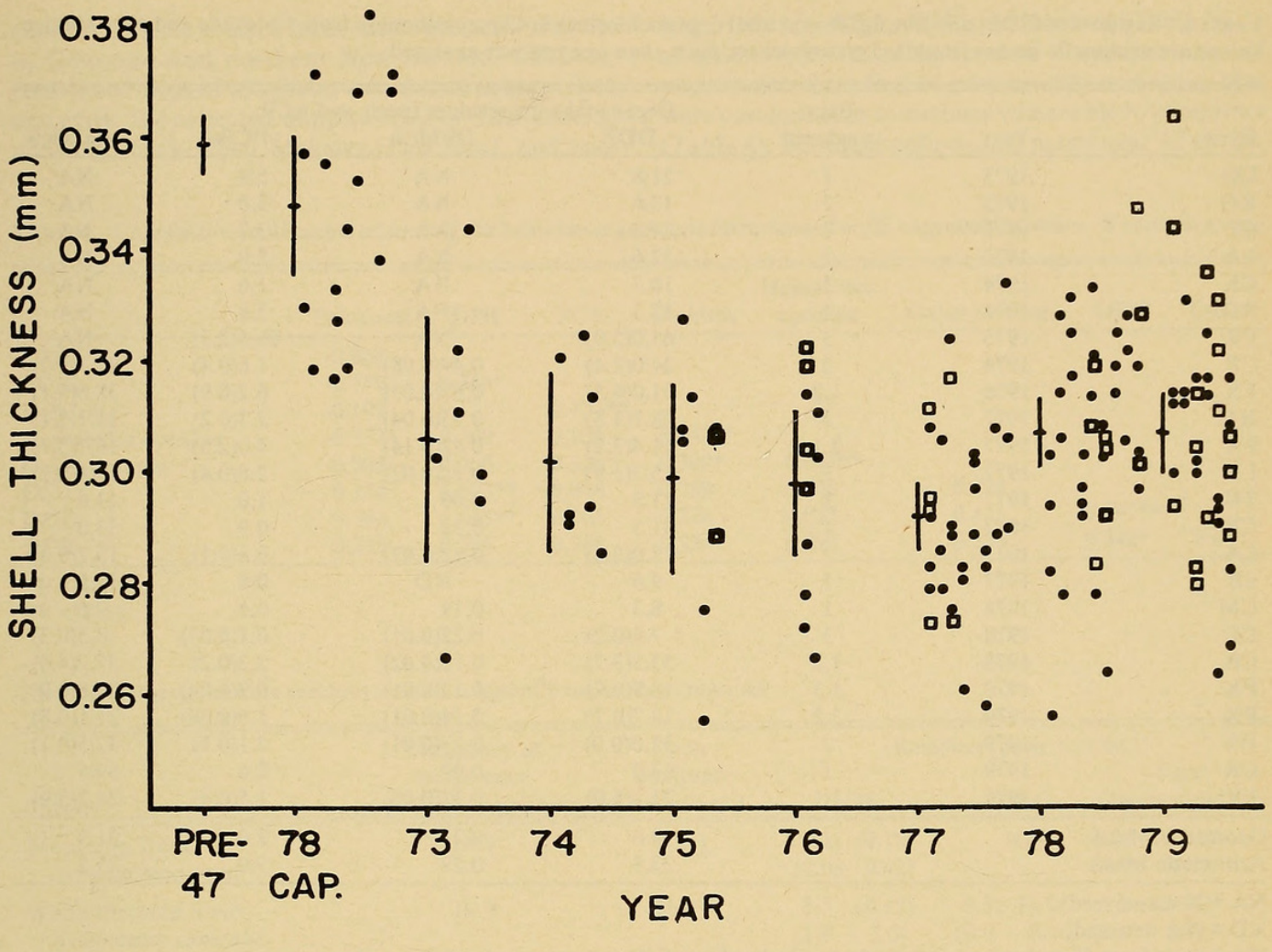

FIGURE 1. Shell thicknesses of pre-1947 (Anderson and Hickey 1972) and captive-laid (1978) eggs compared to eggs from first (dot) and second (open square) clutches of wild peregrines. Shells from each female are arranged vertically. Lines show 95% confidence intervals and means.

lected in the period 1973-79 compared to data obtained by Anderson and Hickey (1972) from collections made prior to 1947 in Alberta, Saskatchewan, and Montana. We also measured 16 eggs with no embryonic development laid in 1978 by nine captive females originating in Colorado or adjoining states and fed Coturnix quail and young poultry. The mean shell thickness of the 141 wild-laid eggs was 0.302 mm (S.E. = 0.002), vs. the means for the captive-laid eggs of 0.348 mm (S.E. = 0.005), and of 0.359 mm (S.E. = 0.003) for the pre-1947 eggs. The 95% confidence limits for the captive-laid eggs and the pre-1947 eggs overlapped substantially and the samples were not statistically different. The 95% confidence limits for recent wild-laid eggshells did not overlap with those for the museum specimens or captive-laid eggs, and the former were thinner by 16% and 13% respectively. The wild-laid eggshells, 1973-79, were significantly different in thickness (one-way analysis of variance, F-ratio = 2.44, $P < 0.05$ between years. Those laid in 1977 were significantly thinner than those laid in 1978 and 1979 (t-tests, $P < 0.05$).

Forty-seven eggs from 30 clutches were analyzed for organochlorines (Table 1). In six cases eggs from first and second clutches from a female in a given year were analyzed and clutch averages for DDE and total organochlorines were calculated. Second clutches usually had lower levels than first clutches, but the differences were not significant (paired t-tests, $P > 0.05$) either for DDE or total organochlorines.

Prior to 1976 egg contents were not analyzed for materials other than DDE and PCBs. From 1976-79 other residues were included in the total organochlorine column of Table 1 and are shown in order of frequency in single eggs: heptachlor epoxide (97%; range 0.10-1.10 ppm), oxychlordane (79%; 0.08-0.35), DDT (66%; 0.10-2.6 ppm), DDD (47%; 0.08-0.41 ppm), β-BHC (45%; 0.12-0.25 ppm), and HCB (32%; 0.05-0.40 ppm). Three eggs from eyrie PR in 1975 averaged 66.0 ppm DDE and 66.6 ppm PCBs, both

TABLE 1. Residues of DDE, dieldrin, PCBs and total organochlorines in 47 peregrine eggs from Colorado and New Mexico. Values are arithmetic means (standard errors) where more than one egg was analyzed.

Eyrie	Year	Eggs[1] analyzed	Organochlorine residues (ppm, wet wt.)[3] DDE	Dieldrin	PCBs[2]	Total Ocls.
CO	1973	1	21.8	NA	5.0	NA
RG	1973	1	13.6	NA	3.0	NA
CE	1973	1	24.8	NA	3.7	NA
LA	1973	1	32.6	NA	5.0	NA
CE	1974	1	10.7	NA	1.6	NA
RG	1974	1	12.3	NA	3.8	NA
PR	1975	3	65.0(5.0)	NA	66.6(2.3)	NA
CE	1976	2	24.0(2.4)	0.49(0.08)	1.6(0.4)	27.7(3.2)
FX	1976	1,2	31.0(4.5)	0.67(0.03)	6.2(0.9)	38.6(5.1)
HH	1977	3	28.1(1.8)	0.13(0.04)	2.3(0.2)	31.1(2.1)
FX	1977	2,1	11.4(3.2)	0.42(0.14)	4.0(2.5)	16.7(5.7)
LV	1977	2	15.3(1.9)	0.22(0.02)	2.8(0.4)	18.8(2.2)
TU	1977	1	11.3	0.09	1.0	13.6
CR	1977	1	31.5	0.32	0.9	33.0
LA	1977	2	13.0(0.6)	0.12(0.02)	0.8(0.1)	15.2(0.8)
SB	1977	1	9.6	ND	0.6	10.5
CM	1978	1	8.3	0.19	0.6	9.6
CE	1978	3	7.8(0.2)	0.23(0.01)	0.1(0.03)	8.5(0.3)
CR	1978	1,2	33.3(3.7)	0.15(0.02)	2.2(0.2)	37.2(4.0)
PX	1978	1,3	18.9(0.7)	0.12(0.01)	0.9(0.04)	20.8(0.9)
PX	1979	3,2	18.7(0.7)	0.14(0.01)	1.5(0.08)	21.1(0.8)
HS	1979	2	32.0(0.0)	0.13(0.01)	2.1(0.1)	37.5(0.1)
CR	1979	1	63.0	0.09	2.6	69.5
LV	1979	1,1	21.1(5.0)	0.17(0.05)	1.5(0.4)	24.2(5.9)
Geometric Mean			19.6	0.21	2.0	21.9
Arithmetic Mean			23.3	0.22	5.0	25.5

NA = Not analyzed
ND = Not detected
[1]Eggs were from first clutches except where number from first and second clutches are shown.
[2]Residues corrected for desiccation.
[3]In 1973-74 PCBs were quantified as Arochlor 1254, and in 1975-79 as Arochlor 1260.

unusually large values. This set was found abandoned.

The correlations among eight commonly occurring organochlorines in peregrine eggs are shown in Table 2. DDT and its metabolites DDD and DDE had significant positive correlation coefficients (t-tests; $P < 0.01$), an expected result. Several other compounds showed significant positive correlations suggesting that many of these lipid-soluble compounds are acquired by peregrines collectively. Only heptachlor epoxide showed weak significant inverse correlation with shell thickness ($P < 0.05$). No significant negative correlation was found between DDE and shell thickness ($r = 0.068$). Similarly, a plot of log DDE against shell thickness for the 47 eggs collected since 1973 showed no apparent inverse relationship contrary to expectation. However, only 5 (11%) of the eggs had residues below 10 ppm, and none below 6 ppm DDE. Most eggs contained enough DDE to correlate with shells 20-25% thinner than normal, interpolated from regressions for Brown Pelicans (*Pelecanus occidentalis*) (Blus et al. 1972), Prairie Falcons (*Falco mexicanus*) (Enderson and Wrege 1973), and Alaskan peregrines (Cade et al. 1971). The present sample of eggs is probably so uniformly and highly contaminated that the regression cannot be shown. Lacking from the sample are eggs with thicker shells and low DDE levels.

Residue levels in 14 individual eggs collected in 1973-76 were compared with levels in 1977-79 eggs, the latter collected when all clutches found were obtained for artificial incubation. The early group averaged 32.3 ppm DDE (S.E. = 5.2), the later group averaged 20.9 (S.E. = 2.0). These means are significantly different (Mann-Whitney U-test, $0.05 > P > 0.01$). However, multiple regression analysis of the DDE values, or their logarithms, vs. years failed to show a significant decrease of DDE from 1973-79.

Organochlorine Residues in Prey

We identified the remains of 107 individuals of

small and medium-sized birds of 31 species at 14 eyries in Colorado and northern New Mexico. Of these, remains of birds of 13 species were found at more than one eyrie. We collected samples of 12 of these species, omitting Black-billed Magpies (*Pica pica*), and analyzed them for organochlorine residues (Table 3). In addition we collected samples of 17 species, some of which were identified as prey at only one eyrie, that were common and sometimes vulnerable to peregrines (Table 4). All these collections, made near 12 eyries,

TABLE 2. Correlation coefficients (r) among shell thickness and concentrations of eight organochlorines in 38 peregrine eggs

	Thickness	DDE	PCBs	Dieldrin	Heptachlor epoxide	Oxychlordane	DDT	DDD
DDE	-0.068							
PCBs	-0.179	0.346*						
Dieldrin	-0.199	0.115	0.731**					
Heptachlor epoxide	-0.373*	0.200	0.256	0.488**				
Oxychlordane	-0.303	0.200	0.326*	0.369*	0.629**			
DDT	0.174	0.603**	-0.048	-0.298	-0.008	0.023		
DDD	0.103	0.445**	0.005	-0.226	0.035	0.121	0.587**	
HCB	-0.235	0.246	0.249	0.334*	0.297	0.299	0.340*	0.087

*$P < 0.05$
**$P < 0.01$

TABLE 3. Organochlorine residues in prey frequently taken by peregrines

Species	Frequency of occurrence (individuals-territories)	Pools analyzed (individuals)	Residues (ppm, wet wt.)[1] DDE	PCBs	Total Organochlorines
Mourning Dove *Zenaida macroura*	14–9	3(21)	0.21 (0.10) (0.08– 0.42)	ND –	0.22 – (0.10) (0.08– 0.42)
White-throated Swift *Aeronautes saxatalis*	16–8	5(39)	1.5 (0.17) (1.0 – 2.0)	0.32 (0.14) (0.0 – 0.76)	1.9 (0.12) (1.9 – 2.1)
Common Flicker *Colaptes auratus*	7–6	3(21)	0.06 (0.01) (0.04– 0.09)	0.04[2] (0.0 – 0.13)	0.14 (0.08) (0.04– 0.30)
Clark's Nutcracker *Nucifraga columbiana*	3–2	2(14)	0.04 (0.01) (0.03– 0.04)	ND	0.05 (0.01) (0.04– 0.05)
American Robin *Turdus migratorius*	10–8	7(51)	0.52 (0.27) (0.10– 2.1)	0.13 (0.01) (0.0 – 0.14)	0.65 (0.29) (0.12– 2.4)
Mountain Bluebird *Sialia currucoides*	2–2	1(11)	0.10	ND	0.10
Starling *Sturnus vulgaris*	5–5	1(7)	0.45	ND	0.58
Western Meadowlark *Sturnella neglecta*	6–6	3(21)	0.86 (0.48) (0.31– 1.8)	0.07[2] (0.0 – 0.21)	1.0 (0.51) (0.45– 2.0)
Reg-winged Blackbird *Agelaius phoeniceus*	7–6	4(26)	0.49 (0.28) (0.17– 1.3)	0.12 (0.02) (0.0 – 0.15)	0.60 (0.24) (0.14– 1.3)
Brewer's Blackbird *Euphagus cyanocephalus*	6–5	5(35)	6.0 (3.1) (0.84–16.7)	0.04[2] (0.0 – 0.21)	6.2 (3.2) (0.87– 17.4)
Western Tanager *Piranga ludoviciana*	2–2	2(14)	0.35 (0.10) (0.25– 0.45)	0.13[2]	0.05 (0.01) (0.25– 0.72)
Pine Siskin *Carduelis pinus*	4–2	1(7)	0.08	ND	0.19

[1]Means (standard errors) (range)
[2]Detected in only one pool
ND = Not detected

TABLE 4. Organochlorine residues in additional prey species available to peregrines

Species	Individuals found as prey	Pools analyzed (individuals)	Residues (ppm, wet wt.)[1] DDE	PCBs	Total Organochlorines
Killdeer *Charadrius vociferus*	1	3(25)	19.5 (6.4) (10.0–31.7)	0.10[2] (0.0–0.31)	20.5 (6.9) (10.4–33.8)
Common Nighthawk *Chordeiles minor*	1	2(18)	0.35(0.15) (0.19–0.50)	ND	0.44(0.15) (0.28– 0.59)
Western Kingbird *Tyrannus verticalis*	–	2(14)	1.1 (0.68) (0.42–1.8)	0.12[2] (0.0–0.24)	1.22(0.8) (0.42–2.0)
Say's Phoebe *Sayornis saya*	–	1(7)	2.0	ND	2.1
Western Wood Pewee *Contopus sordidulus*	–	1(7)	1.2	0.15	1.5
Violet-green Swallow *Tachycineta thalassina*	1	6(42)	5.9(1.2) (0.96–8.5)	0.55(0.19) (0.21–1.5)	7.3(1.3) (2.3–11.3)
Tree Swallow *Iridoprocne bicolor*	–	1(7)	32.8	0.42	33.5
Cliff Swallow *Petrochelidon pyrrhonota*	–	1(9)	2.0	0.12	2.3
Steller's Jay *Cyanocitta stelleri*	2	1(7)	0.51	ND	0.52
Piñon Jay *Gymnorhinus cyanocephalus*	1	1(7)	0.12	0.51	0.63
Western Bluebird *Sialia mexicana*	1	1(6)	0.09	ND	0.09
Townsend's Solitaire *Myadestes townsendi*	2	2(14)	0.28(0.02) (0.26–0.30)	ND	0.40(0.01) (0.39–0.41)
Solitary Vireo *Vireo solitarius*	–	1(7)	1.9	ND	2.0
Yellow-rumped Warbler *Dendroica coronata*	–	2(13)	0.97(0.03) (0.82–1.1)	0.09[2] (0.0–0.18)	1.1(0.09) (0.84–1.3)
Brown-headed Cowbird *Molothrus ater*	1	2(14)	1.2(0.41) (0.80–1.6)	ND	1.4(0.43) (0.93–1.78)
Black-headed Grosbeak *Pheucticus melanocephalus*	–	2(14)	0.06(0.02) (0.04–0.08)	ND	0.11(0.03) (0.08–0.13)
Red Crossbill *Loxia curvirostra*	1	1(7)	0.02	0.11	0.13

[1]Means (standard errors) (range)
[2]Detected in only one pool
ND – Not detected

included species taken while peregrines were resident in the region.

There was wide variation in DDE, PCBs, and total organochlorine levels among the 12 species of prey most often found in peregrine eyries (Table 3). The White-throated Swift, American Robin, Red-winged Blackbird, Western Meadowlark, Brewer's Blackbird, and Starling were represented by sample pools where DDE was about 0.5 ppm or greater; those species clearly represented major sources of DDE to peregrines in the region. In some cases, such as Brewer's Blackbird, wide variation existed between DDE levels in pools from different localities. The White-throated Swift, the most frequently found species, had the highest average for PCBs in this group and one pool contained 0.76 ppm. The Common Flicker and Clark's Nutcracker, although represented by more than one pool, had very low organochlorine levels.

Single pools for the Pine Siskin and the Mountain Bluebird also had low residues.

Other birds in the region available to peregrines but not known to be eaten frequently also bore substantial residues (Table 4). Seven of these species seemed especially vulnerable to peregrines including the Killdeer, Brown-headed Cowbird, Western Kingbird, Common Nighthawk, Cliff Swallow, Tree Swallow, and Violet-green Swallow. The latter was abundant at many peregrine eyries and six pools averaged 5.9 ppm DDE. Although Killdeers were much less numerous, three pools averaged 19.5 ppm DDE. PCBs also were about 0.5 ppm in the Violet-green Swallow, Tree Swallow, and Pinon Jay. The latter, and the Red Crossbill, eat conifer seeds and both bore little DDE but much higher amounts of PCBs. The Violet-green Swallow had the most PCBs; six pools averaged 0.55 ppm.

Of the 29 species of birds analyzed, 17 were represented by more than one sample pool. Where only a single pool was analyzed, care must be taken in interpreting the reported residue values because of occasional wide variation between pools for the same species.

We grouped the DDE data for the 29 species by their predominant food-habits and migratory status to characterize the sources of this compound to peregrines (Table 5). The migratory category included several species that remained in the region in low numbers in winter but that generally winter to the south.

TABLE 5. Average DDE levels in peregrine prey grouped by food habits and migration status.

Status	DDE (ppm, wet wt.)		
	Granivores[1]	Omnivores	Insectivores
Migratory	0.14(0.07)[2,3]	1.30(0.80)[4]	5.81(2.98)[5]
	0.11	0.51	2.15
Permanent resident	0.07(0.03)[6]	0.32(0.11)[7]	0.06[8]
	0.06	0.23	

[1]Primarily granivores in the non-breeding season; most eat some insects in the breeding season.
[2]Arithmetic mean (standard error)
Geometric mean; where more than one pool was analyzed for a species, the average for the species was used.
[3]Mourning Dove, Black-headed Grosbeak
[4]Mountain Bluebird, Western Bluebird, Red-winged Blackbird, Western Meadowlark, Brewer's Blackbird, Brown-headed Cowbird, Western Tanager.
[5]Killdeer, White-throated Swift, Common Nighthawk, Say's Phoebe, Western Wood Pewee, Western Kingbird, Tree Swallow, Cliff Swallow, Violet-green Swallow, American Robin, Solitary Vireo, Yellow-rumped Warbler.
[6]Piñon Jay, Pine Siskin, Red Crossbill.
[7]Clark's Nutcracker, Steller's Jay, Townsend's Solitaire, Starling.
[8]Common Flicker.

Despite great variation, DDE levels among insectivorous prey were clearly higher than among omnivores and granivores. Similarly, migratory forms appeared to bear more DDE than non-migratory species of equivalent food habits. These patterns also appeared in the geometric means which tend to minimize the effect of extremely high levels found in a few species. The Common Flicker was the only resident insectivore collected, and it had an exceptionally low DDE value.

On average, peregrine eggs were 23 times more contaminated than peregrine prey. In 1977-79 peregrine eggs averaged about 21 ppm DDE. Pools of the 12 species frequently eaten by peregrines in that period (Table 3) averaged about 0.9 ppm. This degree of biomagnification of organochlorine residues is consistent with that reported for peregrines elsewhere (Cade et al. 1968; Enderson and Berger 1968).

Discussion

Peregrine Falcons in Colorado and northern New Mexico are exhibiting low occupancy of historical territories, poor reproduction, and thin-shelled eggs. Their prey contains substantial amounts of organochlorines. The population decline since the advent of DDT was estimated at about 50% by 1973 (Enderson and Craig 1974). This situation apparently has not improved. In 1980, only 5 of 18 eyries that had adult pairs sometime in 1970-77 were occupied by pairs. Two others had lone adults, and two more had pairs including immature birds, suggesting that the recruitment of adults had been inadequate. In 1973 natural reproduction was known to be very poor (0.2 young per adult pair, Enderson and Craig 1974), since 1975 the removal of eggs and substitution by captive-bred young has obscured the natural reproductive rate. Some pairs, however, were still reproducing naturally. From 1975 to 1980 we found six pairs with a total of 13 flying young late in the breeding season. Despite restriction of DDT in North America, peregrines in this region were not recovering and this contrasts with Brown Pelicans (*Pelecanus occidentalis*) (Anderson et al. 1975) and ospreys (*Pandion haliaetus*) (Spitzer et al. 1978).

Eggshells laid in 1973-79 averaged 16% thinner than pre-1947 museum eggshells, showed high variation in thickness within clutches, and some approached normal thickness (Figure 1). W. Burnham (unpublished data) has hatched all of over 30 wild eggs received intact and incubated artificially in 1979-80, but the shell condition of the majority of those eggs would almost certainly have precluded their hatching under natural incubation. Among wild peregrines egg

breakage is unusual where the thinning is less than 10% (Anderson et al. 1969; Blus 1970; Coulter and Risebrough 1973). Peregrine eggs laid in California in 1947-52 by a declining population were about 12% thinner than those laid before 1947 (Hickey and Anderson 1968) and 17% thinning was associated with lowered reproduction in Alaskan peregrines (Cade et al. 1971). An 18% thinning was associated with the declining British peregrine population (Ratcliffe 1980).

We found about 20 ppm DDE (geometric mean) in egg contents (Table 1). That value corresponds to about 18% thinning from the pre-1947 value, as predicted by a regression of thickness plotted against log DDE in egg contents for Alaskan peregrines (Cade et al. 1971). That amount of thinning is in close agreement to the 16% thinning we found.

DDE and PCBs are closely correlated in our egg samples (Table 2) and the significance of the latter is unknown. In a careful statistical analysis of organochlorine residues in Sparrowhawks, Newton and Bogan (1978) found PCBs showed the strongest relationship of any compound with egg addling, and they concluded from the literature that PCBs have not been linked to eggshell thinning in field or controlled laboratory studies. McLane and Hughes (1980) found no effect on eggshell thickness, young hatched, and young fledged in captive Screech Owls fed Aroclor 1248 where levels reached from 3.9-17.8 ppm in egg contents. In the present study, PCB levels are below these, and since the peregrine eggs incubated artificially hatched successfully there is no evidence PCBs have impaired reproduction in this population.

Prey available to peregrines in the region showed extreme variation in DDE contamination (Tables 3 and 4), and the intake of contaminants by individual peregrines would depend on the prey species taken. At least six species of commonly eaten prey are ubiquitous and are represented by pools of individuals with about 0.5 ppm DDE or more. Among the 29 species of prey we analyzed, 19 had at least one pool with about 0.5 ppm DDE or more and 11 had 1.0 ppm or more. Even if peregrines accumulated DDE in wintering areas, we believe that the major sources were migrant prey available near peregrine eyries in summer.

Because prey selection by peregrines in the region is no doubt subject to many vagaries, and because of the great variation of DDE contamination in prey, it is difficult to correlate the residues we found in prey with the DDE and shell thinning in falcon eggs. In fact, a day-to-day variation in DDE intake by a laying peregrine may have caused the wide variation in eggshell thickness within a clutch. Several laboratory and field studies have found shell thinning in birds fed DDE. Captive Black Ducks (*Anas rubripes*) and Mallards (*Anas platyrhynchos*) produced eggs 8 to 22% thinner than controls when fed about 3 ppm DDE (wet weight) for periods up to a year (Heath et al. 1969, Longcore and Samson 1973). Ring Doves (*Streptopelia risoria*) fed about 3 ppm DDE (wet weight) produced eggs 9.2% thinner than controls (Peakall et al. 1973). Among raptors, Screech Owl (*Otus asio*) eggs were found to be thinned by 13.3% when the birds were placed on a diet containing 2.8 ppm DDE (McLane and Hall 1972). Lincer (1975) fed captive American Kestrels 3 ppm DDE 2-3 months prior to egglaying and recorded a 14% decrease in eggshell thickness compared to controls. Dose-response curves he calculated predicted that 1 ppm of dietary DDE would produce about 7% thinning, and 2 ppm DDE about 11% thinning. He was also able to show that both experimental and wild kestrels showed the same shell-thinning response to DDE. The experimental birds did lay thinner-shelled eggs overall, perhaps due to genetic differences or the effects of captivity.

Aleutian peregrines are apparently reproducing normally. They are non-migratory and suffer only 7.7% shell thinning (White et al. 1973). Analyses of up to three individuals of 12 commonly eaten prey species revealed that only two migrant birds had whole-body DDE levels above 0.37 ppm DDE, and none above 1.88 ppm. These few analyses and a count of many food remains found at eyries indicated that the bulk of Aleutian peregrines prey contained less than 0.5 ppm DDE.

The above studies suggest that peregrines feeding heavily on prey exceeding about 1 ppm DDE in the breeding season could be expected to produce eggs with shells thinned by the amount we found even if they had no important previous exposure to DDE. The presence of several pools among our samples with over 5 ppm DDE does not hold much promise for normal peregrine reproduction.

Since 1974, 128 captive-bred young peregrines have been released in Idaho, Wyoming, Utah, Colorado, South Dakota and New Mexico by placing young in eyries, cross-fostering to prairie falcons, or by "hacking" the young until they became independent. When young were placed in the eyries of wild peregrines, fledging success was as good or better than that expected in a DDE-free population (Burnham et al. 1978), but because of the DDE levels revealed in the present study released birds can be expected to reproduce poorly. Under these conditions, the release of captive-bred birds serves to augment reproduction and hopefully increase the population. In 1980, a banded male that was almost certainly a released bird bred in Colorado. Released birds surely will help to maintain the occupancy of traditional eyries, and

because of the diversity of the captive breeding stock they will enhance the genetic variability of the small wild population.

Moreover, this augmentation should arrest the decline until DDE levels subside in peregrine prey, especially migrant species. A report of such a reduction in migratory songbirds is encouraging (Johnston 1974), but is offset by the finding that, nationwide, DDE in starlings increased significantly from 1974 to 1976 so that they returned to 1970 values (White 1979). The pronounced contamination by DDE in migratory prey suggests acquisition of residues on their wintering grounds. This possibility needs prompt study requiring international cooperation because several of the migrant species winter south of the United States. If the residues in migrants could be reduced to those found in resident prey, the peregrine population in the Rocky Mountain region would very likely become self-sustaining.

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